Effects of Travel Technique and Gender on a Divided Attention Task in a Virtual Environment

Evan A. Suma* Samantha L. Finkelstein* Seth Clark* Paula Goolkasian* Larry F. Hodges†

*University of North Carolina at Charlotte † Clemson University

Abstract

We report a user study which compared four virtual environment travel techniques using a divided attention task. Participants used either real walking, gaze-directed, pointing-directed, or torso-directed travel to follow a target through an environment while simultaneously responding to auditory stimuli. In addition to travel technique, we investigated gender as a between-subjects variable and task difficulty (simple or complex) and task type (single or divided) as within-subjects variables. Real walking allowed superior performance over the pointing-directed technique on measures of navigation task performance and recognition of stimuli presented during navigation. This indicates that participants using real walking may have had more spare cognitive capacity to process and encode stimuli than those using pointing-directed travel. We also found a gender-difficulty interaction where males performed worse and responded slower to the attention task when the spatial task was more difficult, but no differences were observed for females between difficulty levels. While these results may be pertinent for the design of virtual environments, 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.

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

Keywords: virtual environments, locomotion, navigation, user study

1 Introduction

Navigation is perhaps the most important and universal task performed when interacting with any 3D user interface [6]. The physical control of the user's viewpoint, known as *travel*, 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 drawbacks of this approach make empirical evaluation against cheaper alternatives valuable to justify the potential tradeoffs. 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. In this paper, we describe a user study which compared real walking to three virtual travel techniques during performance of a divided attention task.

*e-mail: {easuma, sfinkel1, seclark1, pagoolka}@uncc.edu
†e-mail: lfh@clemson.edu

IEEE Symposium on 3D User Interfaces 2010
20-21 March, Waltham, Massachusetts, USA
978-1-4244-6847-8/10/$26.00 ©2010 IEEE

Real walking allows users to travel by walking through the virtual environment in a natural manner. Consequently, the size of the virtual environment is restricted by the amount of available walking space, making this technique impractical for settings with limited physical workspace. Additionally, real walking requires position and orientation tracking over areas that are much larger than the 1.5-3 meter diameter spaces typically supported by electromagnetic tracking technology [30]. Wide-area tracking solutions such as the Intersense IS-900 and the 3rdTech Hiball are more expensive than limited-area trackers, and this cost increases as the tracking area is expanded. As a result, alternative travel techniques are often used to avoid the limitations of real walking. Many attempt to replicate the energy and motions of real locomotion while keeping the user within a limited physical area. *Walking-in-place* techniques achieve this goal by having the user march in a stationary location to travel through the environment (ex. [14]). Mechanical devices such as treadmills (ex. [24]) and bicycles (ex. [2]) have also been developed to simulate real motion when traveling. Alternatively, *redirected walking* has also been proposed as a method to overcome the space limitations of real walking by introducing a rotational discrepancy between the real and virtual world [21]. Another proposed technique accomplishes this goal by applying a scaled translation gain to allow walking over greater virtual distances [13].

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. In the context of this paper, we are concerned with steering techniques, which allow continuous control of the direction of travel [6]. The simplest technique is gaze-directed steering, which uses the user's view vector as the direction of motion. Pointing-directed steering is another common technique which uses the hand orientation to indicate travel direction. Torso-directed steering, on the other hand, uses the orientation of the user's body. The latter two techniques decouple the view direction from the travel direction, which allows the user the advantage of looking around while moving, though the torso-directed technique is rarely used in practice. While other steering techniques have been developed which use more complicated props or controllers, this paper concentrates on these three basic steering methods which rely on the user's body to specify travel direction.

We conducted a user study which investigated real walking, gaze-directed, pointing-directed, and torso-directed steering along with gender and difficulty effects using a divided attention task. In Section 2, we outline previous work evaluating travel in immersive virtual environments and describe the novel contributions of our study. In Section 3, we explain the methodology of our experiment. We describe the results of the user study in Section 4 and provide a discussion in Section 5. Finally, in Section 6, we describe future directions for this work and conclude the paper.

