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Estimating distances and traveled distances in virtual and real environments

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ESTIMATING DISTANCES AND TRAVELED DISTANCES IN VIRTUAL AND REAL ENVIRONMENTS

by

Tien Dat Nguyen

An Abstract

Of a thesis submitted in partial fulfillment of the
requirements for the Doctor of Philosophy
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Thesis Supervisor: Professor James Cremer

ABSTRACT

Virtual environments (VEs) have gained widespread use in recent years as a tool for training new skills, particularly in cases where training in the real environment can be risky or dangerous. But while there are many potential applications that could benefit from using VEs, our understanding of several basic perceptual and cognitive tasks in VEs - distance and traveled distance estimation, speed estimation, spatial orientation, and wayfinding - is not yet well developed. This dissertation increases understanding of two of these problems through three experiments on distance estimation and three on traveled distance estimation.

The first experiment directly compared participants' distance estimates across several visual presentation methods and measurement protocols. Results, for instance, showed no significant differences between estimates made when VEs are displayed in a head-mounted or a large-screen immersive display. In the second distance estimation experiment, participants made a series of distance judgments with feedback during an adaptation phase, and then made a series of "test phase" judgments without feedback in an environment that was similar but differently scaled. Under certain scaling conditions, there were significant differences between adaptation accuracy and test accuracy, suggesting that people's perceptual judgment is less well grounded in VEs than in the real world. Finally, our third distance estimation experiment was a pilot that further confirmed underestimation of distances in VEs while providing initial experience with a travel distance task valuable for the second half of our research.

The fourth experiment is one of the first to directly compare traveled distance estimates between real and virtual environments. Results, for instance, showed a significant difference between estimates made by people who were passively moved through a real environment and people who experienced simulated self-motion in a virtual environment. The fifth and sixth experiments investigated whether scene density and richness affect people's sense of traveled distanced. Participants were surprisingly accurate in some circumstances. However, in each of these experiments, feature-sparse environments were judged significantly differently than feature-rich environments, and these differences varied by population.

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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

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To Mi and Mi

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ABSTRACT

Virtual environments (VEs) have gained widespread use in recent years as a tool for training new skills, particularly in cases where training in the real environment can be risky or dangerous. But while there are many potential applications that could benefit from using VEs, our understanding of several basic perceptual and cognitive tasks in VEs - distance and traveled distance estimation, speed estimation, spatial orientation, and wayfinding - is not yet well developed. This dissertation increases understanding of two of these problems through three experiments on distance estimation and three on traveled distance estimation.

The first experiment directly compared participants' distance estimates across several visual presentation methods and measurement protocols. Results, for instance, showed no significant differences between estimates made when VEs are displayed in a head-mounted or a large-screen immersive display. In the second distance estimation experiment, participants made a series of distance judgments with feedback during an adaptation phase, and then made a series of "test phase" judgments without feedback in an environment that was similar but differently scaled. Under certain scaling conditions, there were significant differences between adaptation accuracy and test accuracy, suggesting that people's perceptual judgment is less well grounded in VEs than in the real world. Finally, our third distance estimation experiment was a pilot that further confirmed underestimation of distances in VEs while providing initial experience with a travel distance task valuable for the second half of our research.

The fourth experiment is one of the first to directly compare traveled distance estimates between real and virtual environments. Results, for instance, showed a significant difference between estimates made by people who were passively moved through a real environment and people who experienced simulated self-motion in a virtual environment. The fifth and sixth experiments investigated whether scene density and richness affect people's sense of traveled distanced. Participants were surprisingly accurate in some circumstances. However, in each of these experiments, feature-sparse environments were judged significantly differently than feature-rich environments, and these differences varied by population.

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CHAPTER 1
INTRODUCTION

1.1 Overview, motivation and goals

Virtual environments (VEs) have gained widespread use in recent years as a tool for training new skills, particularly in cases where training in the real environment can be risky or dangerous. For example, immersive virtual environments have been used for training fire fighters, medical doctors, and military personnel [30, 67]. The reason is that VEs can be easily controlled and manipulated, and trainees' errors do not result in deadly consequences.

While many applications could benefit from using virtual environments, there are also many aspects of interacting with VEs that are not well understood. Accordingly, there is substantial active virtual environment research on several perceptual and cognitive problems such as distance estimation, traveled distance estimation, speed estimation, spatial orientation, wayfinding, immersion and presence.

In particular, many studies have shown that people's perception in virtual worlds is different than in the real world, and that their estimates of distances in VEs are shorter than their estimates of the same distances in real environments. Misperception of distances might lead to ineffective training where people trained in VEs end up performing poorly in the real world due to differences in distance perception. Therefore, it is important to investigate the factors that influence people's perception in virtual and real environments. By understanding these factors, we may be able to reduce or counter effects of the differences between the two kinds of environments.

The goal of the research behind this dissertation was to look at what it is about virtual environments that makes people's judgments differ from what they should be. We accomplished this by conducting several experiments comparing people's estimates of distances and traveled distances in virtual and real environments, as well as virtual world-only experiments investigating the effect of scale change in distance estimation and the effects of scene properties on traveled distance estimation. The results from these experiments increase our knowledge and understanding of the distance estimation problem and the related but less well studied traveled distance estimation problem.

1.2 Outline of thesis

The organization of this thesis is as follows.

Chapter 2 presents our first problem of interest: distance estimation. We review prior research about distance estimation for both virtual and real environments.

Chapter 3 presents experiments assessing the effects of presentation methods (e.g. virtual world via head-mounted display, photo-based model via large-screen immersive display, real-world without HMD) and measurement protocols (blindfolded walking, timed-imagined walking) on distance estimation in virtual environments, while keeping many other factors (targets, distances, visual model) constant. More specifically, we compared head-mounted and large-screen immersive displays; assessed the impact of graphics quality and of HMD encumbrance and field of view; and examined the interaction between display systems and measurement protocols.

In chapter 4, we investigate whether experience with making distance estimates in a virtual environment of one scale affects people's perception of the same distances in a similar virtual environment of a different scale.

In chapter 5, we detail a pilot experiment that further confirmed underestimation of distances in VEs while providing initial experience with a travel distance task valuable for the second half of our research.

Chapter 6 presents the problem of traveled distance estimation and background research in that area. Traveled distance estimation is different from distance estimation, answering the question "How far did I just travel?" instead of "How far away is that thing?". We contrast the traveled distance and distance estimation problems, and review research about traveled distance estimation that has been done in both virtual and real environments.

Chapter 7 presents one of the first studies to directly compare traveled distance estimates between virtual and real environments. Three modes of travel were studied: simulated, passive and active motion.

Chapter 8 details an experiment examining the effects of scene density and richness on people's estimates of traveled distance. We hypothesized that people who experienced the same motion in different environments with different levels of density and richness would make different estimates of the traveled distance.

Chapter 9 follows up the experiment in Chapter 8. The result of Chapter 8 was interesting, and suggested that the density, richness and/or interestingness of the environment affect traveled distance estimation. However, it had only two conditions, making it difficult to conclude much. To further investigate this problem, we designed and carried out a second experiment with four conditions and more complete data collection that allowed us to compare participants' walking speeds and times in addition to their distance estimates.

Chapter 10 presents our final conclusions, summarizes our contributions to the distance estimation and traveled distance estimation problems, and suggests experiments for further understanding of these problems.

CHAPTER 2
BACKGROUND: DISTANCE ESTIMATION

This chapter presents background research on the first of the two main problems of this thesis: distance estimation. We first review research work in distance estimation in the real world, then in virtual environments including research work comparing distance estimation between virtual and real environments.

2.1 The distance estimation problem

Overall in action space (approximately 2-30m [12]), people underestimate distance in virtual environments relative to real world, where they are fairly accurate. The factors contributing to distance underestimation may include the display technology, field of view, stereopsis and parallax, the visual targets and settings, the fidelity of the visual virtual model, the range of distances examined, and the experimental methods.

Gilinsky [19] gives a nice description of the distinction between *"perceived distance"* and *"estimated distance"*. According to the author, a perceived distance is an "apparent distance" that is produced from the visual system. So when a person says that a perceived distance is 40 feet, it means that the perceived distance is twice as long as a perceived distance of 20 feet, and 40 times as long as a perceived distance of one foot. The "visual one foot" does not change, although the real distance corresponding to the "visual one foot" increases progressively as the "visual one foot" gets away from the person. An estimated distance is an "intellectual correction" of a perceived distance, derived from past experience or training, to form a judgment of the true distance. So when a person says an object is 100 feet away, it is her estimate of the real distance even though her perception of the distance might be only 30 or 40 “visual” feet.

To figure out the relationship between perceived distances and physical distances, Gilinsky [19] conducted an experiment to compute perceived distances using the method of equally apparent intervals. In this experiment, participants were asked to mark successive increments of equal perceived length, which were supposed to be one foot long. Because physical intervals needed to be larger and larger to match with the same perceived length as the increments went father and father from participants, there should be a strongly negative relation between perceived distances and physical distances. From the data of two participants, Gilinsky found that the desired function had a hyperbolic form $d = D \times A / (D + A)$, where d is the perceived distance, D is the physical distance, and A is the maximum limit of perceived distance for a given participant in a given condition. In this experiment A came out to be about 94 feet. This formula showed that perceived distances are always shorter than the physical distance, and hence people need some other cues to self-correct their distance perception.

