Acquisition and Demonstration of Survey Knowledge using Walking in Place and Resetting Methods in Immersive Virtual Environments

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Abstract—Effective locomotion through an unknown virtual environment requires subjects be able to effectively learn their environment. We investigate how two types of locomotion methods affect the acquisition and demonstration of survey knowledge. Our first experiment showed that directional survey knowledge could be acquired and demonstrated equally well in all tested methods of walking. This experiment showed a difference in distal survey knowledge. This difference was explored in our second experiment. Our results show that subjects can acquire full and accurate distal survey knowledge in both resetting and walking in place. However, demonstration of distal knowledge is hindered by walking in place, this is likely due to optic flow being the only cue available during the demonstration phase.

Index Terms—Computer Society, IEEE, IEEEtran, journal, LaTeX, paper, template.

1 Introduction

Virtual reality (VR) provides engaging experiences and allows for training and simulation in a controllable environment. Virtual worlds, as with the real world, can differ vastly in size and scale. Large virtual environments, then, are necessary to provide analogs to large real-world environments. Exploring these large environments in smartphone-based VR systems (e.g., the Samsung Gear VR) introduces a difficult challenge. There is no native position tracking for these devices, which is disappointing, given the freedom they provide. The rendering and display systems of smartphone-based VR are entirely on-board, making the system tetherless. With the broad adoption of smartphones and the ease of acquiring a cheap housing unit (e.g., the Google cardboard [13]), smartphones provide an enticing platform for VR. In this paper we explore three naturalistic methods of navigating in large environments using smartphone-based VR systems: resetting [48] and two types of walking in place [38], [43], [47]. Resetting utilizes real walking and allows for unbounded space by reorienting subjects towards the center of the room when a boundary is encountered, all the while maintaining virtual heading. Walking in place induces translation based on a subject's stationary motion. This is, to our knowledge, the first evaluative study for spatial cognition using mobile VR and the first to utilize a real walking metaphor in mobile VR.

While many methods have been developed for navigation in large virtual environments [9], [16], [27], [48], the best method of doing so depends on many factors. These factors include room size and layout [1], technology, the virtual environment [19], performance metrics, etc. For example, if the room size is sufficiently large, then a redirected walking technique might be employed [39], [40]; if the room size is small, however, some of these techniques can induce simulator sickness or require pre-computed trajectories, e.g., the methods of Langbehn et al. [19]. If the environment is very large, then some method of locomotion beyond normal bipedal locomotion may be appropriate, e.g., the methods of Williams et al. [48] or Interrante et al. [16]. In this paper, we will consider some of these factors and make assumptions about others. In particular, for resetting, we assume a reasonably sized open room (roughly 4m x 4m) is available for the real world enclosing space, and that the virtual environment is easily navigable by ordinary locomotion. Walking in place methods, of course, do not have any space requirements beyond standing space.

There are various performance metrics used to judge the success of locomotion methods [46], such as breaks in presence [26], simulator sickness [12], [14], [25], and judgments of relative direction [48], etc. Because we are interested in training and simulation, we believe the acquisition of spatial knowledge to be a valuable metric. Navigation methods have been linked to the acquisition of spatial knowledge [33], [34], [49], [50] with walking methods outperforming other methods, e.g., joystick, teleportation, and flying. In this paper we compare how well three methods of navigation afford the acquisition of spatial knowledge, specifically survey knowledge [5], [17].

The four components of spatial knowledge are landmark, route, graph, and survey knowledge [5], [17]. Of most interest is survey knowledge, the acquisition of which pro-

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Manuscript received April 19, 2005; revised August 26, 2015.

vides subjects with knowledge of the straight-line distances and directions between places defined in a common frame of reference. To test the acquisition of survey knowledge we employ three metrics: initial angular error [6], [29], estimated path length [6], and orientation time, a measure of how quickly subjects recall the relative direction of objects. These measurements are collected to determine how well spatial knowledge is acquired in the three modes of navigation. The VR interfaces provide varying levels of body based information during both learning and testing. In experiment 1, we find that there is a difference in the expressed spatial knowledge. Experiment 2 shows that the difference was an effect of how we tested spatial knowledge.

2 Background

2.1 Walking in Virtual Environments

The idea of exploring large virtual environments within a limited physical space has a rich history, e.g., [9], [16], [27], [48]. Suma et al. [41] has a succinct review of this area. These systems of navigation, however, all require a positional tracking system. When lacking a tracking system, one must employ other methods of navigation. Many methods of walking in place have been presented [10], [20], [38], [42], [43], [47], [50], [53] that permit users to emulate walking without physically translating. Standard techniques for walking in place [38] have been found to be better than joystick based motion, but not as good as actual walking [4], [32], [33], [49].

2.2 Body Based Cues

The body-based cues generated from natural walking can be divided into two functions, cues that inform rotation or translation. Rotation-based cues are provided naturally in smartphone based VR systems. Smartphones have built in orientation tracking using gyroscopes and compasses. Rotational-based cues inform people of the angles they have turned, and therefore are useful for keeping oneself oriented in the environment. Providing a translational based cue for a smartphone interface requires some external tool, e.g., a tracking system. Translational cues inform people of the distance they have traversed, and are therefore useful for estimating the distances between objects and gauging the scale of the environment. In our work we provide translational cues in two ways. Resetting provides translational cues by allowing participants to access information from the movements of their muscles and the speed changes of their head. Walking in place techniques are body-active surrogates [44] and therefore provide translational cues only from the movements of their muscles. Work from Ruddle et al. [33] and Riecke et al. [28] together suggest that rotation cues facilitate spatial learning in small-scale environments, whereas translational cues facilitate spatial learning in large-scale environments (for a review, see Ruddle et al. [31]).

