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# Evaluating the Impact of Limited Physical Space on the Navigation Performance of Two Locomotion Methods in Immersive Virtual Environments

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## ABSTRACT

Consumer level virtual experiences almost always occur when physical space is limited, either by the constraints of an indoor space or of a tracked area. This observation coupled with the need for movement through large virtual spaces has resulted in a proliferation of research into locomotion interfaces that decouples movement through the virtual environment from movement in the real world. While many locomotion interfaces support movement of some kind in the real world, some do not. This paper examines the effect of the amount of physical space used in the real world on one popular locomotion interface, resetting, when compared to a locomotion interface that requires minimal physical space, walking in place. The metric used to compare the two locomotion interfaces was navigation performance, specifically, the acquisition of survey knowledge. We find that, while there are trade-offs between the two methods, walking in place is preferable in small spaces.

**Keywords:** Virtual Reality, Locomotion Methods, Walking in Place, Resetting

**Index Terms:** Human-centered computing—Human computer interaction (HCI)—Interaction Paradigms—Virtual Reality

## 1 INTRODUCTION

The ability to successfully navigate through large immersive virtual environments is critical for the success and widespread adoption of this technology, yet major challenges with navigation and locomotion interfaces exist [1]. In particular, most users of virtual environments are confined to a limited physical space in which to move, but the virtual environments through which they want to move are usually substantially larger than this physical space. The limits of physical space are a problem that has been examined for virtual locomotion interfaces in a variety of contexts [4, 56, 58, 64, 90]. In this paper, we directly and comparatively examine how the size of the physical space affects the performance of virtual locomotion interfaces by examining it as a factor when comparing two well-known interfaces, walking-in-place [21, 65, 70] and resetting [41, 45, 83, 88].

An important question is how to judge whether a locomotion method works *well*. Different performance criteria exist by which a locomotion interface can be designed, tuned, or optimized to perform well [80]. Common performance metrics include breaks in presence [44], simulator sickness [18, 19, 38], and judgments of relative direction [83]. The main applications that drive our research are motivated by spatial learning and thus we focus on the acquisition of spatial knowledge as a key performance metric. A significant body of work shows that the locomotion interface can play a key role in the acquisition of spatial knowledge [53, 54, 85, 86]. This research tends to show that walking methods outperform other methods, e.g., joystick, teleportation, and flying, and that the addition of body-based motion is important [51]. In this paper we compare two methods of navigation with the acquisition of spatial knowledge as our primary performance criterion. Specifically, we look at how the locomotion method affects the acquisition of survey knowledge [10, 29], which refers to the knowledge of the straight-line distances and directions between places defined in a common frame of reference.

When acquiring spatial knowledge of an environment, people use information gathered from both external and internal sources to determine their position and the location of goals. External, or *allothetic* cues are aspects of the environment, such as landmarks, that provide information to the navigator about the layout of the environment and their position in it. Internal, or *idiothetic* cues provide information about self-motion, and include such information sources as proprioception, vestibular cues, and optic flow. In sufficiently limited physical spaces, all locomotion methods for virtual environments interfere with idiothetic cues in some way. For example, joystick locomotion removes the proprioceptive and some or all vestibular cues of self-motion [51], depending on its implementation. Teleportation removes optic flow, proprioceptive cues, and vestibular cues [9]. Redirected walking can cause conflicts between optic flow and other idiothetic cues if done in limited spaces [19, 63].

From this point of view, the two locomotion methods we choose to compare in this paper, walking-in-place and resetting, have certain advantages. Walking-in-place is a locomotion method in which walking is simulated using walking-like leg motions in a stationary position [66]. In our implementation, turning is accomplished by users rotating their body. This method of locomotion takes only standing space, and provides some form of vestibular, proprioceptive, and optic flow cues. Disadvantages of the method are that the simulated walking motion can be fatiguing and the idiothetic cues are not completely natural. Regardless, this is a popular locomotion and has been shown to have reasonable performance in some spatial knowledge tasks [21, 41, 47, 70]. Resetting is a method that permits natural walking except when the boundaries of the physical space are reached, where rotational gains are amplified to turn the user back toward the center of the space in discrete resetting motion. Thus, this method of locomotion interferes with vestibular cues when the reset occurs. Its advantage is that it permits natural walking outside of these resets and is naturally amenable to modification of the walking area. Its disadvantage is that there is an interruption in the locomotion that can incur a cognitive cost or a break in presence. While this cognitive cost has not been quantified in any prior work of which we are aware, this locomotion has also been shown to have reasonable performance in spatial knowledge tasks [83].

In particular, both resetting and walking in place have previously been evaluated in terms of the acquisition of survey knowledge for a fixed space [41]. Specifically, Paris et al. [41] compared resetting and walking in place in 4 m x 4 m space. That paper discovered that resetting outperformed walking in place in terms of how well users acquired survey knowledge. But, of course, walking in place

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methods require significantly less space than that to work, essentially only requiring comfortable standing space. Thus an open question is how resetting would perform when the available space is smaller, and that is the primary research question we address in this paper.

Survey knowledge, among other types of spatial knowledge, allows the planning of independent routes of travel, that is, independent navigation [13, 69]. People's ability to navigate, however, varies among individuals and depends on different skills and cognitive processes [24, 29, 79]. We are interested in how these individual differences might be affected by the choice of locomotion method and by the surrounding environment (amount of space) that a locomotion interface operates in. This is a concern particularly for resetting, as Williams et al. [83] noted that there was a cognitive cost to resets. It is possible that a reset represents interference in people's ability to acquire the directional component of survey knowledge. Resetting could interfere in other ways, as well, since people might, for example, infer distance information from the breaks that occur when a reset happens. Likewise, walking in place methods deprive the user of vestibular information that has been found to be important in navigation [11,41], but do provide body-based cues [12]. It is possible that some individuals are able to use body-based cues more effectively in navigation than others. Thus, an additional research question we seek to answer is how we can assess and understand individual differences that occur when using these locomotion interfaces and environmental constraints.

To answer these questions, we designed a between groups user study where participants first learned a locomotion interface, walking in place or resetting, and then learned the layout of a virtual maze that was larger than the physical space available to them. There were three groups who used the resetting interface, walking in a 2 m x 2 m space, a 3 m x 3 m space, or a 4 m x 4 m space, respectively, and one group using the walking in place locomotion interface. After learning the spatial layout of the maze, participants were tested on their knowledge of directions and straight line distances within the maze. This experimental paradigm for assessing the acquisition of survey knowledge is based on one used by Chrastil & Warren [12]. We also assessed participants using a self-reported measure of sense of direction [25], a test of spatial working memory [30], a test of ability to imagine spatial transformations [72], and measured self-reported simulator sickness [17]. Our results show that individuals can acquire survey knowledge using both locomotion interfaces in all spaces, but that performance of resetting in the 2 m x 2 m and 3 m x 3 m physical spaces is significantly worse than walking in place.

This paper therefore makes the following contributions. To our knowledge, this paper is the first to use physical space as a factor in comparing the performance of the resetting locomotion interface to walking in place. The paper is also the first to establish the effect of individual differences on these locomotion interfaces. These findings can provide direct guidance on when to use a walking interface versus a standing only interface. Theoretically, it provides some insights into the significance of body-based cues compared to proprioceptive ones, which has been the topic of significant study in virtual environments [9, 20, 51, 52].

In Section 2 we review related work. Section 3 describes the experimental protocols and design approaches. In particular, we describe the specific implementation details of our locomotion methods in Section 3.3. To preview, the first locomotion method is the walking in place algorithm taken from Hanson et al. [21]. We implemented the basic walking in place method for the Oculus Go. Walking in place works by inducing forward motion when a step is detected. The specific resetting method uses the algorithm from Paris et al. [41] and is a variant of the 2:1 resetting method of Williams et al. [83]. It was adjusted only to fit into one of three spaces (see Section 3.4). Section 4 describes our performance measures and Section 5 presents the results of the experiment in terms of these measures. Finally, Sections 6 and 7 critically discuss these results and conclude.