We are interested in distance estimation instead of distance perception because distance estimation has more direct practical impact. Our success at throwing trash in a garbage can or hopping across puddles depends on accurately estimating distances. First, we will review what is known about distance estimation in real environments.

2.2 Distance estimation in real environments

A lot of work has been done investigating distance estimation in real environments.

Harway [25] conducted experiments to see the effect of eye-height and age in distance estimation in real environments. The method used in his experiment was similar to Gilinsky's [19]: the task was to estimate successive one foot intervals using a foot-ruler, starting at one foot in front of the subject. An experimenter moved a pointer along the ruler from the one end, and the subject had to tell the experimenter to stop when the pointer reached the other end. Then a marker was placed at the same location as the pointer, and the pointer would be moved along the same direction starting from the marker. The subject needed to tell the experimenter to stop when the pointer was moved as far from the marker as the length of the ruler (which was one foot). The next trial would start from the position where the pointer stopped. There were two conditions: in the first condition, participants made judgments with normal eye-height, then with adjusted eye-height (5 ft 6.5 inches); in the second condition, participants made judgments with adjusted eye-height, then with normal eye-height. The results showed that changing subjects' eye heights did not influence their distance judgments: There was no significant difference in their distance estimates in both conditions. There was a noticeable effect of age in the results: Adults and 12-year-old children made distance estimates with significantly smaller error than children who were 10 years old or less. The author suggested that probably children less than 10 years old had not fully developed their cognitive system to perform the task accurately.

Loomis *et al.* [43] suggested that people can estimate the egocentric location of targets accurately, but this does not necessary mean that they can correctly estimate the distance between targets. They conducted three experiments to confirm their hypothesis. In the first experiment, participants could perform blindfolded walking accurately to previously seen targets (four, six, eight, 10 or 12 meters away), but they consistently estimated sagittal intervals to be much shorter than the equal frontal intervals (when being asked to put two objects in the sagittal plane so that the distance between them was equal to a given frontal interval, participants consistently made it to be 30 to 100 percent larger). In the second experiment, participants first saw two targets, then were asked to walk without vision to the first target, and then kept walking without stopping to the second target (they said “here” when reached the first target). There were two conditions: in the width condition, the second target was on the right or left of the first target; in the depth condition, the second target was in the same frontal direction and beyond the first. The distances between the two targets were one, 1.5 or two meters. The results showed that their performance was highly accurate, which suggested that even though their initial estimation of the sagittal distances is incorrect (as experiment 1 suggested), their estimation of the location of each target is correct. The third experiment showed that participants could correctly point continuously to a previously seen target while walking blindfolded. Because visually directed pointing is a form of triangulation, the results from the three experiments confirmed the idea that people can: correctly estimate the location of the target; correctly update their current self-position based on integration of perceived self-velocity; in the case of walking, correctly update the target location based on updated self-position; and in the case of pointing, correctly update the pointing direction based on updated target position.

Daum and Hecht [12] investigated distance estimation in vista space (distances that are longer than 30m). Verbal report was used as the measurement protocol. Three experiments showed that people tend to underestimate distances in "near vista space" (less than 75m) and overestimated distances in "far vista space" (longer than 75m). The results also showed that eye height and the size of the target seem to be important in estimating distances in vista space. In another study, Canter and Tagg [8] had participants from seven different cities (Glasgow, Edinburgh, Heidelberg, London, Sydney, Tokyo and Nagoya) estimate, based on their memory/knowledge, the direct distances (as the crow flies) of several pairs of two places in each city. The distances were from 1.28 miles to 13.61 miles. They found that all participants overestimated the distances, and there was a strong correlation between the actual distance and the amount of overestimation (i.e. the longer the actual distance, the larger the amount of overestimation).

Lappin *et al.* [41] found an interesting effect of surrounding environments in estimating distances in real environments when using a bisection protocol. In this study, the participant saw experimenter A as a target person at some distance. Then experimenter B started walking from the participant toward experimenter A, or from experimenter A toward the participant until was told by the participant to stop at the mid-point between the participant and the target person. The distances were 15 and 30 meters. The experiment was carried out in three different conditions: in a lobby, in a hallway, and on a grassy lawn. The results showed that in all three conditions, participants tended to judge the midpoint farther away from themselves than it actually was. There was a significant difference in their estimates between lobby, hall conditions and lawn conditions. Participants significantly overestimated the mid-point in the lobby and hall conditions, but did not in the lawn condition. The variability of the data also showed the effect of the surrounding environment, with the variance in the hall condition significantly higher than the other two conditions. Therefore the authors suggested that the environmental context influenced distance estimation in real environments.

Witt *et al.* [77] found a different type of environmental effect on distance estimation. They explored effects of the environment beyond or behind the target being viewed. In this study, participants viewed a Target person at a distance, then turned 180 degrees and adjusted a Match person so that the distance to the Match person was perceived to be the same as to the Target person. Distances were from one to four meters. There were two conditions: in the Near condition, the area behind the Target person is limited (less than 12m); in the Far condition, this area is expanded much longer (more than 21m). Results from two experiments with different types of environments (indoor, outdoor) showed that having a substantial expanse of space behind the target seemed to increase the accuracy of participants' estimates of distance to the target. This suggested that the space beyond the target (was called "vista space" by the author, with "vista space" having the same meaning as in [12]) has an influence to distance estimation in real environments.

Ooi and his colleagues have found several important factors in estimating distances in the real world. First, continuous ground is important [68]. In this study, participants first saw a target, then turned 180 degrees and walked with their eyes closed until they thought they covered the same distance as the initial distance to target. Distances were up to five meters. The results showed that when there was a gap in the ground between participants and targets, they overestimated the distance. When the ground texture changed from where the participants stood to where the targets were (concrete to grass or vice versa), they underestimated the distances. This result suggested that texture gradient on the ground surface is an important depth cue for people to correctly estimate distances in the real world.

Second, angle of declination from the horizon is important [54]. In this study, participants first wore a pair of base-up prisms (which tilt rays downward increasing the angle of declination to the target) and made distance estimates with blindfolded walking and throwing protocols. Then the prisms were removed and participants completed a post-adaptation phase with blindfolded walking protocol. The results showed that distances were significantly underestimated in adaption and overestimated in post-adaptation compared to the baseline condition. Because two types of protocols were used in adaptation, it ruled out the possibility that the effect in post-adaptation phase was solely due to an adaptation within the locomotion system. Therefore, the authors concluded that the eye level and the angle of declination are important in distance estimation in the real world.

Third, near ground surface information and scanning from self to target are important in estimating distances, even when field of view (FOV) is restricted [79]. In the first experiment of this study, participants wore a pair of goggles which restricted their FOV to the ground surrounding the target. Participants kept their head still while looking at the target, then closed their eyes and walked without vision to the target location. Distances were four, five, six and seven meters. There were three conditions with three different FOVs. The results showed that when the FOV was 38.6 degrees x 39.5 degrees, participants' estimates were very accurate (approximately 100%). Participants significantly underestimated distances when the FOV was reduced to 21.1 degrees x 21.2 degrees or 13.9 degrees x 13.5 degrees. Hence, the authors suggested that the size of the visual ground surrounding targets was important in distance estimation, and that a large ground surface was essential to accurately estimate distances.

To further assess the role of the size of ground surface surrounding the target, a second experiment was conducted involving a perceptual matching task. There was an L-shaped target with its width in the frontal plane and its height in sagittal plane. Its width was fixed in length (40.5cm) but its height could be adjusted. The participants' task was to adjust the target's height so that its width and its height were equal. The same three conditions as the previous experiment were used. Again, the results showed that people accurately matched the target's height with the target's width when their FOV was 38.6 degrees x 39.5 degrees, but underestimated significantly in the other two conditions. Taken together, these two experiments suggested that the large ground surface surrounding the target was important in distance estimation in the real world.

A third experiment aimed to investigate which part of the ground contained more essential information: the left-right ground surface or the near-far ground surface. There were two conditions. In the first condition, participants wore a pair of goggles whose vertical FOV was fixed to 50.9 degrees while the horizontal FOV could be adjusted (29.2, 21.5, or 14.3 degrees). In the second condition, the goggles had fixed horizontal FOV (57.7 degrees) and adjustable vertical FOV (39.9, 20.6, 21.1 and 13.6 degrees). A blindfolded walking protocol was used and the distances were from three to seven meters. The results showed that participant' performance did not change in the first condition in which the vertical FOV was fixed. In the second condition, participants significantly underestimated distances when the vertical FOV was smaller than 21 degrees. So it seemed that the near-far ground surface was an important factor.

A fourth experiment was to examine the importance of near ground and far ground. Participants estimated the distance by scanning the ground from self to target (condition 1), or from horizon to target (condition 2), then walked with their eyes closed to the target location. They wore a pair of goggles that restricted their FOV, so they had to move their head upward from initial downward position to the target in the first condition, or move their head downward from looking straight position to the target in the second condition. The results showed that participants' estimates were significantly better when they scanned from self to target, which confirmed that the near ground information was essential.