2.3 Spatial Microgenesis

There are two aspects of spatial knowledge that we must acquire to build an accurate map of an environment: relative direction and interpoint distances. A abundance of research has been conducted to ascertain how this map-like model is both acquired [17], [22], [23], [35] and represented [6], [7], [24], [30], [36], [51]. To determine how this knowledge is acquired Siegel and White [37] proposed three stages of spatial knowledge acquisition: landmark, route, and survey knowledge. Chrastil [5] argued for a fourth type of spatial knowledge, namely the graph knowledge, to be added to this spatial knowledge framework. The stage of most interest for this work is survey knowledge. Survey knowledge is the highest and most complete form of knowledge and includes metric information and configural knowledge of non-landmark objects [17], [37].

2.4 Optic Flow

When trying to express distance with only optic flow as feedback subjects tend to over express distance [2]. There is an expectation that optic flow match a user's speed of walking and people will modulate their walking speed to match (Richard: cite paris BR and schubert) In VR people are able to experience the sensation of motion through vection (Richard: cites) which in this work should mean a strengthened sense of distance traveled.

[2]

2.5 Individual Differences

In many navigation tasks subjects show large variation in individual performance. Studies [**?**], [15] have shown that various tests of individual difference correlate with performance in general navigation tasks. These navigation tasks use environmental spatial abilities [**?**] which are predicted strongly by self reported sense-of-direction (SOD) measures. Other studies [3], [11], [15] have found mental rotation abilities [45] to be highly predictive of performance in VR navigation. Since we are interested in explaining these large variations we include these tests in our methodology.

3 Research Design

3.1 Techniques of Walking

We implemented three techniques for locomotion in this work: the reorientation method called resetting [48], which uses real locomotion with interventions at the boundaries of the tracked space, and two techniques of walking in place, which require only the space to stand up.

3.1.1 Resetting

Our implementation of resetting was originally developed by Williams et al. [48] and Xie et al. [52], involves real walking, and grants full idiothetic cues to self motion. Resetting consists of two phases, the traditional walking phase in which no modification is done to either the orientation or position of the subject, and a reorientaion phase that occurs when a collision with the boundary of the tracked space occurs. During the first phase resetting is functionally equivalent to real walking. When a subject reaches a boundary of the tracked space the system initiates the second phase of resetting. During this phase the actual reset takes place and the rotational gain of the system is modified so that a virtual turn of 360 degrees is equivalent to a real world turn towards the exact center of the room. Thus, subjects believe themselves to have turned completely around and maintained their headings, while they have actually been reset away from the boundary. In the original Williams et al. [48] work, the gain was modified by a factor of 2, but, consistent with later work, our implementation dynamically adjusts the gain to point subjects to center of the room. This manipulation results in fewer resets. Resetting provides full translational and idiothetic cues to self-motion, but the process may cause some degradation in the acquisition of rotational information because of the body rotations inserted into the path.

3.1.2 Walking in Place

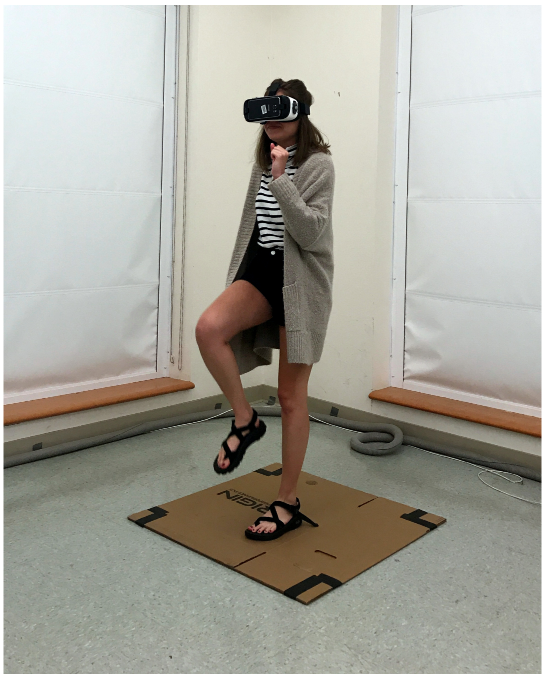

Fig. 1. A demonstration of walking in place. Cardboard is placed on the floor to prevent subjects drifting as they walk in place.

Our walking in place techniques are body-based turning methods, with turning indicated by head rotation. This means that all linear motion is in the direction of a subject's gaze which prevents looking around when walking. The first walking in place technique (Gear Only) we use takes inertial measurement unit (IMU) data directly from the smartphone of a Gear VR to determine head motion. This method is similar to how pedometers in smartphones and smartwatches work. Pedometers use pattern analysis techniques to search for repeating motions that are assumed to be steps. The repetition requirement of pedometers leads to either unreliability when the number of repetitions is low or severe lag when the number of repetitions is high. For this reason, we chose not to implement a standard pedometer. Instead, we extract the up and down acceleration of the head to impart motion in the direction of a user's gaze.