## 2 Related Work

This section discusses prior research on locomotion interfaces, spatial learning, and the impact of individual differences, placing the present research in context.

### 2.1 Locomotion Methods

There is a large volume of literature on locomotion methods for navigation throughout immersive virtual environments [1]. Some of these works facilitate natural walking [28, 49, 83, 84], while others simulate walking [70, 91], or use more abstract metaphors for locomotion [22, 31, 60]. Each method has its advantages and disadvantages, which requires developers to carefully consider them before implementation. Factors like room size and layout [3], tracking and input technology, the virtual environment [35], performance metrics, etc. dictate which locomotion method is most appropriate. Performance metrics such as breaks in presence [44], simulator sickness [19], and judgments of relative direction [83] can all reveal the success of the locomotion method used. In some cases, locomotion methods can be improved with machine learning implementations [58]. The two locomotion methods that we focus on in this work are resetting and walking in place.

Overt manipulation of a user's rotation when navigating about a virtual environment has been shown to be tolerable [33, 48], which has allowed for the development of resetting. In this methodology, users are reoriented away from objects and boundaries in order to stay within a tracked space. Visual cues can dominate proprioceptive and vestibular cues when in conflict [34], and this allows reorientation to be believable and natural. Several works have shown that resetting can be successful without being perceptible [44, 50, 83], but sometimes not without some cognitive cost [83].

Another locomotion method for navigating about a virtual environment is walking in place, which uses proprioceptive information from the action of walking to translate the user. To detect walking, information is taken from head [70], arm [85], and leg [71, 81, 86] motion. There are several studies that have found walking in place to be better at eliciting presence from users than joystick-based motion [44, 45, 61, 62] along with better spatial ability [43, 51, 54, 55].

### 2.2 Spatial Learning

Theories of how people acquire spatial knowledge have proposed at least three forms of how space is represented mentally [59]: landmark knowledge, that is, knowledge of visual structures that can help people orient themselves; route knowledge, the memory of a sequence of locations and environmental features that comprise a navigable path; and survey knowledge, metric knowledge of straight line distances and directions between locations in space. A fourth type of knowledge, graph knowledge, quasi-metric information of paths and their approximate lengths and angles, also seems to be learned [13,15,75]. Survey knowledge implies the cognitive development of a survey map of landmarks in an environment (i.e., one with distance and directional information). One attains this knowledge through experience; when familiarizing oneself with an environment one gains knowledge about the distances along previously traveled paths, and through the process of path integration, acquires knowledge about the directions and distances between landmarks. Survey knowledge is considered the highest and most complete form of knowledge one can attain about an environment [59].

There is a large amount of literature that looks at active and passive spatial knowledge acquisition in immersive virtual environments, and most of it is concerned with how body-based cues facilitate spatial learning [11, 12, 16, 46, 73, 74]. Typically, active learning facilitates better knowledge acquisition in these environments when both translational and rotational body-based cues are provided. There is a cluster of work that looks at how different locomotion methods affect spatial knowledge acquisition. Paris et al. studied the difference in survey knowledge acquisition between resetting and walking in place locomotion methods to find that resetting outperforms walking in place in a fixed resetting area [41]. Continuous methods of walking are the most beneficial to acquiring survey knowledge [42, 89], and dyads have been shown to acquire survey knowledge better than individuals in immersive virtual environments [7]. This work builds upon the work of Paris et al. [41] by examining the performance of those locomotion methods with the physical space is flexible.

### 2.3 Individual Differences

Cognitive psychologists have shown that individual differences contribute to spatial ability, and it takes some individuals longer than others to acquire accurate spatial knowledge [24]. There is evidence that genders differ in spatial learning. Many studies have found men to perform better than women in sense of direction tasks [8, 27]. Another predictor of spatial ability is self perception of spatial ability. People are accurate at reporting their own spatial abilities, and thus several questionnaires have been developed to capture this like the *Santa Barbara Sense of Direction Scale* (SSBOD) [25] and the *Philadelphia Spatial Abilities Scale* (PSAS) [23]. Various cultural differences can also lead to a difference in spatial ability. For example, there are some languages that do not have or use words for lateral direction, but rely primarily on cardinal directions [77].

Cognitive skills, like one's ability to visualize an environment, can be a predictor of spatial ability. A test to determine one's spatial visualisation ability is the *Mental Rotation Task* (MRT) [72]. The MRT correlates with spatial knowledge acquisition, or with the development of survey knowledge. Additionally, learning strategy is an important component of spatial ability. Work has shown that the application of visual or verbal strategy predicts the level and type of spatial knowledge acquired [32]. Verbal strategy results in stronger landmark knowledge, while visual strategy results in higher survey knowledge. It has also been shown that individual differences affect the way additional spatial information (i.e., the inclusion of a map) is used [57].

Likewise, there are significant individual differences in working memory, and working memory is necessary to transform spatial cues into a valid spatial representation [87]. To assess the importance of working memory, we administer a *Corsi block tapping test* (CORSI) [30], a test for measuring the visuo-spatial working memory span. The task involves tapping blocks in the sequence in which they appeared on a computer display, much like the game 'Simon'. Spatial working memory is known to be important in navigation [5].

## 3 Experiment

In this experiment, we evaluate two locomotion methods in different sized tracking spaces by measuring spatial knowledge acquisition and individual differences. Based on our research questions, we developed three hypotheses that we have for this experiment:

**H1:** Walking in place will result in the lowest angular error. Additionally, when resetting, as the size of the tracked space decreases, the angular error will increase.

**H2:** An increased number of resets will lead to increased simulator sickness.

**H3:** All three individual difference questionnaires (MRT, SBSOD, and CORSI) will be predictive of navigation performance. Individuals with higher scores will perform better.

We hypothesize **H1** based on extrapolating the results of Paris et al. [41]. That work did not find a significant difference between walking in place and resetting in a 4 m x 4 m area. We will use an improved walking in place algorithm (described in the following), and smaller spaces, which should increase the cognitive costs of resetting. Next, in small spaces, people will be performing resets quite frequently, and these resets require them to turn in a virtual environment. While virtual reality equipment has improved significantly and latencies are now small, we believe that the increased turning caused by smaller spaces will lead to a measurably higher amount of simulator sickness, hence **H2**. Finally, as described in the following, we believe that there are individual differences in people's ability to use locomotion interfaces, even with training. We believe that this experiment has the experimental power to detect those differences, and the measures we have described have been used in the real world studies just for this purpose. This reasoning leads us to **H3**.

### 3.1 Participants

We completed an a priori power analysis with G Power[1] using variances from prior work [40] to determine the sample size required for our experiment. To obtain a medium effect size (Cohen's d = 0.3) we used an alpha error probability $\alpha = 0.05$, and power $\beta = 0.8$. We determined that 104 subjects (26 per condition) would be sufficient.

We recruited subjects from our city between the ages of 18-25. This was a between subjects study, thus 140 (58 men, 82 women) subjects between four conditions participated and were compensated $15. All subjects who entered VR were included in the simulator sickness portion of the experiment. Twenty-five subjects dropped out before completion of the experiment and were excluded from part of the analysis. Eleven subjects had to be excluded from part of the analysis due to computer errors. Conditions were balanced so that 26 subjects completed each of the four conditions and subjects were assigned their condition randomly.