The authors also conducted a fifth experiment, in which participants did the same task in the same two conditions as the fourth experiment, but in a dark environment so that they could only see a lighted target, but not the ground texture. The results showed that participants' performance was virtually the same in both conditions, which implied that when the ground information was not available, scanning did not help.

Altogether, the author concluded that the near ground information and scanning from self to target were important in estimating distances in real environments.

2.2.1 Summary

People's *perception* of distances in real environment is fairly accurate in personal space (within 2m [12]), but not in action space or vista space. Though accurate in personal space with good cues, when the cues are greatly reduced, people typically overestimate distances to targets closer than 2m, and undershoot targets farther than 2m [55]. In action space, when important cues such as the near ground surface or angle of declination are available, people can use these cues in addition to their experience to fairly accurately *estimate* distances. For example, by scanning the near ground surface, people's estimates become much better than if they don't scan the near ground surface or when the near ground surface is not available [79]. In vista space, people's estimates are not very good, as shown in [12], perhaps because of the lack of people's experience in vista space and the cues there are not clear.

We also notice that the finding of [25], that eye height is not an important factor in estimating distances, is somewhat in conflict with the findings of [54, 12]. One can argue that increasing the eye height by standing on a box would increase the angle of declination, and therefore would make people underestimate distances in a similar way that a pair of base-up prisms would do. But it's possible that the changed circumstances of standing on a box is more obvious and noticeable than the changed circumstances of wearing a pair of prisms. In the case of standing on a box, people know the differences right away (i.e. they got taller), and with experience they can undo some of the effect. But in the case of wearing a pair of prisms, people may not notice the difference. Their eye height is still the same and the horizon is still the same. Everything may seem unchanged, so they adapt to the change without noticing it. For the disagreement between [25] and [12], one possible explanation is that perhaps people use a different set of cues to estimate distances in vista space, possibly because of the lack of experience.

In the next section, we will see that the situation in virtual environments is quite different. People underestimate distances in action space in virtual worlds, and the reasons are still not well understood.

2.3 Distance estimation in virtual environments

Messing and Durgin [45] tested the effect of live video of a real environment displayed in an monocular head-mounted display (HMD). Three conditions were used: live video via HMD, real world with restricted FOV (no HMD, but FOV was restricted to be the same as wearing HMD and one eye was covered), and real world with unrestricted FOV (no HMD with one eye covered). Distances were from two to seven meters. Estimates were made via blindfolded walking without feedback. The results showed that participants significantly underestimated distances in the HMD condition (77%) compared to the restricted FOV (96%) and the unrestricted FOV (96%) conditions. This suggested that mechanical characteristics of the HMD were the main factor contributing to the differences between the HMD and non-HMD conditions. As the authors noted in the paper, it is possible that the combination of very short accommodation of the HMD (one meter), the low resolution of the screen and the distortion of the optical system contributed significantly to the compression in distance estimation.

Plumert *et al.* [56] compared distance estimation between real and virtual environments displayed on a large-screen immersive display (LSID) system. The environment was a grassy lawn in front of a university building. Distances were from six to 36 meters and timed-imagined walking was used as the measurement protocol. Participants' normal walking speeds were measured at the beginning of the experiment, then estimated distances were computed by multiplying their imagined walking times and their walking speeds. The results of the first two experiments showed that people tended to accurately estimate distances less than 18 meters and underestimate distances longer than 18 meters, but their estimates of distances were virtually identical for both real and virtual environment (this was true for adults and 12-year-old children, though 10-year-old children significantly underestimated distances in the virtual environment). A third experiment compared timed-imagined walking with blindfolded walking in the real environment. The authors found that there was no significant difference in people's estimates of distances between the two protocols. The results therefore suggested that distance estimation might be better in LSID setups compared to HMD setups, and that the non-encumbrance of the LSID system might be more important than the lack of stereo and motion parallax in distance estimation tasks.

Bodenheimer *et al.* [5] investigated the role of environmental context in distance estimation in real and virtual environment using a bisection task. This work was a replica of [41] with virtual environments. There were three viewing conditions: 1) virtual via an HMD; 2) real world with restricted FOV; and 3) real world without restricted FOV. Two environments, a hallway and a grassy lawn in front of a building, were used to make six conditions. Distances were 15m and 30m (so the bisection distances were 7.5m and 15m). Each participant saw a "target" person and then adjusted another person to the position they judged to be the midpoint between the participant and the target. The results showed that there was a compression in participants' estimates of the midpoint in the virtual conditions: participants judged the midpoint to be closer to themselves than it actually was. However, there was no compression in participant's estimates of the midpoint in the real conditions, both with and without restricted FOV. In contrast with [41], they did not find an effect of environment context: for each viewing condition, the performance of participants was the same for both environments. Thus, the authors suggested that the characteristics of the HMD such as restricted FOV and low resolution seemed to contribute to the underestimation of distances in virtual environments.

Interrante *et al.* [28] investigated the role of presence in distance estimation in virtual environments. The authors wanted to see if being in a high fidelity model of a real environment after seeing this real environment could reduce the amount of underestimation in virtual environments. The results from two experiments showed that with a blindfolded walking task, participants' estimates of distances from three to nine meters were not significantly different between real and virtual environments. The estimates in the virtual environment were slightly lower than those in the real world, but not significantly different. The authors suggested that presence and the feeling of being there are important factors in estimating distances in VEs.

Jones *et al.* [31] investigated distance estimation in augmented reality using an optical see-through HMD. The experiment was carried out in a hallway, distances were from two to eight meters, and blindfolded walking was used as the measurement protocol. Four conditions were used: Real without HMD, Real with HMD, Virtual with HMD and Augmented Reality (AR) with HMD. The results showed underestimation in the Virtual condition, but not in the AR condition or Real with/without HMD condition. This suggests that people can estimate distances correctly in augmented reality, with virtual targets displayed in a surrounding real environment. In this experiment, the mechanical characteristics of the HMD seem not to have a great effect.

Willemsen *et al.* [73, 74] investigated the role of HMDs' mechanical characteristics in contributing to the underestimation of distances in VEs. In this study, participants either saw the virtual world through a real HMD, the real world through a mock HMD (a fake HMD with the same FOV, mass and moments of inertia as the real one) or the real world with unrestricted viewing. Using two different protocols for distance estimation (direct blindfolded walking or triangulated blindfolded walking), they found that the distances were significantly underestimated when participants wore the HMD or the mock HMD compared to the unrestricted viewing condition. And, there was no significant difference between the real HMD and the mock HMD. Hence, the result indicated that the mechanical properties of the HMD (weight, moments of inertia, limited FOV, etc.) account for some of the distance underestimation in virtual environments.

There are a few studies about distance estimation in VEs after period of adaptation in similar or different VEs. These studies demonstrate some interesting results that may give us more insights about how people estimate distances.

Ziemer *et al.* [81] examined whether there is an order effect of experiencing real or virtual environments before making distance judgments. In this study participants made two sets of distance estimates in one of these four conditions: 1) real environment (Real) first, virtual environment (Virtual) second; 2) Virtual first, Real second; 3) Real first, Real second; 4) Virtual first, Virtual second. The distances were from six to 36 meters. The results showed that participants' first estimates were significantly more accurate in the real than in the virtual environment. When the second environment was the same as the first environment (Real-Real or Virtual-Virtual), the participants' second estimates were also significantly more accurate in the real than in the virtual environment. But when the second environment was different from the first one (Real-Virtual or Virtual-Real), there was no significant difference between the participants' second estimates across the two conditions. Therefore, the authors suggest the experience in either real or virtual environments plays an important role in distance perception.

Steinicke *et al.* [69] examined the effect of a transitional world in distance estimation in VEs. The authors wanted to see if people's estimates of distances would be improved if they first experienced a virtual replica of the real laboratory where the experiment takes place (i.e. the transitional world) before entering a unfamiliar virtual world. Distance estimates were made via blindfolded walking, and distances were three, five and seven meters. There were two conditions: in the T-V condition, participants first made distance judgments in the transitional world, then made distance judgments in the virtual world, which was a virtual city; and in the V-T condition, participants made distance estimates in the reverse order. The authors found that participants' estimates in the virtual city were significantly less underestimated in the T-V condition compared to the V-T condition, which indicated that people could improve their distance estimation in an unfamiliar virtual environment after experiencing a transitional virtual environment. On the other hand, participants in the V-T condition made worse estimates in the virtual replica than participants who experienced the virtual replica first, right after the real room.

2.3.1 Summary

Although estimates of action-space distances are accurate in the real world, distance underestimation in virtual environments has been shown by many studies. The question that comes to mind is: why do people underestimate in VEs even though many of the same cues that people use in real environments are present? Research has investigated many characteristics of the VE such as graphics fidelity, familiar environment, indoor versus outdoor, as well as the characteristics of the display systems such as the weight, encumbrance and limited FOV of HMDs, and non-stereo, non-parallax and limited accommodation/convergence of LSIDs. But single factors by themselves don't appear to be main cause of the difference between virtual and real environments. And there are many conflicting results from different studies when looking at any particular cue. For example, Wu *et al.* [79] found that limited FOV seems to be a significant factor for underestimation distances in the real world. However, Knapp and Loomis [35] conducted real-world experiments with full FOV and restricted FOV and found no significant differences in distance judgments (tests up to 15m). Willemsen *et al.* [74] found that the HMDs' mechanical properties contribute to some of the compression in distance estimation in virtual and real environments with blindfolded walking protocol, but Jones *et al.* [31] did not find a similar effect in both AR and real+HMD conditions.