For our method walking is divided into two repeating states. We say the subject is stepping when the magnitude of the upward acceleration is greater than 0.1 m/s/s and not stepping otherwise. We assume an average walking pace of 3 m/s with each step taking 0.5s. The true target velocity in the system is the ratio of the the average rate to a user's rate of stepping multiplied by the average walking speed in the direction of the gaze. When a step begins we exponentially decay in an increasing form, (i.e., $1-e^{-kt}$) to that maximum speed and remain there until we detect the current step has stopped, at which time we decay to half of the maximum speed. This decay upward and downward repeats for as long as the user is considered to be walking. A user is no longer considered walking if enough time (50% of a user's rate of stepping) has passed since the end of the previous step. If this cessation is detected we decay to a speed of zero. The time constant for each of these decays is 0.2 seconds to make the change in speed subtle but noticeable. Note that while optic flow and motion do not stop immediately, they do stop within roughly 0.5 seconds of a user stopping.

The Kinect v2.0, which directly tracks users' feet and legs, offers a more direct method of measuring walking in place. This second walking in place technique utilizes the Microsoft Kinect v2.0 to track the angle formed (for both the left and right leg) by the hip, the knee, and the ankle joint. We assume the user is currently stepping if the angle formed is less than 145 degrees. We add an additional modification to the algorithm to allow for quicker detection of cessation of steps. We assume that if both leg angles are over 165 degrees for 0.1 seconds then stepping has stopped. The Kinect produced errors with step detection in certain orientations. Tracking was most stable when users faced either towards or directly away from the Kinect. When facing to the side and obscuring the back leg from the camera the system was prone to missing steps and causing unintended slow downs. This occurred primarily during the initial practice phase as subjects learned to adjust rapidly and controlled their motion effectively. In both methods we placed a 1m x 1m piece of cardboard on the ground and instructed subjects to walk in place, only on the cardboard; the cardboard, in effect, prevented drift.

3.2 Metrics

Since we are interested in how well our tested methods of walking facilitate the acquisition of spatial knowledge, in particular survey knowledge, we employ two metrics that allow us to measure how well survey knowledge has been acquired. As stated in Section 2.3 there are two important aspects of survey knowledge: interpoint distance information and direction information. Another important aspect in any of the types of spatial knowledge is recall time, and for this reason we look at orientation time, the time a subject takes to determine the direction of the target object and begin walking.

3.2.1 Initial Angular Error

To measure how well a subject is able to judge relative direction we employ a task similar to the classic pointing task [21], [29]. The task we use is to have a subject walk from a temporarily visible object to an instructed invisible, unseen target object [6]. Subjects are instructed to walk directly (in a straight line) to the target object as if there were no walls (noting that the walls were actually gone at this point) and the direction they walk measures the strength of their configural knowledge without respect to scale. Specifically, we measure the difference in angle between the direction of the actual target and the direction of walking after 1 meter [6].

3.2.2 Estimated Path Length

The other component of survey knowledge is interpoint distance information, which is typically acquired slowly. We test how well subjects have acquired this metric information by employing a simple walking task. By controlling for the amount of time spent searching through the environment we can analyze how quickly survey knowledge is obtained, in particular its metric component. Note that metric information in this experiment is gained primarily through path integration and is therefore not likely subject to biases in perception that have generated a significant body of work in the virtual environments community (see Creem-Regehr et al. [8] for a recent review).

3.2.3 Recall time

We can also measure the strength of subjects' survey knowledge by testing their recall time in determining the relative direction. Before subjects can begin walking they must know in what direction the target object is. By measuring the time the starting object is presented to the time subjects begins walking we can measure how well subjects can recall the relative direction of objects and orient themselves in the maze.

3.3 ID Tests

Participants completed short pretests to assess their individual levels of skill in various measures which have been shown to relate to performance in similar tasks. The first was the extended range vocabulary test (EVRT) which served to measure the general verbal abilities of subjects. Subjects next completed a mental rotation test which has shown high correlation with navigation performance in VR Hegarty et al. [15]. The MRT serves to measure small scale spatial abilities which should be interesting in the case of resetting performance which requires mental rotation. The final test is the Santa Barbara Sense of Direction test (SBSOD). Various papers have shown this self report measure to correlate with general navigation performance, but this correlation is lessened in VR. Questions ask subjects to report their own abilities in wayfinding.

3.4 Environment

In this experiment each subject was presented with three distinct environments. The first was a training maze shown in Figure 2. Subjects were placed in a practice maze in order to train in their assigned technique(s) of walking. The second was the learning maze shown in Figure 3; subjects were instructed to learn the spatial relations among the eight objects contained in this maze. Four landmarks were present to aid in learning the overall layout. A first person view of the learning maze is shown in Figure 4, with one of the eight objects. Due to the geometry of the maze, a subject could not see any two objects at the same time. The final environment is presented during the actual testing phase. Figure 5 shows a first person view while the subject is in a sparse environment with a Voronoi textured ground plane to give the subject some ocular flow for feedback on distance traveled.

Fig. 2. 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).

Fig. 3. 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.

4 Experiment 1 Methods

4.1 Hypotheses

Given the fundamental differences in the proposed locomotion methods we developed two hypotheses for this experiment. First, given that the subjects are only actually translating during the resetting condition, we expect users in the resetting condition to exhibit better performance on the path length metric than users employing the other methods to walk. Our hypotheses derives from prior literature (Ruddle et al. [33]; Chrastil and Warren [6]) that demonstrates the importance of locomotion in acquiring spatial knowledge.