### 3.2 Equipment

The environment was developed in Unity and based on the maze developed by [12]. An Oculus Go head-mounted display (HMD) provided visual information to subjects. The resolution in each eye is 1280 x 1440 with a refresh rate of 60 Hz. The field of view of the Oculus Go was at least $110^\circ$. We tracked position in two ways. In all conditions we tracked subjects using a WorldVIZ Precise Position Tracking system, which allowed us to provide 6DOF tracking. The physical space was roughly 6 m x 5 m and the tracked space was 5 m x 5 m. We placed foam interlocking mats on the floor to mark off the 5 m x 5 m space, which ensured subjects could not walk into a wall. For one of the four conditions, walking in place, we used the IMU of the Oculus Go to detect vertical linear acceleration. To allow subjects to interact with the experiment, they were given an Oculus Go controller.

### 3.3 Locomotion Methods

Both of our locomotion methods are based on prior implementations. Here we describe specific implementation details.

#### 3.3.1 Walking in Place

The walking in place method used in this paper is a body-based turning method, with turning facilitated by head rotation [21]. We take data from the inertial measurement unit (IMU) of the Oculus Go to determine head motion. This method is similar to how a pedometer works by using a pattern analysis technique that detects repeating motions that can be assumed to be steps. In this instance, we extract the up and down acceleration of the user's head to impart motion in the direction of the user's gaze. For this method, walking is divided into two repeating states. We say that a subject is in motion when the magnitude of the upward acceleration is greater than 0.1 m/s and not stepping otherwise. We make the assumption

[1] https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower.html

that the average walking speed is 1.65 m/s with each step taking 0.5 s. If a cessation in walking occurs, the speed decays to zero, and the time constant for this decay is 0.2 so that the change in speed is subtle but noticeable. While the optic flow and motion do not stop immediately, they do stop within about 0.5 s of a user stopping. This "hand-tuned" version of walking in place was found to perform well in Hanson et al. [21] in terms of minimizing the latencies of the response. It has some computational advantages over their convolutional neural network implementation. One issue that can arise with walking in place methods, called unintended positional drift, occurs when people move (or drift) due to the simulated leg motions of the locomotion method [6, 39, 82]. The drift can be sufficiently large that users reach the boundary of available space. To solve this problem, we placed a cardboard sheet (approximately 0.75 m x 0.75 m) on the floor, and told users to stay on that while walking in place. If they began to drift off it, they could easily correct their position.

#### 3.3.2 Resetting

When a boundary in the environment is encountered, resetting is activated. During resetting, the rotational gain is adjusted, causing the world to rotate around the user at a faster rate. Our resetting algorithm was initially developed by Williams et al. [83] and Xie et al. [88], and is deigned so users do not notice the manipulated rotational gain. Users are required to walk, and thus from self motion they receive full idiothetic cues. There are two phases in this locomotion method: *traditional walking* and *reorientation*. During traditional walking, there is no modification made to the orientation or the position of the user. The reorientation phase occurs when a user reaches the physical boundary of the tracked space. Unlike the method developed by Williams et al. [83], which implements a rotational gain of 2, our algorithm dynamically adjusts rotational gains, resulting in fewer resets. To dynamically adjust the gain, when reorientation is initiated, the rotational gain of the system is calculated so that a virtual turn of 360° is equivalent to a real turn toward the center of the tracked space. Subjects believe they have successfully completely turned around and have maintained the correct heading while they have been turned away from the boundary of the tracked space. Additionally, during this phase we used a feather distractor, following Peck et al.'s [44] method. Our distractor appeared and disappeared. Even though this was found to be a cause of complaint in that work, we decided to use this approach given the frequency at which resets were likely to happen in our experiment.

### 3.4 Tracked Spaces

The four conditions in this experiment corresponded to four differently sized tracking spaces: 4 m x 4 m, 3 m x 3 m, 2 m x 2 m, and 1 m x 1 m (standing space), which we will refer to as 4 x 4, 3 x 3, 2 x 2, and 1 x 1 throughout the rest of the paper. For the largest tracking space, we thought that a 4 m x 4 m space was close to the largest open space that is reasonable to expect for use in most homes. While a slightly larger tracking space would have been possible in our laboratory, we wanted to test our methods with this idea of home use in mind. Before we conducted the study, we informally piloted the smallest tracked space (1 x 1) with our lab members to determine if it was possible to employ resetting. Piloting showed that resetting in a 1 x 1 space was too difficult — users would take about one step before each reset occurred and it was too distracting and unusable — so we determined that we could only use walking in place in that space. In the other three spaces we used the resetting locomotion method. Table 1 has complete details on the conditions, tracked space, and locomotion method used in each part of the experiment. Section 3.6 describes the testing phase of the experiment.

| Condition | Training | Learning | Testing |
|---|---|---|---|
| WiP | WiP | WiP | Resetting (4 m x 4 m) |
| 4x4 | Resetting (4 m x 4 m) | Resetting (4 m x 4 m) | Resetting (4 m x 4 m) |
| 3x3 | Resetting (3 m x 3 m) | Resetting (3 m x 3 m) | Resetting (4 m x 4 m) |
| 2x2 | Resetting (2 m x 2 m) | Resetting (2 m x 2 m) | Resetting (4 m x 4 m) |

Table 1: The four conditions in this study as well as the locomotion method (and tracked space if applicable) in each of the three VR phases of the experiment.

Figure 1: Top-down view of the environment used in the practice phase of Experiment 1. There are four objects for the subject to find and four landmarks (paintings).

Figure 2: Top-down view of the environment used in the learning phase of Experiment 1. There are eight objects for the subject to find and four landmarks (paintings) to facilitate learning.

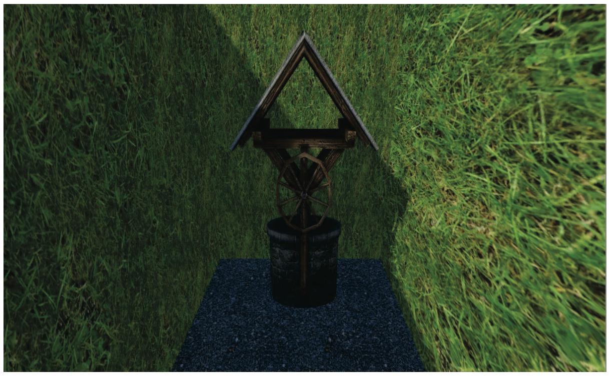

Figure 3: This figure shows the well as would be seen by subjects during the orientation phases of the experiment.

### 3.5 Environment

Our environments are identical to those used in Paris et al. [41]. There are three distinct environments in which subjects were immersed: a training (Figure 1) and learning (Figure 2) maze, and an assessment environment (Figure 4). The training maze was roughly 6 m x 6 m. This maze was used to allow subjects to train in the appropriate room size. The learning maze was roughly 10 m x 10 m. In this maze, subjects were instructed to learn spatial relations amongst eight objects (a car, snowman, phone booth, table and chair, clock, treasure chest, guitar, and well) that were contained within the maze. There were four landmarks – paintings – that were present to aid subjects in learning the overall layout of this maze. A first-person view of this maze is also shown in Figure 3, with one of the eight objects present. Due to the geometry of this maze, subjects were unable to see the other objects when they were located near one of the objects (i.e., they could not see two objects simultaneously). The final environment, the assessment environment, is presented to subjects in the final phase of the experiment. The purpose of the textured ground plane provided in this environment is to provide ocular flow to allow subjects to get a sense of distance travelled during the assessment phase.

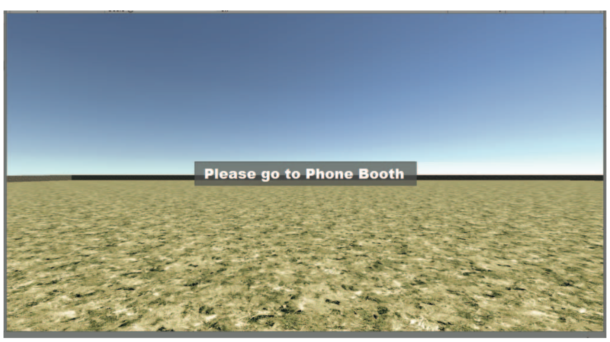


Figure 4: At the beginning of the testing phase subjects are informed of the target object via a heads up display. This disappears shortly so as not to distract the subject during walking.