Another example is quality of visual, which recently has been raised as a potentially important factor in estimating distance in virtual environments. Loomis and Knapp [44] hypothesized that photorealistic rendering of virtual environments can lead to more accurate perception of distance. However, Thompson *et al.* [70] found significant underestimation of distances in a virtual photorealistic panoramic environment displayed in the HMD. Significant underestimation of distances was also reported in an HMD environment that showed live video from a head-mounted video camera [45]. No underestimation was found in [28] when a high fidelity model of a real environment was used, though the participants viewed the real environment before hand.

So, underestimation in virtual environments seems to be caused by a combination of several factors. People in VEs generally seem less well grounded than in the real world, hence their distance estimates can be more easily broken when visual models or display systems change. Further research is needed to determine how to design virtual environments where people are better grounded and gain effective knowledge from the available cues.

2.4 Research evaluating protocols for measuring distance judgments

Research studies have also used a number of different methods to measure participants' perception of distance, such as throwing, bisection, triangulated blindfolded walking, verbal report, timed imagined walking and direct blindfolded walking [66, 5, 27, 56, 6, 34]. In throwing protocols, participants throw objects such as beanbags to indicate distances. More frequently used protocols are direct blindfolded walking and timed imagined walking. HMD-based studies often use the blindfolded walking protocol, in which participants physically walk towards previously seen targets with their eyes closed. Participants stop when they believe that the targets have been reached, and the distance they walked serves as a measure of the perceived distance. Throwing and direct blindfolded walking are usually suitable for use with HMD systems. The main difference between throwing and blindfolded walking is that throwing does not involve continuous updating about the space. Both protocols need vision to initiate the movement, but throwing requires no further interaction with the space. Timed imagined walking is typically employed in LSIDs, which requires participants to start a stopwatch when they imagine beginning to walk toward a target and to stop the stopwatch when they imagine reaching the target (without ever looking at the stopwatch).

Sahm *et al.* [66] tested distance judgments made via blindfolded throwing versus blindfolded walking in real and modeled hallways, with target distances of three to six meters. For blind throwing conditions, participants saw the target, then covered their eyes with a blindfold and threw a beanbag to the target. There was no feedback after each trial. Participants were given practice before testing, in which they threw the beanbag to the target with their eyes open. The practice was carried out in a different location and the distances used for practice were also different from (but in the same range as) those used for testing. The results showed that there were no significant differences between blindfolded throwing and blindfolded walking for indicating judged distances, and both protocols showed accurate performance in the real world (98%) but underestimation in the virtual environment (70%). Since throwing requires no spatial updating of the surrounding environment, it should reflect the initial estimate of the subject about the distance. Thus, both protocols seemed to be useful for expressing judgments of distance.

Swan *et al.* [27] found that blindfolded walking was better than verbal report for making judgments. This study examined distances from three to seven meters, with two measurement protocols (blindfolded walking and verbal report) and four conditions (Real, Real + HMD, Augmented + HMD and Virtual + HMD). An optical see-through HMD was used, without head tracking (the HMD was mounted on a frame that could only change its height to match participants' eye height). Participants first viewed the target object on the ground, and then either 1) walked blindfolded toward the target and stopped when they thought they had reached it, or 2) gave verbal report of how far the target was (in the unit of their choice). The results showed that the blindfolded walking protocol had less underestimation than the verbal report protocol. The verbal report protocol, in fact, had such high variability that it did not seem to be useful as a measurement protocol.

Plumert *et al.* [56] found no significant difference between blindfolded walking distances and distances computed by multiplying imagined walking times and participants' previously measured normal walking speeds (distances from six to 36 meters, LSID setup).

Klein *et al.* [34] found no significant difference between timed-imagined walking, triangulated walking and verbal report as protocols in estimating distances in real world (distances were from two to 15 meters). They also found no significant difference between timed-imagined walking and verbal report when using LSID and Wall display setups, but triangulated walking was significantly different from the other two protocols with the same virtual display setup.

Campos *et al.* [6] found that blindfolded walking and imagined walking were significantly different when a pointing task was used. In this study, participants viewed the target, then they continuously pointed to the target while walking blindfolded along a straight line (5-6m) passing the target, or imagining that they walked along that line. The author found that participants could point to the target fairly accurately when walking blindfolded, but significantly performed worse when imagining walking.

2.4.1 Summary

Together, these results seem to suggest that timed imagined walking, blindfolded walking, and throwing, are all good effective protocols for expressing distance judgments. There is some evidence that blindfolded walking is more accurate than timed-imagined walking. The result from [6] also suggests that blindfolded walking is better than imagined walking for providing spatial awareness and orientation. However, the encumbrance of an HMD seems to remove this advantage. Along similar lines, it has been shown that participants who wore a heavy backpack made larger distance estimates via verbal report than those who did not (even though they did not attempt to walk at all) [58], and that after throwing a heavy ball to a target, participants estimated the distance to the target much larger than when they estimated after throwing a light ball [78]. So both effort and encumbrance seem to influence distance estimation and should be considered when designing or evaluating protocols for distance estimation. One of the goals of Chapter 3's experiments was to further investigate measurement protocols.

CHAPTER 3
EFFECTS OF PRESENTATION METHODS AND MEASUREMENT PROTOCOLS ON DISTANCE ESTIMATION

This chapter presents experiments assessing the effects of presentation methods (e.g. virtual world via head-mounted display, photo-based model via large-screen immersive display, real-world without HMD) and measurement protocols (blindfolded walking, timed-imagined walking) on distance estimation in virtual environments, while keeping many other factors (targets, distances, visual model) constant. More specifically, we compared head-mounted and large-screen immersive displays; assessed the impact of graphics quality and of HMD encumbrance and field of view; and examined the interaction between display systems and measurement protocols.

This chapter is a slightly updated version of work originally published as [23].

3.1 Motivation and goals

As presented in Chapter 2, many studies have shown that people can accurately estimate distances up to 20 meters in the real world, but significantly underestimate those same distances in virtual environments. This effect has been observed in both head-mounted display systems [76, 70, 9, 5, 31, 74] and in large-screen immersive display systems [34, 81]. The factors contributing to distance underestimation in virtual environments are not well understood. Part of the problem stems from the fact that studies of distance estimation in virtual environments often vary widely on several dimensions. These include the display technology, the visual targets and settings, the fidelity of the visual virtual model, the range of distances examined, and the experimental methods employed. As a consequence, it is difficult to directly compare results across studies. In the experiments of this chapter, our goal was to more comprehensively assess distance perception in real and virtual environments by controlling for many of these factors.

Virtual environments are commonly displayed using one of two different technologies: a head-mounted display (HMD) or a large-screen immersive display (LSID) system. HMDs typically restrict the user's field of view (FOV) and encumber the user with a helmet that often has significant weight. By contrast, LSID systems typically provide a wider FOV and impose little encumbrance on the user. Willemsen *et al.* [74] found that the HMD helmet, by itself, can contribute to underestimation of distances relative to the real world. However, this effect was not clearly present in the experiment performed by Jones *et al.* [31]. Reduced FOV can also be detrimental to distance judgments in the real world [79] and in LSID setups [34]. Little is known about distance estimation in augmented reality (AR), though a study by Jones *et al.* [31] reported no distance compression. To the best of our knowledge, however, no study has directly compared distance perception between HMD (virtual or augmented reality) and LSID systems. The experiments of this chapter were designed to increase our understanding of how the unique characteristics of each display system impact distance perception.

Research studies have also used a variety of different methods to measure participants' perception of distance. Klein *et al.* [34] surveyed a number of such measurement protocols, including bisection, triangulated blindfolded walking, verbal report, timed imagined walking and direct blindfolded walking. HMD-based studies often use the blindfolded walking protocol, in which participants physically walk towards previously seen targets with their eyes closed. Participants stop when they believe that the targets have been reached, and the distance they walked serves as a measure of the perceived distance. Direct blindfolded walking is not usually suitable for use with large screen immersive systems. Instead, LSIDs typically employ the timed imagined walking protocol, which requires participants to start a stopwatch when they imagine beginning to walk toward a target and to stop the stopwatch when they imagine reaching the target (without ever looking at the stopwatch). The two protocols were previously found to agree well in the real environment [56]. One advantage of the imagined walking protocol is that it can be used in both HMD and LSID systems, allowing for direct comparison between the two. Here, we used both direct blindfolded walking and timed imagined walking to explore the interaction between the effects of the measurement protocol and the display system used.

The visual settings used in studies of distance perception in VEs can also vary widely. Some researchers have used indoor environments such as hallways [76, 70], whereas other researchers have used outdoor environments such as lawns [56, 81, 34]. Previous work on distance perception in the real world has shown that the type of surrounding context can influence people's judgments of distances [41]. Thus, it is important to control the visual settings when comparing distance estimates across real and virtual environments.