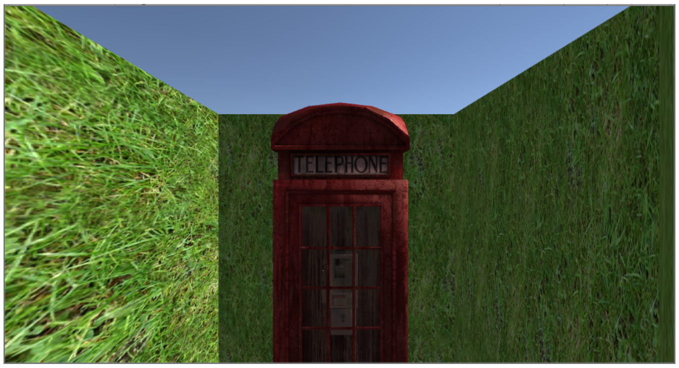

Fig. 4. This figure shows the telephone booth as would be seen by subjects during the orientation phases of the experiment.

Fig. 5. 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.

Regarding initial angular error, we have two walking in place methods which do not manipulate rotation-based cues, and resetting, which does. We hypothesize that resetting's rotational manipulation will result in degraded performance for initial angular error.

4.2 Participants

For this study we recruited college age students from our institution between the ages of 18 and 25 (mean=20.7, median=21). Twenty subjects participated (9 male, 11 female), gave written consent, and were compensated $10 for participating in the experiment, which was approximately one hour in duration. Subjects were informed of their method of walking and the metrics we would collect (initial angular error and path length). Two subjects were excluded from data analysis due to system malfunctions, and therefore six subjects remained in each of the three conditions.

4.3 Equipment

The environment was developed in Unity and based on the maze developed by Chrastil and Warren [6]. A Samsung Gear VR head-mounted display (HMD) provided visual information to subjects. Subjects used either a Samsung S6 or S7 phone as the rendering device. The resolution in each eye is 1280x1440. The field of view of the Gear VR varies somewhat depending on the phone used; we did not measure this, but Samsung reports it as 96°; however, online reports place it at about 90°. Subjects' motion was tracked in one of three ways. The first was using a Vicon Motion Capture system in which body data were transmitted directly to the phone. Our system used 8 MX40 cameras to track the position of 6 optical markers and reconstruct the orientation and position of each subject's head. The physical space used was roughly 6x5 meters; the available tracked space was 5x4 meters. The second utilized the built-in IMU of the Gear VR to detect steps and the final method used a Microsoft Kinect v2.0, which used KinectVR [18] to transmit data using a Node JS server to the phone. All data were transmitted over a LAN using a NETGEAR WNR3500 router. Subjects provided input using the Gear VR's touchpad.

4.4 Procedure

Subjects were first given instructions on how to move in their technique of walking. The first phase of the experiment was to place the subject in the training maze (Figure 2) and give them five minutes to freely explore the maze to learn how to walk around in their condition. Subjects were required to complete the full five minutes of this phase to ensure they were confident and competent at navigating. After this phase subjects were taken out of the headset and given instructions on what to do in the next maze. Subjects were also told to try and remember relative locations of objects as they would be tested later on them.

Next they were placed in the learning maze (Figure 3) and given 10 minutes to freely explore and learn the layout. They were not able to walk through the walls. At the end of 10 minutes subjects began the assessment phase and were placed in the Voronoi textured environment where they were given their next set of instructions.

In this phase subjects experienced a series of trials to find objects from various locations within the maze. To begin, subjects pressed the touchpad on the Gear VR and were placed back in the learning maze directly in front of an object, which allowed subjects to orient themselves. They were instructed not to walk around to prevent seeing any more of the maze. When oriented, subjects pressed the touchpad again placing them back in the Voronoi environment. The time taken to orient themselves in the environment was recorded as orientation time. Upon being placed in the Voronoi environment subjects were given another object in the maze to walk to via a heads up display (see Figure 5). Subjects were instructed to walk directly to the target object in a straight line. A second measurement of time (target acquisition time) was taken here to denote the time taken to recall the direction of the target object. This straight line condition ensured their walked path was a novel shortcut. The position in the maze, time, acceleration (for the Gear only condition), and orientation of the headset were recorded at every frame for potential reconstruction. Subjects indicated the conclusion of a trial by pressing the touchpad a final time. Each subject completed forty trials in total. Beginning and end objects were randomly selected for each subject.

5 Experiment 1 Results

To simplify analysis and remove the variability we divide our 40 trials into four blocks of 10 trials each. We present three measures of how well subjects have acquired spatial knowledge and, in particular, survey knowledge. All ANOVAs were performed using SPSS and the tests for normality and homogeneity of variances were met. Error bars in all figures denote standard errors of the mean.

5.1 Initial Angular Error

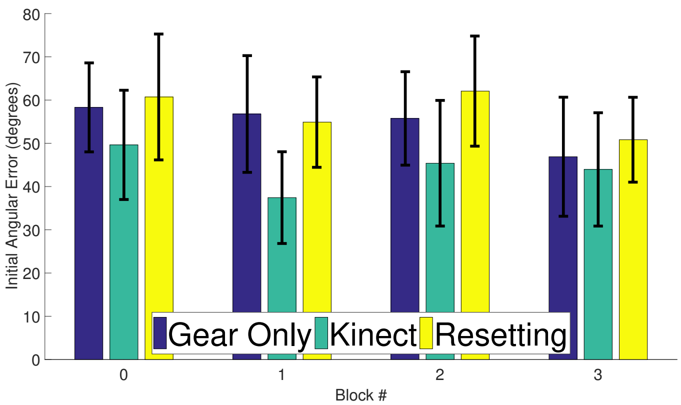

Fig. 6. This figure shows the mean initial angular error of subjects by condition and blocks of 10 trials.