### 3.6 Navigation Task

The navigation task was the same employed in Paris et al. [41]. First, subjects were given instructions on how to locomote and navigate about the environment. In the first phase of the experiment, subjects were placed in the training maze (See Figure 1), and were required to explore the maze for five minutes so they could familiarize themselves with the locomotion method. They were required to utilize the full five minutes, as we wanted to be sure that subjects were confident and competent in their ability to complete the study. After the training phase, subjects were taken out of VR and were given instructions on how to complete the next phase of the experiment. In this second phase, subjects were placed in a second maze (See Figure 2) in which they were told they should explore and try to remember the relative locations of objects since they would be required to recall them later. They were given 10 minutes to freely explore and learn the layout of this second maze. Once subjects had explored for the allotted time period, subjects began the assessment phase. In this phase, subjects were placed in a Vornoi textured environment and were given their next set of instructions. Subjects who learned in the walking in place condition were also given instructions on resetting. We note that, in both mazes, subjects were unable to walk through the walls as we had enabled collisions.

In the final assessment, or testing, phase, subjects experienced a series of trials in which they were told to navigate to the locations of different objects from various locations in the maze. To begin each trial, subjects pressed the button on the Oculus Go and were placed in the learning maze directly in front of one of the objects. In this phase, subjects could turn to orient themselves but could not translate. Thus, they were unable to navigate about the maze during orientation, and could not see any of the other objects in the maze from their viewpoint. It was important for subjects to see the maze in order to gain context about the direction they were facing, and the additional information provided by the maze was only enough to re-establish that orientation. Once oriented, subjects pressed the button again and were placed once again in the Voronoi textured environment. They were given the name of an object to which they were required to navigate via a heads-up display (see Figure 4). Subjects were instructed to walk to the named object in a straight line. This ensured that the path subjects walked was a novel shortcut. At the conclusion of each trial, subjects indicated that they had reached the target object by again pressing the button a final time. To reduce potential variance, the location of the subject was the center of the tracked space. Subjects were not given any feedback about their performance in the testing phase. In total, subjects completed forty trials, which consisted of five repetitions of eight pairs of objects.

The testing phase was conducted in a 4 m x 4 m space and used the resetting locomotion method. It was important that the locomotion method for testing survey knowledge be kept constant across each condition during testing, so that any differences between groups could be attributed to the learning phase of the experiment. Ideally, we would have used natural walking for this phase, but our lab is not large enough to support this. Note that our primary performance metrics are directions and straight line differences. Direction, or heading, would not be affected by the choice of locomotion method, but straight line distances might be, a shortcoming of the method used in Paris et al. [41]. This method of testing removes that difficulty.

## 4 Measures

This section describes the quantitative and qualitative measures we used to evaluate the performance of the locomotion interfaces in the differently sized areas.

### 4.1 Individual Difference Measures

Prior to the experiment participants completed a number of tests to detect individual differences. Specifically, participants completed the MRT [72], the CORSI Block Tapping Test [30], and the SB-SOD [24].

### 4.2 Angular Error

A measurement that we acquired during the testing phase of the navigation task was absolute angular error. Angular error helps to determine how well participants are able to determine relative direction and is the equivalent to a classic pointing task [36]. The direction participants walk from one location to a target object measures configural knowledge without respect to scale, and represents the difference in the angle that the user is facing and the angle at which the object is located is measured after 1 m of walking. This was done to make sure that the heading was calculated by actual displacement and not neccesarily facing direction, it also ensured that this measurement would be independent of the method of walking. The angular error gives a measure of how well participants have learned the direction component of survey knowledge.

### 4.3 Distance

We also acquired the straight line distance that participants thought separated the origin object from the destination object, the second component of survey knowledge. Our measurement was actually a proxy for the true distance that participants thought separated the objects, since it was mediated by the resetting locomotion interface. We could not acquire the actual distance using a technique like blind-walking [14, 68] because the virtual environment exceeded the size of our laboratory.

### 4.4 Simulator Sickness

To assess the undue simulator sickness caused by each of the four conditions, we measured the discomfort induced as in Fernandes & Feiner [17]. During the learning portion of the experiment (see Section 3.6), which lasted 10 minutes, every minute participants reported their current level of simulator sickness on a scale from 1–10. A baseline measurement was taken at the beginning of the learning phase immediately following the participant donning the HMD.

### 4.5 Post-Test

After completing the experiment participants completed a post-test questionnaire designed to determine if they were able to notice the manipulated rotation. Each participant was then interviewed and asked questions regarding the rotation of the environment and strategies for exploring, learning, and recalling the environment. We were interested in seeing if participants could detect the rotation induced from resetting and asked various masking questions to ensure they did not know our intent. The questionnaire can be seen in Table 2. The questions were presented as a Likert scale from 1 to 5. The interview was semi-structured and questions were asked based on the responses to the questions in Table 3.

| | |
|---|---|
| 1 | I felt like the virtual world was turning |
| 2 | I saw the virtual world get smaller or larger |
| 3 | I saw the virtual world flicker |
| 4 | I was getting bigger or smaller |
| 5 | I saw the virtual world get brighter or dimmer |
| 6 | I felt like I was turning when I wasn't |

Table 2: Post test questionnaire presented to each participant. Questions 3-6 were masking questions and all 6 questions were presented in a random order.

## 5 RESULTS

We analyzed our results using a between groups ANOVA at the 5% significance level, and t-tests with Bonferroni correction for our pairwise comparisons. We additionally conducted Pearson correlations to analyze the effect of any covariates. All assumptions for the ANOVA were confirmed or corrected in SPSS.

| | |
|---|---|
| 1 | Did you notice anything unusual about the environment? |
| 2 | How did you go about exploring the environment? |
| 3 | What was your strategy to learn the objects? |
| 4 | What was your strategy to recall the locations of the objects? |
| 5 | How did you decide how far to walk? |
| 6 | Did you use the resetting intervention to measure distance? |

Table 3: Post test interview presented to each participant. Followup questions were asked based on responses to each question in this table.

### 5.1 Angular Error

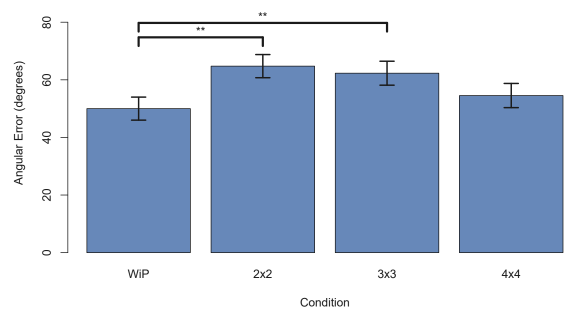


Figure 5: This chart shows the estimated marginal mean angular error in each of the four conditions and the standard error of the mean.

A 4 (condition) x 2 (gender) ANOVA on absolute angular error with covariates of MRT, CORSI, SBSOD, and simulator sickness revealed a main effect of condition ($F(3,92) = 2.742, p = .048$) and SBSOD ($F(1,92) = 10.31, p = .002$). Post test comparisons revealed significant differences between the walking in place ($M = 50.0°$, $SE = 4.0$) and 2 x 2 ($M = 64.7°$, $SE = 4.0$) conditions, as well as the 3 x 3 ($M = 62.3°$, $SE = 4.2$) and walking in place conditions, but not between the 4 x 4 condition ($M = 54.5°$, $SE = 4.2$) and other conditions. The walking in place condition resulted in significantly better configural knowledge than those (3 x 3 and 2 x 2) conditions. These results can be seen in Figure 5. These findings confirm our first hypothesis **H1**, that angular error was lowest during the walking in place condition.

| | Mean | Median |
|---|---|---|
| SBSOD | 3.953 | 4.000 |
| MRT | 28.09 | 27.00 |
| Corsi | 6.722 | 6.333 |

Table 4: Mean and median SBSOD and MRT scores among all participants

We performed a correlation analysis on our dependent measures and covariates and found several significant correlations. Angular error was significantly correlated with both MRT scores ($r = -.211, p = .032$) and SBSOD scores ($r = -.386, p < .001$). MRT scores were also correlated with SBSOD scores ($r = .290, p = .003$) and CORSI scores ($r = .306, p = .002$). Refer to Table 5 for the full correlation analysis and to Table 4 for mean and median individual difference scores among subjects in this experiment.