2 Previous Work

2.1 Real Walking Studies

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 [28]. In a spatial orientation study, real walking was also shown to perform better than gaze-directed travel

Previous Travel Technique Studies

Study	*RW*[1]	*WIP*[2]	*GD*[3]	*PD*[4]	*TD*[5]	*DESK*[6]
[4]			√	√		
[5]			√	√	√	
[8]	√		√			√
[15]			√			√
[22]	√		√			√
[23]	√		√			√
[25]	√		√	√		
[26]	√		√			
[28]	√	√		√		
[31]	√	√	√			
[33]	√		√			√

Table 1: Comparison of previous studies of 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.

and traditional joystick control [8]. Ruddle and Lessels found in two studies that real walking resulted in superior performance over gaze-directed travel on a navigational search task [22] [23]. Suma et al. found that real walking allowed fewer collisions and faster completion times in a virtual maze than pointing-directed travel, though they did not find any difference between travel techniques on measures of information gathering [25]. In this context, "information gathering" refers to performance on tests of memory about environment details noticed during exploration. In a study of cognition, Zanbaka et al. found benefits for real walking over gaze-directed steering on cognitive measures involving higher mental processes [33]. However, in a study comparing real world navigation to virtual environment navigation using real walking and gaze-directed travel, similar cognitive benefits and information gathering differences were not found between travel techniques, although participants in the virtual environment conditions performed worse than in the real world [26]. They did, however, find that quantitative measurements of navigational behavior did not resemble real world behavior. Similarly, in a study to characterize task behavior and performance, Whitton et al. found that that walking-in-place and gaze-directed steering do not correlate well with motions when walking naturally [31].

2.2 Virtual Steering Technique Studies

In studies that specifically compared virtual steering techniques, it has been shown that pointing-directed travel has advantages over gaze-directed for a relative motion task [4]. This is because pointing decouples view and travel direction, making it easier to track a target object while moving. In one information gathering study, no differences were found between gaze-directed, pointing-directed, and torso-directed steering, and complexity of the environment was the only determining factor of performance [5]. In another information gathering study, participants gathered less information in a virtual environment using gaze-directed steering than in an identical real world environment [15]. Since they did not test real walking in the virtual environment, it is impossible from their data to conclude whether this difference was due to travel technique or differences between the real and virtual environments.

2.3 Summary of Previous Work

In general, studies of travel have been inconsistent in selecting the travel technique to evaluate, especially among the three virtual steering techniques (see Table 1). Gaze-directed travel was the most commonly evaluated technique. However, while four out of 11 studies evaluated pointing-directed travel, only one compared the torso-directed technique. These three techniques, though similar in that they rely on parts 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, the goal of our study is to comprehensively evaluate real walking, gaze-directed, pointing-directed, and torso-directed travel. This experiment will allow us to examine the whole picture of the relationship between real walking and body-based steering techniques. 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 the cognitive difficulty of navigation.

Information gathering was investigated by several studies and presented as a measurement of relative cognitive difficulty between travel techniques, but none of them found significant differences. However, this measurement could be confounded by individual differences in wayfinding strategy and proficiency of the user. 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 [3]. More specifically, the resulting differences in the participants' explorations in the environment could result in each participant seeing different stimuli for varying amounts of time. To remedy this problem, our attention task presented stimuli auditorily as the participant moved through the environment. Thus, subsequent memory tests of these stimuli will be less subject to bias from individual differences in navigation between participants. Additionally, the navigation task was designed as pursuit of a visible moving target instead of naive exploration to reduce effects of different wayfinding strategies as much as possible.

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 [9]. We also investigated gender effects, since they have been shown to be a strong determining factor of performance on spatial tasks [29]. 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 [17]. Recent work has also investigated gender differences in abilities to discriminate between real and virtual motions [7]. 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 [3] [5]. Therefore, we designed two levels of difficulty for our spatial navigation task. Additionally, previous studies have suggested that inconsistent spatial abilities across between-subjects groups could skew experimental results [25] [26]. Thus, we administer two common pen-and-paper pre-tests of spatial ability, along with an immersive virtual reality spatial orientation test, in order to explore potential confounds of our results.