Figure 6 shows the initial angular error by condition and four blocks of 10 trials. A 3 (navigation method) x 4 (block) repeated measures ANOVA on absolute angular error found no effect of condition (F(2,15) = .338, p = .718) or block (F(3,45) = 1.171, p = .331). The lack of a significant effect differs from our second hypothesis, a surprising result given that the walking in place conditions do not manipulate orientation whereas resetting does. In all conditions, the mean absolute angular errors are in line with those found by Chrastil:2013:APSL.

To further explore this result we turned to Bayes factors, an analysis method that can provide support for the null hypothesis and expresses that evidence in an odds ratio[1]. The following analyses use the methods of Rouder et al. Rouder:2009:BTA which, because they account for sample size, adjust for power. We set the prior odds to 1 as this favors neither the null nor the alternative. We first compare the methods of Gear only and Resetting which gives us a Jeffrey-Zellner-Siow (JZS) Bayes factor of 4.47 indicating strong evidence in favor of the null hypothesis. Comparing the Gear only and Kinect conditions gives us a JZS Bayes factor of 1.45 and the Kinect vs Resetting conditions gives us .47 which are marginal and do not strongly support either the alternative nor the null.

5.2 Path Length

The second type of information needed to accurately walk to target object is interpoint distance information. Figure 7 shows how accurately subjects were able to walk the true distance. A 3 (navigation method) x 4 (block) repeated measures ANOVA on the error in relative path length shows a main effect of condition (F(2,15) = 4.923, p = 0.023). A post hoc Tukey HSD revealed that there is a significant difference

1. Online calculators and R packages for calculating these statistics are available at http://pcl.missouri.edu/bayesfactor.

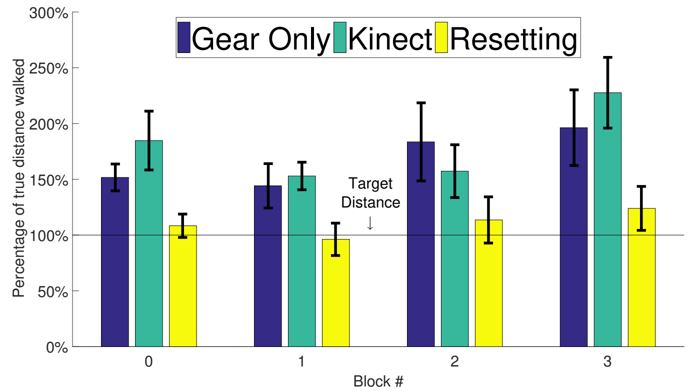

Fig. 7. This figure shows the mean distance subjects walked as a percentage of true distance by condition and blocks of 10 trials.

between the Kinect and Resetting conditions (p = 0.022) and a marginally significant difference between Resetting and Gear only conditions. In both the Gear only and Kinect conditions subjects significantly overwalked the distance to the target (M=168% and M=181%, respectively) whereas in resetting the distance was more accurate (M=111%).

5.3 Recall Time

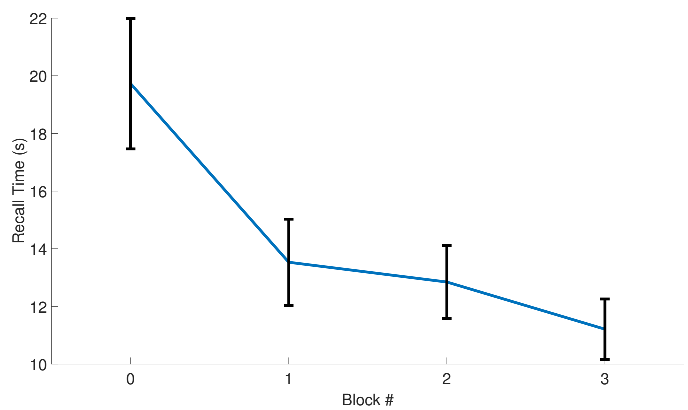

Fig. 8. This figure shows the mean time subjects spent determining the relative direction of the target object. Time is plotted by blocks of 10 trials and collapsed across condition.

Finally, we analyze how quickly subjects are able to recall the maze and the target object. To do this we look at total recall time, i.e., the total time between being presented with the starting object and beginning to walk to the target object. A 3 (navigation method) x 4 (block) repeated measures ANOVA on this total recall time shows a significant main effect of block ($F(3,45) = 21.833, p < .001$, $\eta_p^2 = 0.59$). There is also a large drop-off between the first and second block of 6.2 seconds (a 31.4% drop). Given this large dropoff and the significance of the effect we removed the first block to see if this effect continued throughout the testing procedure. We performed a 3 (navigation method) x 3 (block) repeated measures ANOVA on total recall time for the last three blocks of data and we still find a main effect of block ($F(2,30) = 6.256, p = 0.005$, $\eta_p^2 = 0.29$).

There are two components to total recall time, the first component is the time subjects take to orient themselves within the maze (orientation time). The second component is the time subjects spend determining the direction of the target object (target acquisition time). Exploring further into which of these was the driving force in the previous result, we performed a 3 (navigation method) x 4 (block) repeated measures ANOVA on orientation time and target acquisition time and found significant main effects of block ($F(3, 45) = 16.525$, $p < 0.001$, $\eta_p^2 = 0.52$, and $F(3, 45) = 13.305$, $p < 0.001$, $\eta_p^2 = 0.47$, respectively). We also performed a 3 (navigation method) x 3 (block) repeated measures ANOVA on orientation time and target acquisition time for the final 3 blocks and again found main effects of block ($F(3, 45) = 4.424$, $p = 0.021$, $\eta_p^2 = 0.23$, and $F(3, 45) = 3.900$, $p = 0.031$, $\eta_p^2 = 0.21$, respectively). Thus, both components improve significantly by block.