### 5.2 Distance

We conducted a 4 (condition) x 2 (gender) ANOVA on normalized traveled distance between targets with covariates of MRT, CORSI,

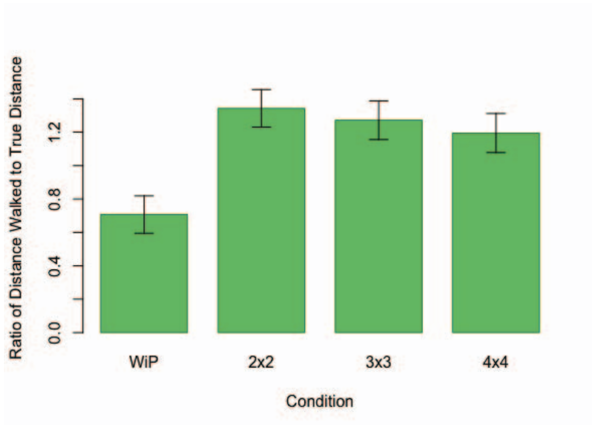


Figure 6: Mean ratios of distance walked to true distance across each condition.

SBSOD, and simulator sickness. The distance traveled by a participant was divided (normalized) by the true distance between the start location and target to provide a basis for comparison over trials. The means for these ratio are shown in Figure 6. The ANOVA revealed a main effect of condition ($F(3,92) = 6.57$, $p < 0.001$). Post test comparisons revealed significant differences between the walking in place condition ($M = 0.71$, $SE = 0.11$) and all resetting conditions (2 x 2: $M = 1.34$, $SE = 0.11$; 3 x 3: $M = 1.27$, $SE = 0.12$; 4 x 4: $M = 1.19$, $SE = 0.12$). Participants underestimated the distance between targets using walking in place, and overestimated it using resetting. No covariates were significantly correlated with traveled distance (see Table 5).

| | Direction | Distance | SBSOD | MRT | CORSI | SSQ |
|---|---|---|---|---|---|---|
| **Direction** | | 0.010 | -0.386 | -0.211 | -0.189 | 0.030 |
| **Distance** | | | 0.023 | 0.141 | 0.082 | -0.150 |
| **SBSOD** | | | | 0.289 | 0.109 | 0.044 |
| **MRT** | | | | | 0.306 | -0.001 |
| **CORSI** | | | | | | 0.030 |
| **SSQ** | | | | | | |

Table 5: Correlations between dependent measures and the individual differences measured in this experiment.

### 5.3 Simulator Sickness

To analyze the simulator sickness scores given, we performed an ANOVA with two factors (gender and condition) with three covariates (MRT, CORSI, and SBSOD). This analysis revealed no main effects of either factor, nor did it reveal an effect of time. Subjects did not in general show an increase in simulator sickness in any of the conditions. There were, however, a number of subjects who did feel sick enough to withdraw from the experiment. The dropout rate was 18%, but condition did not seem to affect the number of dropouts as shown by Table 6. A dropout rate of 18% seems higher than in other locomotion studies, and some aspect of our experiment may have led to a higher than normal dropout rate.

| Condition | Dropouts |
|---|---|
| WiP | 6 |
| 4x4 | 5 |
| 3x3 | 7 |
| 2x2 | 7 |

Table 6: Number of dropouts due to simulator sickness occurring in each of the four conditions.

### 5.4 Questionnaire Responses

Nearly every participant (92%) noticed that something was occurring during the resetting locomotion method. Many of those subjects reported that they noticed something because they walked much further than was reasonable in the physical environment. A few (15%) remarked that they used something external to the virtual world to determine what was going on. For example, some employed a strategy such as turning exactly 90° twice to realize they were only turning halfway around. There did not seem to be any differences in how quickly subjects realized an intervention was occurring based on resetting condition.

Most participants attempted to explore the maze in one of two ways. Many tried a gridlike approach by trying to explore the length of the maze, turn, and then quickly turn again to walk a parallel path. Others tried to explore the entire perimeter and then explore the inner corridors of the maze. When reporting how they memorized object locations, subject reports were split between egocentric and allocentric representations, with egocentric being more common overall. However, there was no difference in the split between conditions. Many subjects had to be given examples of strategies in order to explain what strategy they used. Interestingly, some subjects used the feather not as an indicator of where an object was located, but to aid in knowing the distance they had walked. Subjects indicated that for long distances they would expect multiple interventions, and tried to stay consistent in the number of interventions among similar paths.

## 6 Discussion

Our primary finding regards the acquisition of survey knowledge. When we examine the directional component of survey knowledge, we found that participants performed significantly worse in the 2 x 2 and 3 x 3 spaces using resetting than when they locomoted in the 1 x 1 space using walking in place. This finding is interesting as it places a lower bound on the size of the space that resetting is good for, a finding that we believe is novel and important. In terms of angular errors, walking in place and resetting in the 4 x 4 space were not significantly different. Our angular errors appear are roughly consistent with those of Paris et al [41]. That paper found equivalence between their walking in place method and resetting in a 4 x 4 environment. We believe this demonstrates the cognitive interference that resets generate on acquisition of straight line directions as a component of survey knowledge. We conjecture that as the number of resets decreased even further, the performance would continue to improve. This result, if true, would argue that the use of resets in redirected walking methods [26] does not seriously impact performance. The use of resets for edge conditions seems sensible and has been employed in several contexts [2, 4, 58].

Additionally, participants who had higher scores on the SBSOD questionnaire had significantly lower angular errors. Likewise, participants who scored higher on the MRT also had significantly lower angular errors. These results are broadly consistent with studies of real world navigation [76, 78]. Both MRT and SBSOD scores were positively correlated. Interestingly enough, MRT scores are known to have strong gender biases [67], but our navigation performance showed no significant effects of gender, unlike many real world studies of navigation performance [37]. The correlations between SBSOD and MRT scores occurred across all sub-groups, indicating that increased SBSOD and MRT scores led to lower angular errors for both users of resetting and users of walking in place. Moreover, the size of the resetting area did not seem to affect this.

The MRT measures smaller scale abilities to make object-based spatial transformations [72], while the SBSOD assesses larger scale spatial abilities. The SBSOD has been shown to correlate well with performance in navigation [25, 76]. Both measures were significantly correlated with performance in both methods of locomoting through the virtual environment. Some prior work has shown differences between small and large scale spatial abilities in navigation [24], but we did not find that in the present study. These findings suggest that it may be helpful to provide people with lower scores on these tests scaffolding or additional training in the interface if navigational success is an important measure.