3 Methods

3.1 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). These trials are described in more detail in Section 3.3. 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.

3.2 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.

3.3 Environment and Task

The virtual environment was designed as an empty room with six columns placed to form a grid of corridors (see Figure 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.

3.3.1 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.

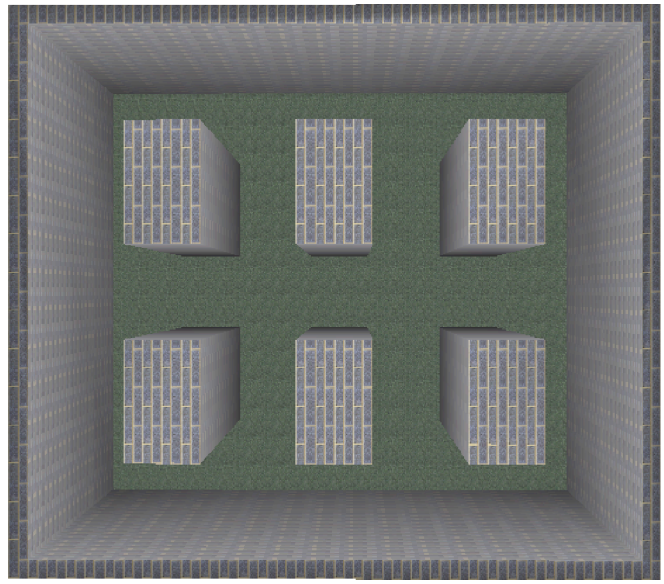

Figure 1: A top-down view of the virtual environment used in this study.

3.3.2 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.

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 [19]. 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 [11]. 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.

3.4 Experiment Setup

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. 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

(a) Real Walking (RW) (b) Gaze-Directed (GD) (c) Pointing-Directed (PD) (d) Torso-Directed (TD)

Figure 2: (a) When using the real walking technique, participants could naturally walk about the space. (b-d) When using virtual travel techniques, physical movement was restricted and movement was controlled using a handheld joystick.

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. Figure 2 shows the equipment used during the study.

In the torso-directed condition, it was 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. For user input, participants held a Nintendo Wii Nunchuk controller in their dominant hand. The Nunchuk was connected with a wire to a Nintendo Wimote 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 Hiball 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. Locomotion was controlled using the thumb stick on the Nunchuk, which allowed participants to control velocity along a continuous spectrum up to a maximum speed of 3 feet per second. In the pointing-directed condition, an arrow was rendered at the position and orientation of the participant's hand to provide visual feedback of the travel direction.

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. While virtual travel could be accomplished 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 (gaze, pointing, and torso-directed) 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. 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, the size of the virtual environment and fast-paced nature of the pursuit task required participants to use the controller for navigation. During the experiment, 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.

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, previous research has indicated that collisions with stationary objects while using the real walking technique are uncommon [26], and this collision-handling technique was necessary to prevents participants from "cheating" by walking through virtual obstacles.

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 [27]. For reading input events from the Nintendo Wiimote, we used the WiiYourself! library [1].

3.5 Measures

3.5.1 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. This allows us to measure the relative cognitive demand of navigation using different travel techniques.

3.5.2 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) [10]. The confidence score was calculated as an average of these ratings.

3.5.3 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 [16].

3.5.4 Spatial Ability Pre-Tests

We used several tests to evaluate spatial ability. Participants took the Vandenberg & Kuse Mental Rotations Test (Redrawn Version) [20] and the Guilford-Zimmerman Aptitude Survey Part 5: Spatial Orientation [12]. 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 [18]. It yielded a score between -9 and 36. In both tests, higher scores corresponded to better performance.

Previous studies and anecdotal evidence suggests that these pen-and-paper spatial tests are difficult for some participants, and may not be always earnestly attempted [25]. 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.