6 Experiment 1 Conclusions

The framework of spatial microgenesis [5], [6], [17] provides a structured methodology to frame the acquisition of spatial knowledge in humans. We use this framework as the primary measure of the usability for the three methods of navigating large virtual environments presented in this paper. These three methods were resetting, walking in place using the Samsung Gear VR, and walking in place using the Microsoft Kinect. Three metrics measured the acquisition of spatial knowledge in each of these three methods. The first metric was the initial angular error, which assessed the directional component of survey knowledge. We found no significant difference between the walking methods, and a Bayes Factor analysis found high odds that the Gear only and Resetting methods had identical performance. We have no theoretical reasons for why the Kinect might differ from the other conditions, and more work would be needed to ascertain if it indeed does.

The second metric was the path length of the novel shortcuts, which measured how well subjects were able to encode distance information into their cognitive map of the environment. Confirming hypothesis one, subjects performed significantly better in the resetting condition than the walking in place conditions, where they overshot the true distance by 68% in the Gear only condition and 81% in the Kinect condition. Walking in place does not seem to permit the same level of acquisition of metric inter-point distance survey knowledge as does resetting. Subjects overwalking in the walking in place conditions might be explained by the complexity of the maze. This complexity may make the maze seem larger than it actually is, and it produced a pattern of overshooting in the absence of developed survey knowledge. It is possible, however, that this method of locomotion biases any attempt to measure the encoded metric information. Subjects were tested with only optic flow as feedback in the walking in place conditions whereas subjects in the resetting condition have full idiothetic feedback.

The final aspect of spatial knowledge we examined was recall time. Across all conditions, subjects consistently improved in both measurements of map recall time. Over blocks, they were more rapidly able to localize themselves in the maze and to remember the relative direction of a target object. The steady decrease in recall time could be attributed to a strengthening of subjects' cognitive maps. Thus, while the maps did not get any more accurate, subjects recalled them faster. Since the directional component of survey knowledge is representative of direction between objects, subjects may be building a stronger but incorrect map from repeated attempts to recall their survey knowledge.

7 Experiment 2

Our first experiment demonstrated that there was a difference between the two walking in place methods and the resetting method. Subjects could not accurately recreate distance in our walking in place methods. Our second experiment seeks to determine why walking in place prevented subjects from being able to recreate distance. We separated the mechanism by which subjects learned and tested their acquisition of spatial knowledge. This allowed us to determine if the walking method used for testing or learning prevented the accurate recreation of distance.

Individual ability in navigation performance varies wildly, a trend that persisted during our task. We wish to understand what causes the origins of these differences so we include standard measures of individual difference. Firstly, by reducing the individual variance inherent in our task we can begin to understand the full effect on navigation performance of our methods of locomotion. Secondly, measuring individual differences allows us to begin to select a locomotion method appropriate for a subject based on skill, strategy, and experience.

7.1 Hypotheses

Based on the work of (Richard: From optic flow BG) and others, we know that optic flow is not sufficient for subjects to fully understand the distance they have traveled. In that work subjects greatly overwalked the intended distance. Additionally since the environments provide a large number of cues for distance traveled we expect that the difficultly will lie in recreation of distance, not in the acquisition of the scale of the environment. While we expect to see a difference in distance recreation for either the mechanism of learning or testing, we do not expect this to effect the reported relative direction.

By testing for individual differences we expect that we will be able to reduce variance and strengthen the conclusions reached in the previous experiment. This will require some correlation between performance and our measures of individual difference, our third hypothesis is that these correlations will be positive as in prior work on navigation in similar tasks hegarty2006spatial, Chrastil:2013:APSL.

7.2 Participants

This experiment had the same subject pool of college age students from our institution (mean = xx.x, median = x). XXX subjects participated (XY male, XX female), gave written consent, and were compensated $15 for participating in a 90 minute study. Instructions were identical to experiment 1 with the exception that some subjects would be told about both methods of locomotion. XX subjects withdrew from the study and XX subjects were excluded due to system errors.

7.3 Equipment

The equipment was as in experiment 1 with the exception of the tracking systems. The kinect was eliminated from consideration and the Vicon system was replaced with the WorldViz Precise Position Tracking (PPT) system which used 4 (Richard: blah) cameras to track the position of a single optical marker. Orientation was tracked using the Gear VR's internal IMU.