For the distance component of survey knowledge, we found a significant effect of condition in that distance estimated by the participants who learned the maze using walking in place was significantly less than those who learned it using resetting, regardless of the size of the resetting area. The mean distances using resetting in the learning phase were all overestimated, a result consistent with the finding of Paris et al. [41]. The mean distances using walking in place between the present work and Paris et al. are likely different, since in the present case the mean distance is underestimated, whereas in Paris et al. it was overestimated. We believe this difference is due to the difference in testing methods, and that people have difficulty estimating distance based on optic flow alone, in the absence of any allothetic cues. One possible reason for the underestimation is the walking in place participants were not trained in resetting, so there was a difference in their learning interface and testing interface. However, we designed the experiment this way intentionally, since prior work has shown that walking in place users are poor at estimating how far they have travelled using a walking in place interface [40]. In designing the experiment we felt that introducing two locomotion interfaces to participants or to a subset of participants would have been confusing. Note that Hanson et al. [21] was able to show that users of walking in place could travel an estimated distance reasonably accurately in the presence of a rich virtual environment; however, our prior work [40] demonstrates that users of walking in place need these visual cues and cannot demonstrate distance accurately in an environment such as is shown in Figure 4. Thus, we conjecture that if the testing phase used real walking (as in Hanson et al.), users would have performed similarly. Post test surveys revealed that some users used the resetting distractor, a feather, as a distance estimate, and we did not foresee this. The presence of the distractor could only be loosely associated with distance information, as it depends on the position of the user within the tracked space. Thus, the inability to comparatively test the distance component of survey knowledge in a better way (such as with real walking) should be viewed as a limitation of our experiment.

Participants who completed the experiment did not exhibit any undue symptoms of simulator sickness, either using our simulator sickness evaluation based on the method of Fernandes & Feiner [17] or in post test reports. However, 25/140 subjects withdrew from the experiment before it ended, giving us a dropout rate (18%) that is higher than other user studies we have run. As described in Table 6, though, the dropout rate seems balanced across conditions, so it is difficult to conclude anything from this.

Future work in this area could explore the the impact of training upon a locomotion interface and how individual differences affect the amount of training needed and the resulting performance of the interface. A large body of work emphasizes the effect of individual differences upon navigation performance in the real world, yet this has not had substantial impact upon the design of locomotion interfaces for virtual environments. Building broad profiles of categories of users and how they would perform at navigation and wayfinding in virtual environment could be helpful for the future design of locomotion interfaces. Assessments such as have been done here to further types of interfaces would be insightful as to impacts that the interfaces have for different types of users. Another area for future investigation is to expand the space used by the resetting technique to a larger area and assess its performance against walking in place or other standing space locomotion methods. The data from our experiment are suggestive that the angular errors from resetting might continue to decrease and that a larger space, e.g., 5 m x 5 m or 6 m x 6 m, resetting would outperform walking in place. Modern commodity hardware, such as the HTC Vive's most recent base stations and the Oculus Quest 2, support such tracking spaces.

## 7 Conclusions

In this paper we compared walking in place to resetting when the walkable area for resetting was constrained to small areas. Since the resetting method was proposed [83] it has been known that there was a cognitive cost to resetting, but this paper is the first to our knowledge to quantify that cost by showing that resetting performs worse in small areas than a standing space locomotion method. Our performance metric for comparison was to judge how well users could acquire survey knowledge of a space when using the locomotion interface, a method that has been applied to judge locomotion interfaces before [41]. Additionally, this work is the first analysis of the relationship of individual differences (e.g., ability to perform spatial transformations of objects and self-reported ability to navigate) and navigation performance in the resetting and walking in place locomotion methods. These types of findings can provide useful information on how to improve locomotion interfaces as they are built for more general populations of users.


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## References


[1] M. Al Zayer, P. MacNeilage, and E. Folmer. Virtual locomotion: A survey. *IEEE Transactions on Visualization and Computer Graphics*, 26(6):2315–2334, 2020. doi: 10.1109/TVCG.2018.2887379

[2] M. Azmandian, T. Grechkin, M. Bolas, and E. Suma. Physical space requirements for redirected walking: How size and shape affect performance. In *Proceedings of the 25th International Conference on Artificial Reality and Telexistence and 20th Eurographics Symposium on Virtual Environments*, ICAT - EGVE '15, pp. 93–100. Eurographics Association, Aire-la-Ville, Switzerland, Switzerland, 2015. doi: 10.2312/egve.20151315

[3] M. Azmandian, T. Grechkin, and E. S. Rosenberg. An evaluation of strategies for two-user redirected walking in shared physical spaces. In *Virtual Reality (VR), 2017 IEEE*, pp. 91–98. IEEE, 2017.

[4] E. R. Bachmann, E. Hodgson, C. Hoffbauer, and J. Messinger. Multiuser redirected walking and resetting using artificial potential fields. *IEEE transactions on visualization and computer graphics*, 25(5):2022–2031, 2019.

[5] K. J. Blacker, S. M. Weisberg, N. S. Newcombe, and S. M. Courtney. Keeping track of where we are: Spatial working memory in navigation. *Visual Cognition*, 25(7-8):691–702, 2017. doi: 10.1080/13506285.2017.1322652

[6] H. Brument, G. Bruder, M. Marchal, A. H. Olivier, and F. Argelaguet. Understanding, modeling and simulating unintended positional drift during repetitive steering navigation tasks in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 27(11):4300–4310, 2021. doi: 10.1109/TVCG.2021.3106504

[7] L. E. Buck, T. P. McNamara, and B. Bodenheimer. Dyadic acquisition of survey knowledge in a shared virtual environment. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 579–587. IEEE, 2020.

[8] X. J. Chai and L. F. Jacobs. Sex differences in directional cue use in a virtual landscape. *Behavioral Neuroscience*, 123(2):276, 2009.

[9] L. A. Cherep, A. F. Lim, J. W. Kelly, D. Acharya, A. Velasco, E. Bustamante, A. G. Ostrander, and S. B. Gilbert. Spatial cognitive implications of teleporting through virtual environments. *Journal of Experimental Psychology: Applied*, 26(3):480–492, 2020.

[10] E. R. Chrastil. Neural evidence supports a novel framework for spatial navigation. *Psychonomic Bulletin & Review*, 20(2):208–227, 2013.