3.6 Procedure

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

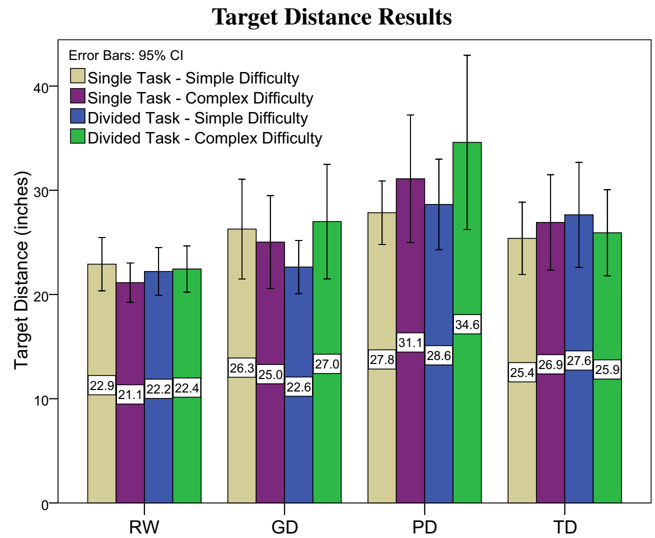

Figure 3: Mean target distance results (in inches) across travel conditions for all four trials with varying task type (single or divided) and task difficulty (simple or complex). Overall, the real walking (RW) technique performed significantly better than the pointing-directed (PD) technique. No other comparisons were significantly different.

3.6.1 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.

3.6.2 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.

3.6.3 Post-Experiment

Immediately after completing the experimental session, the participants filled out the post-test for simulator sickness. Afterwards, they were debriefed and the participants were given a final opportunity to ask questions or provide comments.

4 RESULTS

Unless otherwise noted, all statistical results reported in this paper use a significance value of $\alpha = .05$. All analyses used Type III sum

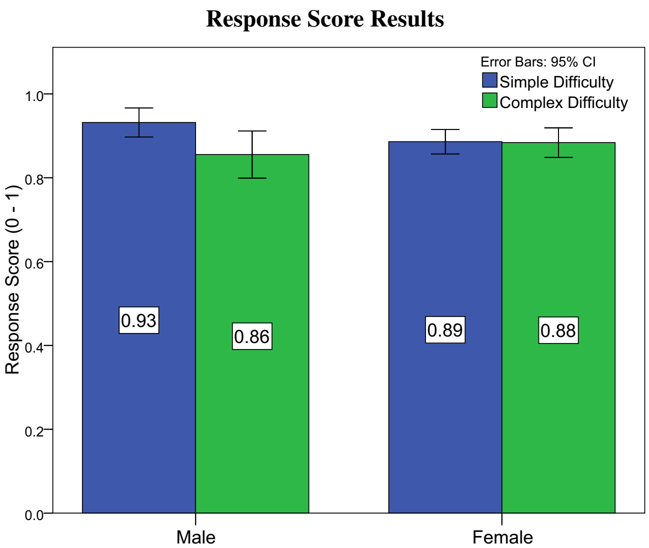

Figure 4: Response scores (between 0 and 1) were calculated by subtracting the percentage of false alarms (responding to distractors) from the percentage of hits (responding to category words). Higher scores corresponding to better performance. Males performed worse in the complex difficulty than the simple difficulty, but this difference was not observed for females.