The quality of rendering of the visual settings has also been raised as a poten-

Figure 3.1: Photo of the real hallway (left) and view of the rendered virtual hallway (right) and targets.

tially important factor in estimating distance in virtual environments. Loomis and Knapp [44] hypothesized that photorealistic rendering of virtual environments can lead to more accurate perception of distance. However, Thompson *et al.* [70] found significant underestimation of distances in a photo-based panoramic environment displayed in the HMD. Significant underestimation of distances was also reported in an HMD environment that showed images from a head-mounted video camera [45]. Klein [34] found significant distance underestimation relative to the real world in a large screen display system using a photo-based panorama of an outdoor background in conjunction with a rendered virtual ground and target. Here, we compare distance perception indoors in a perspectively-correct photo-based presentation with distance perception in the real world and in a rendered virtual world.

Again, the focus of this chapter's experiments was to compare several visual presentation methods using two measurement protocols, while keeping the setting, targets, distances, visual model, and the methods constant. We were particularly interested in the following research questions:

1. How does accuracy of distance estimation in HMDs compare to that in LSID systems?
2. What is the impact of the weight and FOV of the HMD on distance perception? Can it explain distance compression observed in the virtual environments?
3. Can higher rendering quality substantially improve distance perception in an LSID system?
4. Do the effects of a particular display system on distance perception depend on the measurement protocol used (i.e., blindfolded walking vs. imagined walking)?

To answer these questions, we asked participants to estimate the distance to a pair of poles located 6 to 18 meters in front of them in a hallway setting. Each participant viewed the same hallway environment in one of the following six presentation methods:

1. Real: unrestricted real-world view of hallway
2. Real+HMD: real-world view of hallway seen through an HMD
3. Virtual+HMD: virtual model of hallway viewed in an HMD
4. Virtual+LSID: virtual model of hallway viewed on multiple large screens
5. Photo+LSID: photo-based presentation[1] of hallway viewed on multiple large

[1]Participants viewed a photographic panorama of the real hallway and real targets. In order to create perspectively-correct displays for subjects, we hired a professional photographer to capture the scene for eye heights ranging from 55 through 71 inches, in one-inch

screens

6. AR: augmented-reality presentation of virtual target objects superimposed on a real hallway seen through HMD.

Our study consisted of two experiments. Experiment 3a compared the first five presentation methods using the timed imagined walking protocol suitable for assessing distance estimation in both LSID and HMD systems. Experiment 3b compared non-LSID presentation methods (conditions 1 through 3) along with the AR condition (condition 6) using a blindfolded walking protocol.

3.2 Design and procedure

3.2.1 Experimental design

Both experiments used a between-subjects design. Each participant viewed the environment in one of the five presentation conditions in Experiment 3a or in one of the four presentation conditions in Experiment 3b. Participants in Experiment 3a made their judgments using the timed imagined walking protocol, whereas participants in Experiment 3b used the direct blindfolded walking protocol. The targets were placed at a distance of 6, 9, 12, 15 or 18 meters. Each participant was presented with three random permutations of these five distances for a total of 15 trials.

3.2.2 Apparatus and materials

In the HMD conditions, we used an NVIS nVisor ST head-mounted display system with optical see-through functionality. The HMD contains two small LCOS displays each with resolution of 1280 x 1024 pixels. Stereoscopic display was used in

increments, at each target distance.

all HMD conditions. Convergence distance for our HMD was set by the manufacturer to 10m. The field of view is 40.5 vertical and 49.5 degrees horizontal. The optical see-through functionality enables both a virtual-environment-only presentation and an augmented reality presentation, in which virtual objects are superimposed on a view of the real environment. An Intersense Vistracker IS-1200 6 DOF optical tracker was mounted on the HMD to measure participants' position and orientation in the hallway. A black cloth was used to block out light around the sides and back of the HMD and a black piece of foam was attached underneath the HMD lenses to prevent participants from seeing the floor or their feet. The cloth had a flap that could be lifted in some conditions to allow participants to view the real environment.

In the LSID conditions, the VE was displayed on three 10-feet wide x 8-feet-high screens placed at right angles relative to one another, forming a three-walled room. The room's floor was one foot above the bottom of the screens, so the effective screen height was seven feet. Participants stood eight feet from the front screen, midway between the side screens. Three Projection Design F1+ projectors were used to rear project high-resolution graphics (1280 x 1024 pixels) onto the screens, providing participants with approximately (depending on the participant's height) 224 degrees horizontal and 46 degrees vertical FOV of nonstereoscopic, immersive visual imagery. The viewpoint of the scene was adjusted for each participant's eye height, but motion parallax was not available.

In the Real conditions, a simple foam blindfold was used to block out light during the blindfolded walking task. A laser rangefinder was used to measure distances.

The targets were a pair of cylindrical poles. The poles were 0.30 m in diameter and 1.219 m tall. The distance between the centers of the poles was one meter. Virtual targets were a faithful representation of the real ones.

The virtual hallway model was built to match the real hallway as closely as as possible. We determined the HMDs field of view by positioning the HMD so that known hallway features aligned with the outer boundary of the scene visible through the HMD. To ensure proper registration of the virtual and real hallways, we needed to determine the relationship between the coordinate frame of the tracking camera mounted on top of the HMD and coordinate frame of the HMD's display screens. For the relative position, we manually measured the translational distances between the origins of the two coordinate frames. For the relative orientation, we placed the HMD on a person's head and, in see through mode, used a interactive program to adjust a rotation matrix until the wireframe view of the doorway at the end of the hall aligned with the real doorway.

3.2.3 Procedure

The experiments were carried out either in the immersive large screen environment in our laboratory or in the hallway outside the lab. To minimize exposure to the environments immediately prior to the experiment, participants met with the experimenter in the lobby of the building and were escorted to the hallway or lab blindfolded. For HMD conditions, setup and calibration of the HMD were performed prior to reaching the hallway. The goal of the calibration process was to ensure that participants eyes were centered on the HMD display screens. We displayed a test-pattern-style image (cross hairs in the middle and a nested set of colored thin rectangular rings at the outer portion of the image) and first directed participants to use the top and back HMD fit adjustment knobs so that device was snug and they could see the same color at the extreme top and bottom of their view. Next, participants adjusted the HMD's eyepieces to center each eye horizontally on its screen. On the nVisor ST, each eyepiece has its own IPD (inter-pupillary distance) adjustment knob. Participants were told close one eye and use the corresponding IPD knob to adjust the eyepiece so that the same color was visible at the right and left edges of that eyes display. This was then repeated for the other eye.

Before each trial, we positioned the participant at the appropriate starting location. Participants had the opportunity to view the target for four to five seconds before the experimenter told them to close their eyes. Then the blindfold was replaced or the screens were turned off and participants were instructed to make their distance judgment via either blindfolded walking or timed imagined walking. No feedback was given at the end of a trial.

For timed imagined walking, participants started the stopwatch when they imagined starting to walk and stopped the stopwatch when they imagined reaching the target (without ever looking at the stopwatch). The experimenter then recorded the stopwatch time. Headphones were not used in the imagined movement conditions due to low ambient noise in the environment and the fact that participants remained stationary. This also minimized the encumbrance. After each participant completed all 15 trials, the experimenters obtained an estimate of that person's average walking speed by measuring how long it took him or her to walk 18 meters at a comfortable walking speed.

For blindfolded walking, participants walked until they thought they had reached the target. The experimenter then recorded the distance walked and escorted participants back to the starting position blindfolded. For blindfolded walking with the HMD, participants wore headphones that transmitted a constant white noise (with the exception of the Real condition for which participants wore no headphones). The headphones served a dual purpose of both blocking out some of the ambient noise of the hallway and as a guide for walking without vision. If participants deviated too far from the center of the hallway to the right, the white noise in the right ear headphone would get progressively louder. If participants moved too far to the left, the white noise in the left ear headphone would get louder. Differences in amplitude of white noise in the two ears allowed participants to self correct their travel direction while walking with eyes closed. The experimenter demonstrated the white noise guiding tool to the participants at the beginning of the session, instructing them to step left and right to experience the amplitude changes in each ear.

3.3 Experiment 3a: The effect of presentation condition on distance estimation using timed imagined walking

Experiment 3a compared five presentation conditions using the timed imagined walking protocol. This measurement protocol was selected because it was suitable for both HMD and LSID presentation conditions. The conditions were as follows:

1. Real: unrestricted real-world view of hallway ($N = 12$)
2. Real+HMD: real-world view of hallway seen through an HMD ($N = 12$)
3. Virtual+HMD: virtual model of hallway viewed in an HMD ($N = 13$)
4. Virtual+LSID: virtual model of hallway viewed on multiple large screens ($N = 15$)
5. Photo+LSID: photo-based presentation of hallway viewed on multiple large screens ($N = 12$)

3.3.1 Participants

We recruited 64 undergraduate and graduate students to participate. The participants received either course credit or monetary compensation. There were 39 males and 25 females. There were five additional participants who completed the task, but were excluded from the analysis due to the difficulties they experienced with the measurement protocol.