[11] E. R. Chrastil and W. H. Warren. Active and passive contributions to spatial learning. *Psychonomic Bulletin & Review*, 19(1):1–23, 2012.
[12] E. R. Chrastil and W. H. Warren. Active and passive spatial learning in human navigation: Acquisition of survey knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39(5):1520, 2013.
[13] E. R. Chrastil and W. H. Warren. Active and passive spatial learning in human navigation: acquisition of graph knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 41(4):1162, 2015.
[14] S. H. Creem-Regehr, J. K. Stefanucci, and W. B. Thompson. Perceiving scale in virtual environments: How theory and application have mutually informed the role of body-based perception. In B. Ross, ed., *The Psychology of Learning and Motivation*, vol. 63, pp. 195–224. 2015.
[15] J. D. Ericson and W. H. Warren. Probing the invariant structure of spatial knowledge: Support for the cognitive graph hypothesis. *Cognition*, 200:104276, 2020. doi: 10.1016/j.cognition.2020.104276
[16] M. J. Farrell, P. Arnold, S. Pettifer, J. Adams, T. Graham, and M. MacManamon. Transfer of route learning from virtual to real environments. *Journal of Experimental Psychology: Applied*, 9(4):219, 2003.
[17] A. S. Fernandes and S. K. Feiner. Combating vr sickness through subtle dynamic field-of-view modification. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 201–210, 2016. doi: 10.1109/3DUI.2016.7460053
[18] S. Freitag, D. Rausch, and T. Kuhlen. Reorientation in virtual environments using interactive portals. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 119–122, March 2014. doi: 10.1109/3DUI.2014.6798852
[19] T. Grechkin, J. Thomas, M. Azmandian, M. Bolas, and E. Suma. Revisiting detection thresholds for redirected walking: Combining translation and curvature gains. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '16, pp. 113–120. ACM, New York, NY, USA, 2016. doi: 10.1145/2931002.2931018
[20] T. Y. Grechkin and B. E. Riecke. Re-evaluating benefits of body-based rotational cues for maintaining orientation in virtual environments: Men benefit from real rotations, women don't. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '14, p. 99–102. Association for Computing Machinery, New York, NY, USA, 2014. doi: 10.1145/2628257.2628275
[21] S. Hanson, R. A. Paris, H. A. Adams, and B. Bodenheimer. Improving walking in place methods with individualization and deep networks. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 367–376, March 2019. doi: 10.1109/VR.2019.8797751
[22] A. M. Hashemian and B. E. Riecke. Leaning-based 360 interfaces: investigating virtual reality navigation interfaces with leaning-based-translation and full-rotation. In *International Conference on Virtual, Augmented and Mixed Reality*, pp. 15–32. Springer, 2017.
[23] M. Hegarty, R. D. Crookes, D. Dara-Abrams, and T. F. Shipley. Do all science disciplines rely on spatial abilities? preliminary evidence from self-report questionnaires. In *International Conference on Spatial Cognition*, pp. 85–94. Springer, 2010.
[24] M. Hegarty, D. R. Montello, A. E. Richardson, T. Ishikawa, and K. Lovelace. Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence*, 34(2):151–176, 2006.
[25] M. Hegarty, A. E. Richardson, D. R. Montello, K. Lovelace, and I. Subbiah. Development of a self-report measure of environmental spatial ability. *Intelligence*, 30(5):425–447, 2002.
[26] E. Hodgson and E. Bachmann. Comparing four approaches to generalized redirected walking: Simulation and live user data. *Visualization and Computer Graphics, IEEE Transactions on*, 19(4):634–643, 2013.
[27] C. A. Holmes, D. Nardi, N. S. Newcombe, and S. M. Weisberg. Children's use of slope to guide navigation: Sex differences relate to spontaneous slope perception. *Spatial Cognition & Computation*, 15(3):170–185, 2015.
[28] 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*, pp. 167–170, 2007.
[29] T. Ishikawa and D. R. Montello. Spatial knowledge acquisition from direct experience in the environment: Individual differences in the development of metric knowledge and the integration of separately learned places. *Cognitive Psychology*, 52(2):93–129, 2006.
[30] R. P. C. Kessels, M. J. E. van Zandvoort, A. Postma, L. J. Kappelle, and E. H. F. de Haan. The corsi block-tapping task: Standardization and normative data. *Applied Neuropsychology*, 7(4):252–258, 2000. PMID: 11296689. doi: 10.1207/S15324826AN0704_8
[31] A. Kitson, A. M. Hashemian, E. R. Stepanova, E. Kruijff, and B. E. Riecke. Comparing leaning-based motion cueing interfaces for virtual reality locomotion. In *3D User Interfaces (3DUI), 2017 IEEE Symposium on*, pp. 73–82. IEEE, 2017.
[32] D. J. Kraemer, V. R. Schinazi, P. B. Cawkwell, A. Tekriwal, R. A. Epstein, and S. L. Thompson-Schill. Verbalizing, visualizing, and navigating: The effect of strategies on encoding a large-scale virtual environment. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 43(4):611, 2017.
[33] S. A. Kuhl. Recalibration of rotational locomotion in immersive virtual environments. In *APGV 2004*, pp. 23–26, Aug. 2004.
[34] S. A. Kuhl, S. H. Creem-Regehr, and W. B. Thompson. Recalibration of rotational locomotion in immersive virtual environments. *ACM Transactions on Applied Perception*, 5(3):1–11, 2008. doi: 10.1145/1402236.1402241
[35] E. Langbehn, P. Lubos, G. Bruder, and F. Steinicke. Application of redirected walking in room-scale vr. In *Virtual Reality (VR), 2017 IEEE*, pp. 449–450. IEEE, 2017.
[36] J. M. Loomis, R. L. Klatzky, R. G. Golledge, and J. W. Philbeck. Human navigation by path integration. *Wayfinding behavior: Cognitive mapping and other spatial processes*, pp. 125–151, 1999.
[37] A. K. Munion, J. K. Stefanucci, E. Rovira, P. Squire, and M. Hendricks. Gender differences in spatial navigation: Characterizing wayfinding behaviors. *Psychonomic bulletin & review*, 26(6):1933–1940, 2019.
[38] C. Neth, J. Souman, D. Engel, U. Kloos, H. Bülthoff, and B. Mohler. Velocity-dependent dynamic curvature gain for redirected walking. In *Virtual Reality Conference (VR), 2011 IEEE*, pp. 151 –158, March 2011. doi: 10.1109/VR.2011.5759454
[39] N. C. Nilsson, S. Serafin, and R. Nordahl. A comparison of different methods for reducing the unintended positional drift accompanying walking-in-place locomotion. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 103–110, 2014. doi: 10.1109/3DUI.2014.6798850
[40] R. Paris. *Evaluation of Locomotion Techniques in Room and Standing Scale Tracked Spaces*. PhD thesis, Vanderbilt University, March 2020.
[41] R. Paris, M. V. Joshi, Q. He, G. Narasimham, T. P. McNamara, and B. Bodenheimer. Acquisition of survey knowledge using walking in place and resetting methods in immersive virtual environments. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '17. ACM, New York, NY, USA, 2017.
[42] R. Paris, J. Klag, P. Rajan, L. Buck, T. P. McNamara, and B. Bodenheimer. How video game locomotion methods affect navigation in virtual environments. In *ACM Symposium on Applied Perception 2019*, SAP '19, pp. 12:1–12:7. ACM, New York, NY, USA, 2019. doi: 10.1145/3343036.3343131
[43] T. Peck, H. Fuchs, and M. Whitton. The design and evaluation of a large-scale real-walking locomotion interface. *Visualization and Computer Graphics, IEEE Transactions on*, 18(7):1053–1067, 2012. doi: 10.1109/TVCG.2011.289
[44] T. C. Peck, H. Fuchs, and M. C. Whitton. Evaluation of reorientation techniques and distractors for walking in large virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 15:383–394, 2009. doi: 10.1109/TVCG.2008.191
[45] T. C. Peck, H. Fuchs, and M. C. Whitton. Improved redirection with distractors: A large-scale-real-walking locomotion interface and its effect on navigation in virtual environments. In *IEEE Virtual Reality Conference*, Mar. 2010.
[46] P. Péruch, J.-L. Vercher, and G. M. Gauthier. Acquisition of spatial knowledge through visual exploration of simulated environments. *Ecological Psychology*, 7(1):1–20, 1995.
[47] T. Pfeiffer, A. Schmidt, and P. Renner. Detecting movement patterns from inertial data of a mobile head-mounted-display for navigation via

walking-in-place. In *2016 IEEE Virtual Reality (VR)*, pp. 263–264, 2016. doi: 10.1109/VR.2016.7504754

[48] H. L. Pick, J. J. Rieser, D. Wagner, and A. E. Garing. The recalibration of rotational locomotion. *Journal of Experimental Psychology: Human Perception and Performance*, 25(5):1179–1188, 1999.

[49] M. Qi, G. Liu, and J. Cui. Go-in-circles: A directed walking algorithm for vr navigation based on one-step-ahead strategy. *IEEE Access*, 8:49028–49037, 2020.

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

[51] B. E. Riecke, B. Bodenheimer, T. P. McNamara, B. Williams, P. Peng, and D. Feuereissen. Do we need to walk for effective virtual reality navigation? physical rotations alone may suffice. In *Spatial Cognition*, pp. 234–247, 2010.

[52] 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. doi: 10.1145/1502800.1502805

[53] R. A. Ruddle, E. Volkova, and H. H. Bülthoff. Walking improves your cognitive map in environments that are large-scale and large in extent. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 18(2):10, 2011.

[54] R. A. Ruddle, E. Volkova, and H. H. Bülthoff. Learning to walk in virtual reality. *ACM Transactions on Applied Perception (TAP)*, 10(2):11, 2013.