7.4 Procedure

At the start of the experiment, subjects took several tests to measure their innate spatial cognition. First, subjects received a standard vocabulary test. Afterward, subjects matched identical three-dimensional shapes that had been rotated to different perspectives [45]. Lastly, subjects personally rated themselves on the Santa Barbara Sense-of-Direction Scale [15]. All these tests gave us a baseline understanding of the subjects initial spatial aptitude before commencing the virtual reality portion of the experiment. The virtual reality test consisted of two five-minute training sections, one ten-minute learning section, and an un-timed assessment section, in that order. The first training section and the learning section employed the same technique of walking, and so did the second training section and assessment section. Thus, there were four types of experiments, one for each permutation of walking-in-place and resetting. Note that for homogeneous pairs (e.g. two resetting), the two five-minute training section were combined into a single ten-minute section. Subjects were first given instructions on how to move in their walking technique. The first phase of the experiment was to place the subject in the training maze and give them five minutes to freely explore the maze to learn how to walk around in their condition. Subjects were required to complete the full allotted time of this phase to ensure they were confident and competent at navigating. If subjects were in a heterogeneous pair (i.e. first resetting then walking-in-place), then subjects would repeat this phase with a different walking technique. After training was over, subjects were taken out of the headset and given instructions on what to do in the next maze. Subjects were also told to try and remember relative locations of objects as they would be tested later on them. Next they were placed in the learning maze and given 10 minutes to freely explore and learn the layout. This walking technique matched the technique employed in the first training section. They were not able to walk through the walls. At the end of 10 minutes subjects began the assessment phase and were placed in the Voronoi textured environment where they were given their next set of instructions. In this phase subjects experienced a series of trials to find objects from various locations within the maze. To begin, subjects pressed the touchpad on the Gear VR and were placed back in the learning maze directly in front of an object, which allowed subjects to orient themselves. They were instructed not to walk around to prevent seeing any more of the maze. When oriented, subjects pressed the touchpad again placing them back in the Voronoi environment. The time taken to orient themselves in the environment was recorded as orientation time. Upon being placed in the Voronoi environment subjects were given another object in the maze to walk to via a heads up display. Subjects were instructed to walk directly to the target object in a straight line. A second measurement of time (target acquisition time) was taken here to denote the time taken to recall the direction of the target object. This straight line condition ensured their walked path was a novel shortcut. The position in the maze, time, acceleration (for the Gear only condition), and orientation of the headset were recorded at every frame for potential reconstruction. Subjects indicated the conclusion of a trial by pressing the touchpad a final time. Each subject completed forty trials in total. Beginning and end objects were randomly selected for each subject.

8 Experiment 2 Results

Similar to experiment 1 we reduced the amount of data and variability by collapsing across trials to reach a single average for each metric that will be discussed in this section. Data from experiment 1 showed that there was no effect of time between the conditions, either as a main effect or an interaction. This trend persisted in experiment 2 and for that reason we do not include it in our analysis. We present the remaining two measures of survey knowledge as well as our results regarding individual differences. All ANOVAs were performed using SPSS and the tests for normality and homogeneity of variances were met. Error bars in all figures denote standard errors of the mean.

8.1 Path Length

The main purpose of this experiment was to determine the cause of the distal errors revealed in experiment 1. We ran a 2x2 (testing x learning) ANOVA on path length error with MRT and SBSOD as covariates to determine the root cause. We found a main effect of testing $(F(1,90) = 60.047, p < .001)$. Post hoc comparisons showed that the conditions in which subjects tested in walking in place resulted in subjects walking 112% of the true distance further than those who tested in resetting. Learning showed no effect on path length. Figure 9 shows the effect of testing on distance recreation.

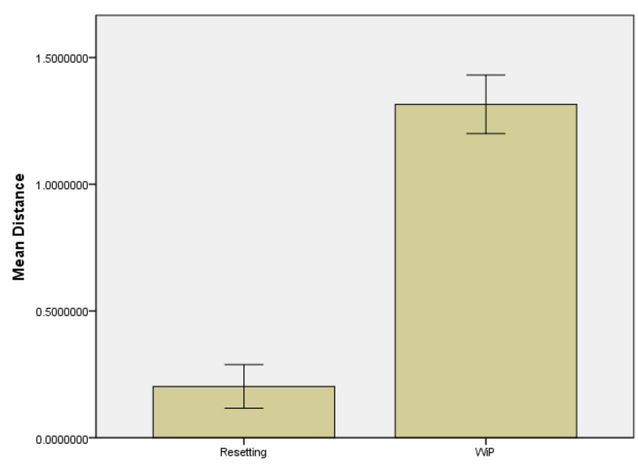

Fig. 9. This figure shows the distance overwalked when testing in each condition.

8.2 Initial Angular Error

To detect differences in configural knowledge we ran a second 2x2 (testing x learning) ANOVA on initial angular error with MRT and SBSOD as covariates. The ANOVA revealed no significant effect of learning or testing but showed that the MRT was highly correlated with performance in this metric ($F(1, 90) = 28.694, p < .001$). Figure 10 shows this correlation.

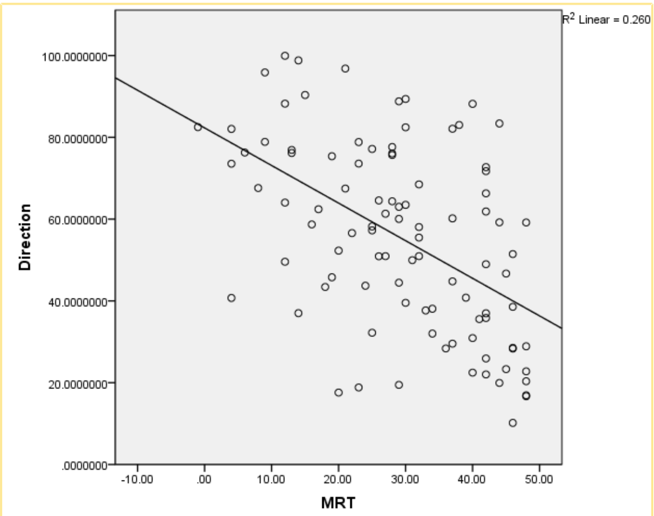

Fig. 10. This figure shows the correlation between direction estimation and mental rotation abilities.