3.3.2 Measures

The primary measure for the timed imagined walking conditions was *Time To Target*. We used each participant's average walking speed to convert each *Time To Target* measurement into an estimate of *Distance Walked*. We used distance walked to calculate *Judged Percentage of True Distance* for each trial, which was expressed as a ratio between the distance walked and the true distance to the target. *Judged Percentage of True Distance* can be used as a measure of the accuracy of a participant's distance estimates:

$$Judged\ Percentage\ of\ TrueDistance = \frac{Distance\ Walked}{True\ Distance}. \tag{3.1}$$

We assessed the precision of the distance estimates by computing *Variable Error*, which is expressed as a coefficient of variation for distance walked. Specifically, *Variable Error* for a given value of true distance and a given participant is the ratio of standard deviation of distance walked to the mean distance walked:

$$Variable\ Error = \frac{SD(Dist.\ Walked)}{Mean(Dist.\ Walked)}. \tag{3.2}$$

3.3.3 Results

Figure 3.2 shows mean judged percentage of true distances for each observed distance in all experimental conditions. These means were obtained by first finding the mean of the three observations for each participant at a given distance and then by averaging across all participants in each condition. The figure suggests that the performance of the participants remained fairly stable across all five distances, though the Photo+LSID and Virtual+LSID conditions showed a noticeable decrement in performance for the 6m distance.

To simplify the analyses of accuracy, we estimated a single value of expected *Judged Percentage of True Distance* for each participant over the whole range of observed distances. To do this, we simultaneously fit a linear regression line for each participant with true distance to target as predictor and distance walked as a dependent variable. The intercept was fixed at zero. In this model the estimated

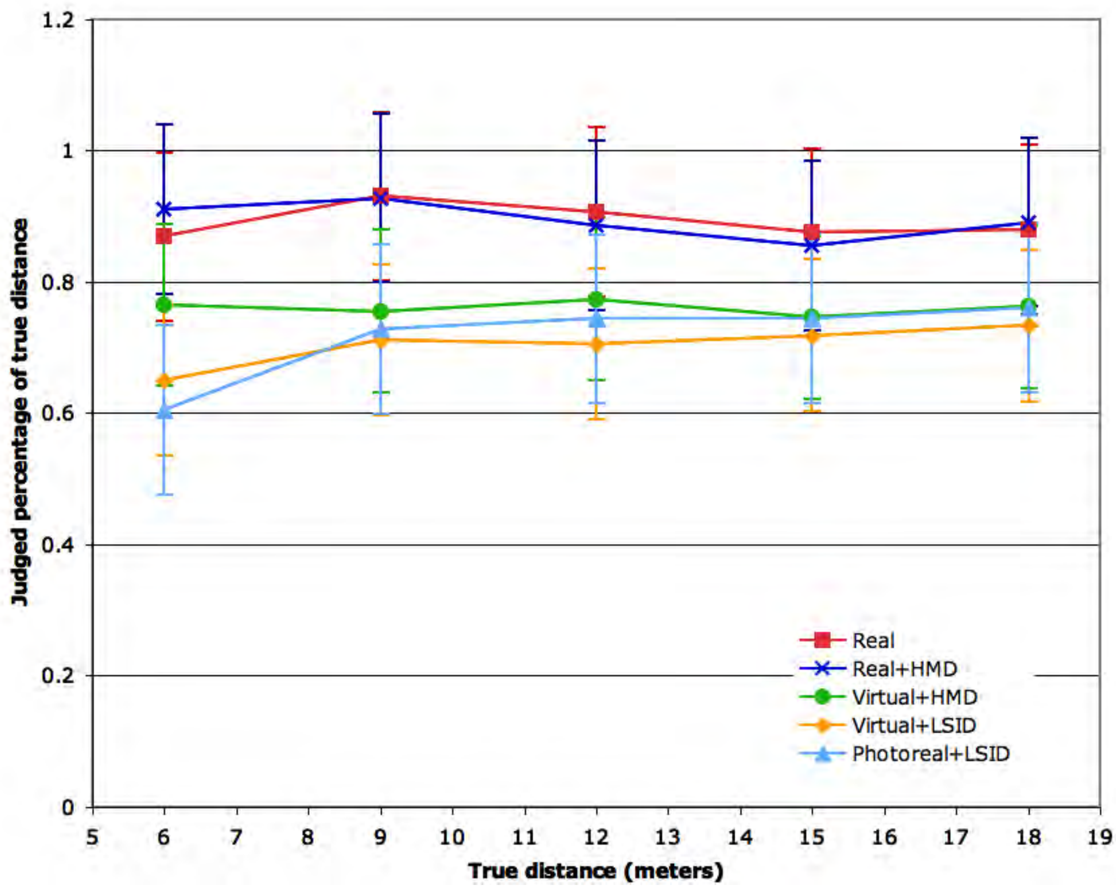


Figure 3.2: Mean percentages of true distance using timed imagined walking. Error bars represent 95% confidence intervals.

slopes correspond to the expected judged percentages of true distances for each of the participants. This method yields results very similar to finding a simple mean percentage of judged true distance. However, it assumes stronger relationship between observations from the same participant over the range of distances and treats the whole distance range as a continuous interval. Overall, we found that the model fit the data well ($R^2 = 97\%$). Figure 3.3 illustrates the resulting linear fit for each condition to the mean distances walked at each true distance. Table 3.1 shows estimates of the mean judged percentage of true distance for each condition.

We compared the mean accuracy of the participants in each condition using a one-way ANOVA with experimental condition as the predictor and *Expected Judged Percentage of True Distance* as the dependent variable. The overall ANOVA F-test was not significant, $F(4, 59) = 1.927, p = 0.118$. However, Figure 3.2 suggests that participants in the Photo+LSID, Virtual+LSID and Virtual+HMD conditions underestimated true distances more than did participants Real and Real+HMD conditions. Therefore, we grouped participants who observed a virtual world or photographic images of the real world (Virtual+LSID, Virtual+HMD, and Photo+LSID conditions) and compared them to participants who observed the real world (Real and Real+HMD conditions). A one-way ANOVA with Group (Real, Virtual) as a predictor and expected *Judged Percentage of True Distance* as the dependent variable confirmed our hypothesis, $F(1, 62) = 7.775, p = 0.007$.

We also compared mean performance of participants in Real condition with ideal performance (i.e., 100% accuracy in judged distance). A one-sample t-test

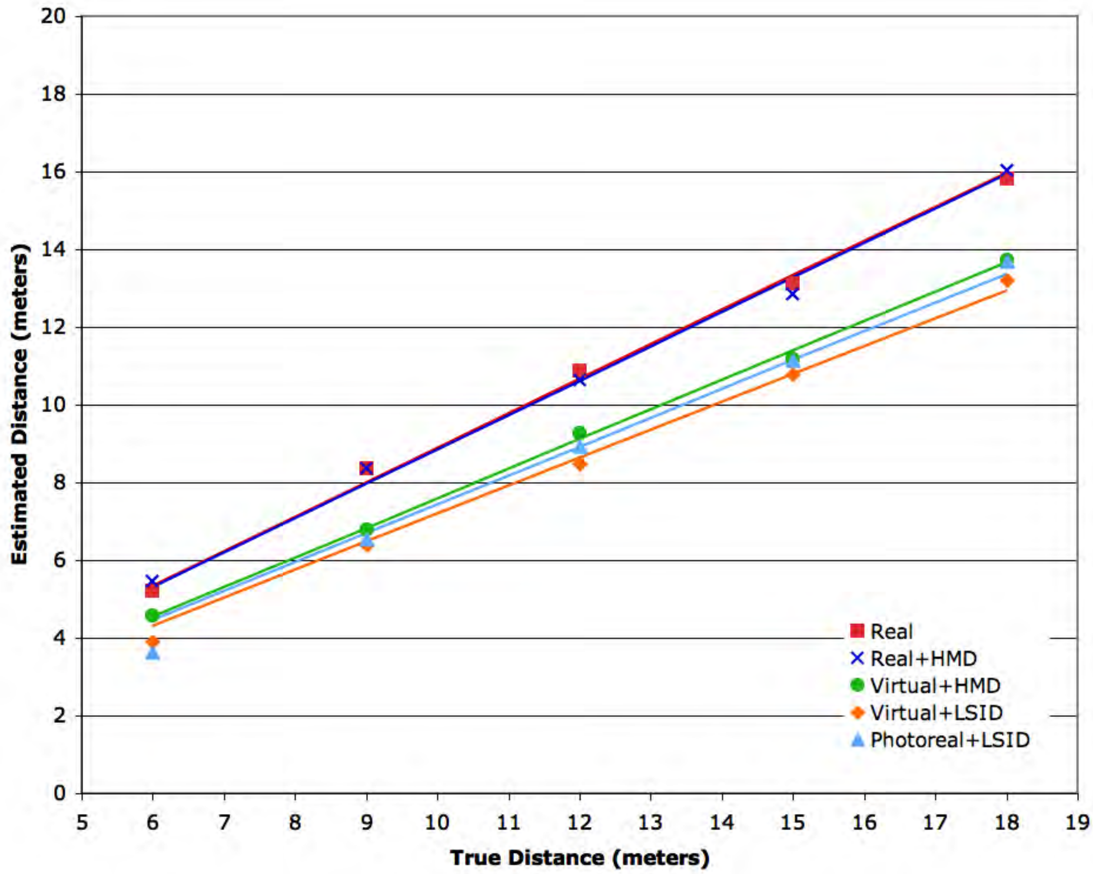


Figure 3.3: Mean accuracy for distance estimation using timed imagined walking. Points represent mean judged distances. The slopes of the lines correspond to expected judged percentages of true distance for each condition.

Table 3.1: Means of expected judged percentages of true distances using imagined walking.