[55] R. A. Ruddle, E. Volkova, B. Mohler, and H. H. Bülthoff. The effect of landmark and body-based sensory information on route knowledge. *Memory & Cognition*, 39(4):686–699, 2011.

[56] E. Sayyad, M. Sra, and T. Höllerer. Walking and teleportation in wide-area virtual reality experiences. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 608–617. IEEE, 2020.

[57] S. Serino and G. Riva. How different spatial representations interact in virtual environments: the role of mental frame syncing. *Cognitive processing*, 16(2):191–201, 2015.

[58] W. Shibayama and S. Shirakawa. Reinforcement learning-based redirection controller for efficient redirected walking in virtual maze environment. In *Computer Graphics International Conference*, pp. 33–45. Springer, 2020.

[59] A. W. Siegel and S. H. White. The development of spatial representations of large-scale environments. *Advances in child development and behavior*, 10:9–55, 1975.

[60] A. L. Simeone, N. C. Nilsson, A. Zenner, M. Speicher, and F. Daiber. The space bender: Supporting natural walking via overt manipulation of the virtual environment. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 598–606. IEEE, 2020.

[61] M. Slater and M. Usoh. Presence in immersive virtual environments. In *Proceedings of IEEE Virtual Reality Annual International Symposium*, pp. 90–96, Sep 1993. doi: 10.1109/VRAIS.1993.380793

[62] M. Slater, M. Usoh, and A. Steed. Depth of presence in virtual environments. *Presence: Teleoperators and Virtual Environments*, 3(2):15, 1994.

[63] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics*, 16:17–27, 2010. doi: 10.1109/TVCG.2009.62

[64] E. A. Suma, M. Azmandian, T. Grechkin, T. Phan, and M. Bolas. Making small spaces feel large: Infinite walking in virtual reality. In *ACM SIGGRAPH 2015 Emerging Technologies*, SIGGRAPH '15, pp. 16:1–16:1. ACM, New York, NY, USA, 2015. doi: 10.1145/2782782.2792496

[65] J. N. Templeman, P. S. Denbrook, and L. E. Sibert. Virtual locomotion: Walking in place through virtual environments. *Presence*, 8(6):598–617, 1999.

[66] J. N. Templeman, P. S. Denbrook, and L. E. Sibert. Virtual locomotion: Walking in place through virtual environments. *Presence*, 8(6):598–617, 1999.

[67] M. S. Terlecki, N. S. Newcombe, and M. Little. Durable and generalized effects of spatial experience on mental rotation: gender differences in growth patterns. *Applied Cognitive Psychology*, 22(7):996–1013, 2008. doi: 10.1002/acp.1420

[68] W. B. Thompson, P. Willemsen, A. A. Gooch, S. H. Creem-Regehr, J. M. Loomis, and A. C. Beall. Does the quality of the computer graphics matter when judging distances in visually immersive environments. *Presence: Teleoperators and Virtual Environments*, 13:560–571, 2004.

[69] E. C. Tolman. Cognitive maps in rats and men. *Psychological review*, 55(4):189, 1948.

[70] S. Tregillus and E. Folmer. Vr-step: Walking-in-place using inertial sensing for hands free navigation in mobile vr environments. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 1250–1255. ACM, 2016.

[71] 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 *SIGGRAPH 99*, pp. 359–364, Aug. 1999.

[72] S. G. Vandenberg and A. R. Kuse. Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, 47(2):599–604, 1978.

[73] R. von Stülpnagel and M. C. Steffens. Active route learning in virtual environments: disentangling movement control from intention, instruction specificity, and navigation control. *Psychological research*, 77(5):555–574, 2013.

[74] D. Waller, J. M. Loomis, and D. B. Haun. Body-based senses enhance knowledge of directions in large-scale environments. *Psychonomic Bulletin & Review*, 11(1):157–163, 2004.

[75] W. H. Warren, D. B. Rothman, B. H. Schnapp, and J. D. Ericson. Wormholes in virtual space: From cognitive maps to cognitive graphs. *Cognition*, 166:152–163, 2017. doi: 10.1016/j.cognition.2017.05.020

[76] S. M. Weisberg. *Where am I? Individual differences in memory, navigation ability, and navigation strategy*. Temple University, 2014.

[77] S. M. Weisberg, D. Nardi, N. S. Newcombe, and T. F. Shipley. Up by upwest: Is slope like north? *The Quarterly Journal of Experimental Psychology*, 67(10):1959–1976, 2014.

[78] S. M. Weisberg and N. S. Newcombe. Cognitive maps: Some people make them, some people struggle. *Current Directions in Psychological Science*, 27(4):220–226, 2018. doi: 10.1177/0963721417744521

[79] S. M. Weisberg, V. R. Schinazi, N. S. Newcombe, T. F. Shipley, and R. A. Epstein. Variations in cognitive maps: Understanding individual differences in navigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 40(3):669, 2014.

[80] 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. *Virtual Reality Conference, IEEE*, 0:123–130, 2005. doi: 10.1109/VR.2005.25

[81] B. Williams, S. Bailey, G. Narasimham, M. Li, and B. Bodenheimer. Evaluation of walking in place on a wii balance board to explore a virtual environment. *ACM Transactions on Applied Perception*, 8(3):19:1–19:14, Aug. 2011. doi: 10.1145/2010325.2010329

[82] B. Williams, M. McCaleb, C. Strachan, and Y. Zheng. Torso versus gaze direction to navigate a ve by walking in place. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '13, p. 67–70. Association for Computing Machinery, New York, NY, USA, 2013. doi: 10.1145/2492494.2492512

[83] B. Williams, G. Narasimham, B. Rump, T. P. McNamara, T. H. Carr, J. J. Rieser, and B. Bodenheimer. Exploring large virtual environments with an hmd when physical space is limited. In *Symposium on Applied Perception in Graphics and Visualization*, pp. 41–48. Tübingen, Germany, July 2007.

[84] N. L. Williams, A. Bera, and D. Manocha. Arc: Alignment-based redirection controller for redirected walking in complex environments. *IEEE Transactions on Visualization and Computer Graphics*, 27(5):2535–2544, 2021.

[85] P. T. Wilson, W. Kalescky, A. MacLaughlin, and B. Williams. Vr locomotion: walking¿ walking in place¿ arm swinging. In *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry-Volume 1*, pp. 243–249. ACM, 2016.

[86] P. T. Wilson, K. Nguyen, A. Harris, and B. Williams. Walking in place using the microsoft kinect to explore a large ve. In *Proceedings of the 13th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and its Applications in Industry*, pp. 27–33. ACM, 2014.

[87] T. Wolbers and M. Hegarty. What determines our navigational abilities? *Trends in Cognitive Sciences*, 14(3):138–146, 2010.

[88] X. Xie, Q. Lin, H. Wu, G. Narasimham, T. P. McNamara, J. Rieser,

and B. Bodenheimer. A system for exploring large virtual environments that combines scaled translational gain and interventions. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, APGV '10, pp. 65–72. ACM, New York, NY, USA, 2010. doi: 10.1145/1836248.1836260

[89] X. Xie, R. A. Paris, T. P. McNamara, and B. Bodenheimer. The effect of locomotion modes on spatial memory and learning in large immersive virtual environments: a comparison of walking with gain to continuous motion control. In *German Conference on Spatial Cognition*, pp. 58–73. Springer, 2018.

[90] R. Yu, Z. Duer, T. Ogle, D. A. Bowman, T. Tucker, D. Hicks, D. Choi, Z. Bush, H. Ngo, P. Nguyen, et al. Experiencing an invisible world war i battlefield through narrative-driven redirected walking in virtual reality. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 313–319. IEEE, 2018.

[91] Y. Zheng, M. McCaleb, C. Strachan, and B. Williams. Exploring a virtual environment by walking in place using the microsoft kinect. In *Proceedings of the ACM Symposium on Applied Perception*, pp. 131–131. ACM, 2012.