8.3 Individual Differences

Analysis of the correlations of SBSOD with the initial angular error performance of those who learned in resetting and those who learned in walking in place revealed drastic differences (r = .064 vs r = -.39 for resetting vs walking in place). We computed a Fisher r-to-z transformation to compare these and found a significant difference ($Z = 2.27, p = .0232$). Figure 11 shows the trends between the two learning methods.

To investigate these differences we coded those with high SBSOD as having higher than the median SBSOD and similarly coded MRT scores. We computed a 2x2x2x2 (learning x testing x MRT x SBSOD) ANOVA and found a interaction of learning x MRT x SBSOD ($F(1, 80) = 5.006, p = .028$). Post hoc analysis showed that while subjects in general improved with higher MRT scores, this trend was not followed for subjects who learned in walking in place and had low SBSOD. This can be seen in Table 1 which shows pairwise t-test comparisons among 4 groups.

Learning Method	SBSOD Score	High MRT	Low MRT
WiP	High	36.209	63.887**
WiP	Low	57.652	64.607
Resetting	High	70.934	46.216**
Resetting	Low	66.190	37.188**

TABLE 1
Comparison of improvement in direction from MRT scores. **p ¡ .01

Further post hoc analysis revealed that resetting outperformed walking in place only when subjects had low SBSOD and high MRT scores ($delta = 27.419, p = .009$) and can be seen in figure 12.

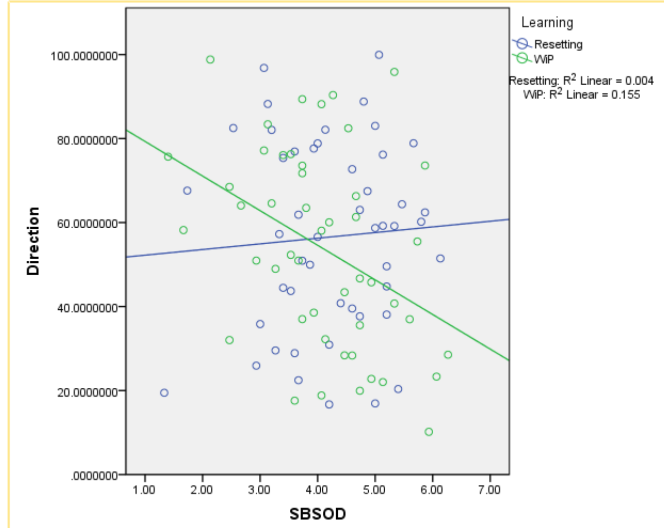

Fig. 11. This figure compares the correlation between direction estimation and sense of direction across learning methods.

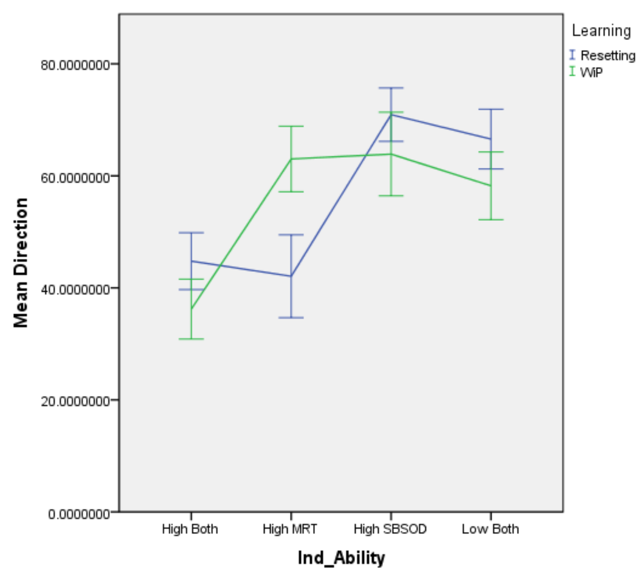

Fig. 12. This figure compares the correlation between direction estimation and sense of direction across learning methods.

9 Discussion

9.1 Testing Method Effects

The results on the second experiment showed that the distance expansion revealed from the first experiment is caused by a testing effect when subjects test using walking in place. This likely indicates that subjects don't have a sense of how far they have traveled under walking in place and are relying on the visual information provided by the environment rather than their own body based cues. This also tells us that any future testing should be done using resetting or some real walking technique to prevent a testing effect on expression. There were no testing effects on direction which makes sense because subjects effectively choose their direction before any locomotion method is used.

9.2 Learning Method Effects

In our analysis we have four groups of people based on individual's mental rotation abilities and sense of direction. Subjects can be strong in both, neither, or only one of the two. Subjects were able to learn an environment in one of two ways either by resetting or walking in place. Resetting showed to be the better method for learning, but only for those that have strong mental rotation abilities but weak sense of direction. In the literature [15] navigation performance is generally correlated with high MRT scores and the work confirms those results. SOD scores are also correlated with navigation performance, however, in this work this result only held when subjects learned by walking in place. Resetting differs from typical walking in that it is in-congruent to directional body based cues. This may explain why those who have a better sense of direction are hindered by resetting. They may either decide to ignore the directional information or may have a more imprecise map created by bad information. We believe the reason this only shows up in those who have strong MRT scores may be they naturally make use of directional body based cues while the other group does not.

9.3 Future Work

This leads to many interesting questions on how different navigators make use of different information. Future work could be done to determine if subjects are making imprecise maps or ignoring the information available to them. The trend only occurring in some navigators makes this difficult to test for, but should inspire the use of other individual difference tests when looking at these walking methods.

Acknowledgments

The authors would like to thank...

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