Condition	**Mean**	**95% Confidence interval**
Real	0.888	[0.767, 1.008]
Real+HMD	0.885	[0.764, 1.006]
Virtual+HMD	0.759	[0.643, 0.875]
Virtual+LSID	0.719	[0.611, 0.827]
Photo+LSID	0.743	[0.623, 0.864]

showed that participants did not significantly underestimate true distances: $t(11) = -1.74, p = 0.11$.

Variable errors were analyzed in a $Condition(5) \times TrueDistance(5)$ repeated measures ANOVA with the first factor as a between-subjects variable and the second as a within-subjects variable. We found a significant main effect of True Distance, $F(4, 236) = 4.86, p < 0.001$. The main effect of condition ($p = 0.226$) and the $Condition \times TrueDistance$ interaction ($p = 0.55$) were not significant. Variable errors tended to decrease with distance. To estimate the linear trend over the range of observed distances, we repeated the ANOVA analysis with Distance as a continuous predictor. There was a statistically significant negative trend for the error which tended to decrease on average by 0.5% per meter of true distance, $F(1, 251) = 15.70, p < 0.001$. The overall mean Variable Error was estimated at 16.7% ($SE = 0.6\%$).

3.3.4 Discussion

These results indicate no difference in accuracy of distance estimation between the participants in Real and Real+HMD conditions, with means of the judged percentages of true distance being almost identical (88.8% and 88.5% respectively). We conclude that the combination of HMD weight and limited FOV are not likely to cause substantial underestimation of distances as measured by the timed imagined walking protocol.

At the same time, our data shows that participants in the Virtual+HMD, Virtual+LSID, and Photo+LSID conditions exhibited similar levels of distance compression relative to the real world. The similarity across the three conditions is especially notable in light of substantial differences between display systems (HMD vs. LSID) and presentation methods. In particular, the lack of difference between judgments in Virtual+LSID and Photo+LSID conditions implies that the improving the quality of virtual model rendering would not improve distance estimation, at least in non-stereoscopic, non-parallax LSIDs systems.

One striking feature in our results is the performance of participants at the 6m distance for both LSID-based presentations, where the accuracy of estimates is apparently lower than for other distances. The participants seem to be placing the targets just beyond the physical location of the screen, suggesting that their awareness of the screens might play an important role in distance estimation.

The analyses of variable error revealed that precision increased with distance. Although this finding might appear counterintuitive at first, we speculate that the gradual increase in precision with distance is due to the decision time and the reaction time of the participant while starting and stopping the stopwatch. Assuming that these timing errors are relatively stable for a given participant, its contribution to the overall variable error will decrease as overall measured time intervals increase with distance.

3.4 Experiment 3b: The effect of presentation condition on distance judgments using direct blindfolded walking

Experiment 3b compared non-LSID presentation conditions using direct blindfolded walking protocol. The conditions were as follows:

1. Real: unrestricted real-world view of hallway ($N = 11$)
2. Real+HMD: real-world view of hallway seen through HMD ($N = 14$)
3. Virtual+HMD: virtual model of hallway viewed in HMD ($N = 10$)
6. AR: augmented-reality presentation of virtual target objects superimposed on real hallway seen through HMD ($N = 8$)

We were specifically interested in further investigating the effect of wearing the HMD on distance estimation by comparing Real+HMD, Virtual+HMD, and AR conditions against the control Real condition. In addition, were interested in comparing distances estimates obtained through timed imagined walking in the first experiment with distance estimates obtained through blindfolded walking, particularly for the Real and Real+HMD conditions.

3.4.1 Participants

We recruited 43 undergraduate students to participate for course credit. There were 21 males and 22 females. Two additional participants in the AR condition completed the task, but were excluded from the analysis due to apparent difficulties with the blindfolded walking protocol.

3.4.2 Measures

The primary measure for the blindfolded walking conditions was *Distance Walked* on each trial. We then used this measure to compute *Judged Percentage of True Distance*.

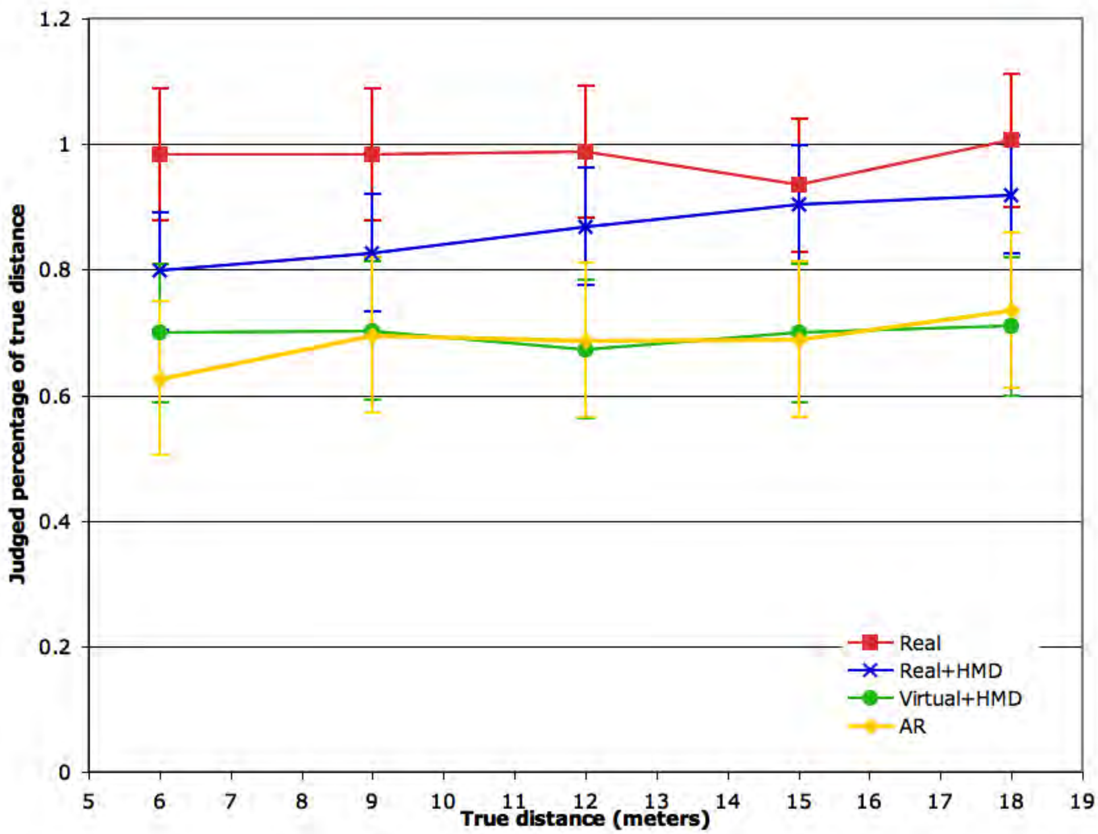


Figure 3.4: Mean percentages of true distance using blindfolded walking. Error bars represent 95% confidence intervals.

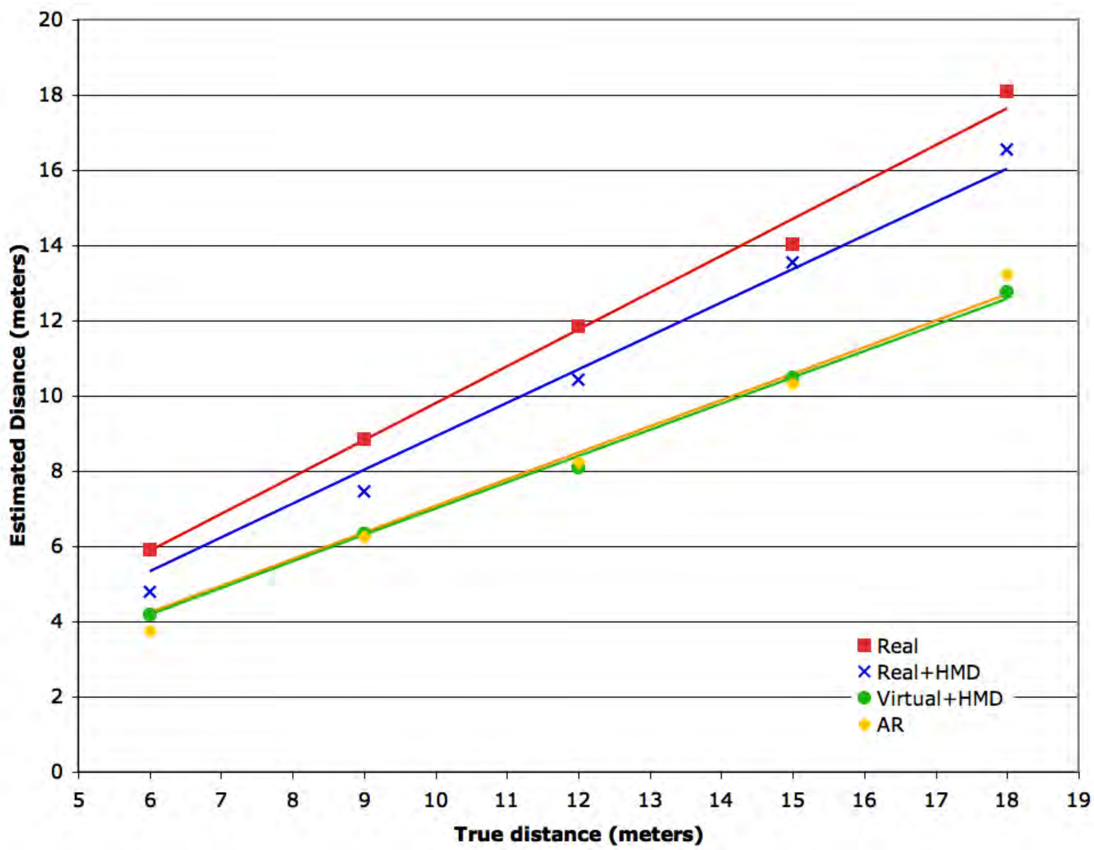


Figure 3.5: Mean accuracy for distance estimation using blindfolded walking. Points represent mean judged distances. The slopes of the lines correspond to expected judged percentages of true distance for each condition.