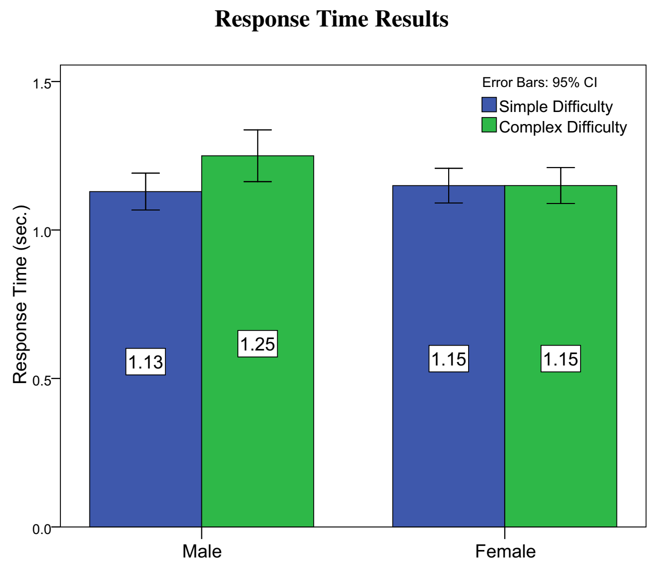

Figure 5: Mean response times (in seconds) according to gender and task difficulty (simple or complex). Lower times correspond to better performance. Males responded slower in the complex difficulty than the simple difficulty, but this difference was not observed for females.

of squares to correct for the uneven gender proportions within each group.

4.1 Task Performance Measures

4.1.1 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.

4.1.2 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 ($M = .89$, $SD = .13$), $p = .92$. Figure 4 shows the mean response score results by gender.

4.1.3 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 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., $SD = 0.20$), $t(43) = 2.85$, $p < .01$. 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 shows the mean response time results by gender.

4.2 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 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 6 shows the mean word recognition scores for each task difficulty across the travel conditions. Table 2 shows the mean and standard deviation results for the recognition scores and confidence ratings.

4.3 Pre-Tests

The scores from each of the spatial ability pre-tests were treated with a one-way ANOVA across the four travel conditions, and none

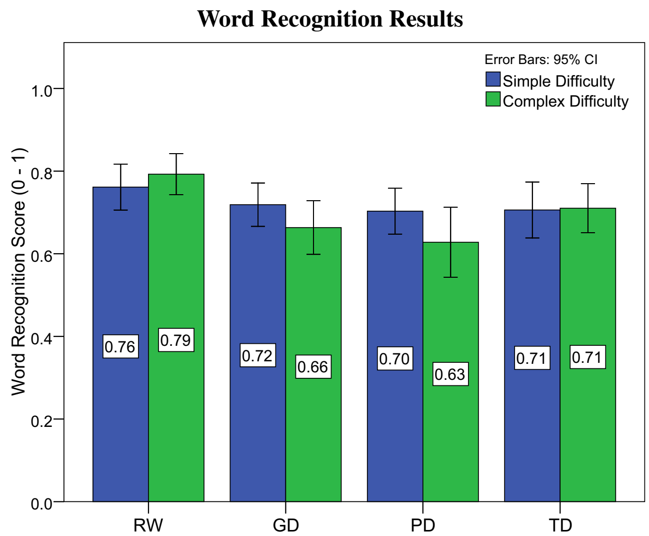

Figure 6: Mean word recognition test scores (between 0 and 1) according to travel technique and difficulty (simple or complex). Higher numbers correspond to better performance. Overall, the real walking (RW) technique performed significantly better than the pointing-directed (PD) technique. No other comparisons were significant.

Word Recognition and Confidence Scores

	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)

Table 2: 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).

of the results were statistically significant. 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 Discussion

Participants that used the real walking technique were able to perform the primary navigation task better than those using the pointing-directed technique. These results are consistent with previous findings which showed that the pointing-directed technique tends to underperform real walking on measures of navigation task performance [26]. Additionally, 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 previous studies of travel techniques with fewer participants were not able to find differences between these travel techniques on tests of short term memory [5] [26] [33]. However, since these previous results were testing memory of objects seen during exploration of the virtual environment, these previous studies may have been biased by 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 most 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.

Intuitively, one may suppose real walking would outperform all the virtual travel techniques. However, there were no significant differences between real walking, gaze-directed, or torso-directed travel. Previous studies that compared real walking to gaze-directed travel did not find differences in measures of information gathering [25] [26]. The one study that compared all three virtual travel techniques (but not real walking) also reported similar findings [5]. Thus, our results are consistent with combined results from existing literature, and add validity to these findings. Additionally, considering that torso-directed travel is rarely used in practice, it is interesting to note that the results for that 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. Although gender differences in spatial abilities generally tend to favor males, this gender-difficulty interaction effect occurred only on performance of a semantic attention task during a simultaneous spatial task. These results may be pertinent when designing virtual environments that require multi-tasking, 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.

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 [32], which is another possible explanation for this small increase.

6 Conclusions and Future Work

In this study, we compared real walking with three virtual travel techniques using a divided attention task. Real walking allowed superior performance over the pointing-directing technique on measures of navigation task performance and recognition of stimuli presented during navigation. These results indicate that real walking provides better performance on navigation tasks than the pointing-directed technique. Additionally, real walking also appears to allow more spare cognitive capacity for processing and encoding stimuli than pointing-directed travel. We also found that males responded slower and performed significantly worse on the attention task when the spatial task became more difficult; however, this effect was not observed for females.

In the future, more study is necessary to investigate the differences between the torso-directed technique and the pointing-directed technique. It may be possible to utilize torso-directed travel to avoid introducing the drawbacks of the pointing-directed technique when the user's travel direction needs to be separated from their view, but this relationship remains unclear from our data. Additionally, other travel techniques should be comprehensively evaluated, including walking-in-place, gesture-based navigation, and virtual travel techniques which are not steering-based, such as path drawing and world-in-miniature techniques.

References

[1] http://wiiyourself.gl.tter.org.

[2] S. Babu, T. Grechkin, B. Chihak, C. Ziemer, J. Kearney, J. Cremer, and J. Plumert. A virtual peer for investigating social influences on children's bicycling. In *IEEE Virtual Reality*, pages 91–98, 2009.

[3] D. A. Bowman, E. T. Davis, L. F. Hodges, and A. N. Badre. Maintaining spatial orientation during travel in an immersive virtual environment. *Presence: Teleoperators & Virtual Environments*, 8(6):618–631, 1999.

[4] D. A. Bowman, D. Koller, and L. F. Hodges. Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In *Proceedings of the Virtual Reality Annual International Symposium*, pages 45–52, 1997.

[5] D. A. Bowman, D. Koller, and L. F. Hodges. A methodology for the evaluation of travel techniques for immersive virtual environments. *Virtual Reality*, 3(2):120–131, 1998.

[6] D. A. Bowman, E. Kruijff, J. J. LaViola, and I. Poupyrev. *3D User Interfaces: Theory and Practice*. Addison Wesley Longman Publishing Co., Inc., Redwood City, CA, USA, 2004.

[7] G. Bruder, F. Steinicke, H. Frenz, M. Lappe, and K. H. Hinrichs. Impact of gender on discrimination between real and virtual stimuli. In *Workshop on Perceptual Illusions in Virtual Environments*, pages 10–15, 2009.

[8] S. S. Chance, F. Gaunet, A. C. Beall, and J. M. Loomis. Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. *Presence: Teleoperators & Virtual Environments*, 7(2):168–178, 1998.

[9] N. Elmqvist, M. E. Tudoreanu, and P. Tsigas. Evaluating motion constraints for 3D wayfinding in immersive and desktop virtual environments. In *ACM SIGCHI*, pages 1769–1778, 2008.

[10] P. Foos and P. Goolkasian. Presentation format effects in a levels-of-processing task. *Experimental Psychology*, 55(4):215–227, 2008.

[11] N. W. Francis and H. Kučera. Frequency analysis of English usage: Lexicon and grammar. *Journal of English Linguistics*, 18(1):64–70, 1982.

[12] J. Guilford and W. Zimmerman. The Guilford-Zimmerman aptitude survey. *Journal of Applied Psychology*, 32:24–34, 1948.

[13] V. Interrante, B. Ries, and L. Anderson. Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In *IEEE Symposium on 3D User Interfaces*, pages 167–170, 2007.

[14] J. J. Feasel, M. Whitton, and J. Wendt. LLCM-WIP: Low-latency, continuous-motion walking-in-place. In *IEEE Symposium on 3D User Interfaces*, pages 97–104, 2008.

[15] D. Jeong, C. Lee, G. Jeon, C. Song, S. Babu, and L. Hodges. Differentiation on information gathering ability in real and virtual world. In *International Conference on Pacific Graphics*, pages 157–159, 2005. Short paper.

[16] R. Kennedy, N. Lane, K. Berbaum, and M. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology*, 3(3):203–220, 1993.

[17] S. Lambrey and A. Berthoz. Gender differences in the use of external landmarks versus spatial representations updated by self-motion. *Journal of Integrative Neuroscience*, 6(3):1769–1778, 2007.

[18] S. Moffata, E. Hampsona, and M. Hatzipantelisa. Navigation in a "virtual" maze: Sex differences and correlation with psychometric measures of spatial ability in humans. *Evolution and Human Behavior*, 10(2):73–87, 1998.

[19] B. B. Murdock. Item and order information in short-term serial memory. *Journal of Experimental Psychology: General*, 105(2):191 – 216, 1976.

[20] M. Peters, B. Laeng, K. Latham, M. Jackson, R. Zaiyouna, and C. Richardson. A redrawn Vandenberg & Kuse mental rotations test: Different versions and factors that affect performance. *Brain and Cognition*, 28:39–58, 1995.

[21] S. Razzaque. *Redirected Walking*. PhD thesis, University of North Carolina at Chapel Hill, 2005.

[22] R. A. Ruddle and S. Lessels. For efficient navigational search, humans require full physical movement, but not a rich visual scene. *Psychological Science*, 17(6):460–465, 2006.

[23] R. A. Ruddle and S. Lessels. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction*, 16(1):1–18, 2009.

[24] M. C. Schwaiger, T. Thummel, and H. Ulbrich. A 2D-motion platform: The Cybercarpet. In *Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 415–420, 2007.

[25] E. Suma, S. Babu, and L. Hodges. Comparison of travel techniques in a complex, multi-level 3D environment. In *IEEE Symposium on 3D User Interfaces*, pages 147–153, 2007.

[26] E. Suma, S. Finkelstein, M. Reid, S. Babu, A. Ulinski, and L. Hodges. Evaluation of the cognitive effects of travel technique in complex real and virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 2009. Preprint.

[27] R. M. Taylor, T. C. Hudson, A. Seeger, H. Weber, J. Juliano, and A. T. Helser. VRPN: a device-independent, network-transparent VR peripheral system. In *ACM Virtual Reality Software & Technology*, pages 55–61, 2001.

[28] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks. Walking > walking-in-place > flying, in virtual environments. In *ACM SIGGRAPH*, pages 359–364, 1999.

[29] D. Voyer, S. Voyer, and M. P. Bryden. Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, 117(2):250–270, 1995.

[30] G. Welch and E. Foxlin. Motion tracking: No silver bullet, but a respectable arsenal. *IEEE Comput. Graph. Appl.*, 22(6):24–38, 2002.

[31] M. C. Whitton, J. V. Cohn, J. Feasel, P. Zimmons, S. Razzaque, S. J. Poulton, B. McLeod, and J. Frederick P. Brooks. Comparing VE locomotion interfaces. In *IEEE Virtual Reality*, pages 123–130, 2005.

[32] S. D. Young, B. D. Adelstein, and S. R. Ellis. Demand characteristics in assessing motion sickness in a virtual environment: Or does taking a motion sickness questionnaire make you sick? *IEEE Transactions on Visualization and Computer Graphics*, 13(3):422–428, 2007.

[33] C. A. Zanbaka, B. C. Lok, S. V. Babu, A. C. Ulinski, and L. F. Hodges. Comparison of path visualizations and cognitive measures relative to travel technique in a virtual environment. *IEEE Transactions on Visualization and Computer Graphics*, 11(6):694–705, 2005.