3.4.3 Results

Figure 3.4 shows mean *Judged Percentage of True Distance* for each observed distance in all experimental conditions. These means were again obtained by first finding the mean of the three observations for each participant at a given distance and then by averaging across all participants in each condition.

As in Experiment 3a, we estimated a single value of expected *Judged Percentage of True Distance* for each participant by fitting a linear regression line with true distance to target as the predictor and distance walked as the dependent variable.

Table 3.2: Means of expected judged percentages of true distances using blindfolded walking.

Condition	**Mean**	**95% Confidence interval**
Real	0.979	[0.875, 1.084]
Real+HMD	0.891 0.825*	[0.798, 0.984] [0.741, 0.909]
Virtual+HMD	0.699	[0.589, 0.809]
AR	0.706	[0.583, 0.829]

*N*otes: Asterisk indicates data excluding two overestimating participants

The intercept was fixed at zero. The model fit the data well ($R^2 = 97\%$). Figure 3.5 illustrates the resulting linear fit to the mean distances walked at each true distance for each experimental condition. Table 3.2 shows estimates of the mean judged percentage of true distance for each condition. See also Figure 3.6 that summarizes the mean judged percentages of true distances for both experiments.

A one-way ANOVA with experimental Condition (4) as the predictor and expected *Judged Percentage of True Distance* as the dependent variable compared the mean accuracy of the participants in each condition. We found a significant effect of experimental condition, $F(3, 39) = 6.68, p < 0.001$.

Planned comparisons between conditions were carried out using a Bonferroni-Holm adjustment. We found significant underestimation relative to Real condition in the Virtual+HMD ($p = 0.002$) and AR ($p = 0.004$) conditions. There was significant underestimation in the Virtual+HMD condition relative to Real+HMD ($p = 0.02$). The difference between Real and Real+HMD conditions ($p = 0.21$) was not significant.

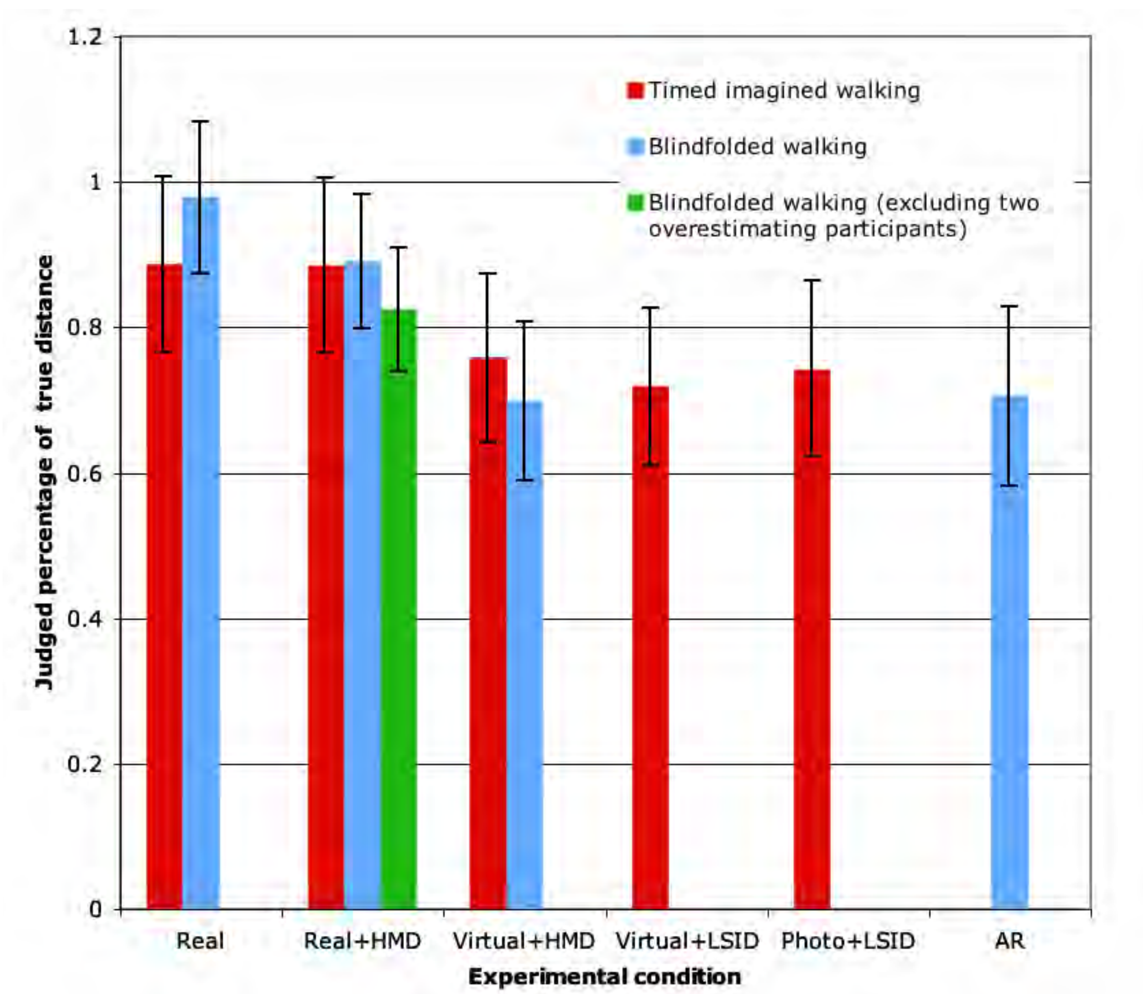


Figure 3.6: Mean accuracy for distance estimation using blindfolded walking and timed imagined walking. Error bars represent 95% confidence intervals.

We observed that performance in Real+HMD condition was substantially influenced by two participants, which on average overestimated true distances by 38.9% and 18.5% respectively. A classical Grubb's test suggested that both these values were potential outliers ($p = 0.013$). We repeated the analysis without the data from these two participants. The planned comparisons showed significant underestimation of distances relative to Real condition in the AR ($p < 0.001$), Virtual+HMD ($p < 0.001$), and Real+HMD ($p = 0.023$) conditions. The difference between the Real+HMD and Virtual+HMD conditions was also significant ($p = 0.048$).

We also compared mean performance of participants in Real condition with ideal performance (i. e. 100% accuracy in judged distance). A one-sample t-test showed that participants did not underestimate true distances: $t(10) = -0.41, p = 0.69$.

Variable errors were analyzed in a Condition (4) x Distance (5) repeated measures ANOVA with the first factor as a between-subjects variable and the second as a within-subjects variable. Neither of the main effects were significant, $F(3, 39) = 1.88$, $p = 0.149$, and $F(4, 156) = 1.57$, $p = 0.185$, respectively. However, the linear trend for Variable Error to increase with distance was significant, $F(1, 168) = 4.69$, $p = 0.032$. On average, the error tended to increase by 0.7% per meter of true distance. The overall mean variable error was 12.2% ($SE = 0.6\%$).

3.4.4 Discussion

Together, our analyses of accuracy indicate that participants in both Real+HMD and Virtual+HMD conditions showed significant underestimation of distances. However, the significant distance compression in Virtual+HMD condition relative to Real+HMD condition indicates that the HMD encumbrance alone cannot account for the degree of distance underestimation observed in the virtual environment. Our initial analysis suffered somewhat due to the large variability in performance of individual participants in Real+HMD conditions, which made the differences between Real and Real+HMD condition less apparent. We were able to clarify this difference, by excluding two participants with somewhat unusual level of overestimation of distances.

We also found that the performance of participants in AR condition, who observed virtual targets in the real visual settings, was similar to that of participants in Virtual+HMD condition, who observed virtual targets in the virtual visual settings. However, it is difficult to draw conclusions based on a relatively small sample of AR participants in our analysis. Finally, the increase in variable error with distance matched our intuitive expectation that the precision should decrease with distance for the tasks based on physical action, such as blindfolded walking.

3.5 Effects of experimental protocols

The impact of the measurement protocol on distance perception can be examined by comparing the performance of participants in Real, Real+HMD, and Virtual+HMD conditions between the two experiments. Figure 3.7 shows the mean expected judged percentages of true distances for both direct blindfolded walking and timed imagined walking in each of the three conditions. The mean value for Real+HMD condition for direct blindfolded walking does not include two overesti-

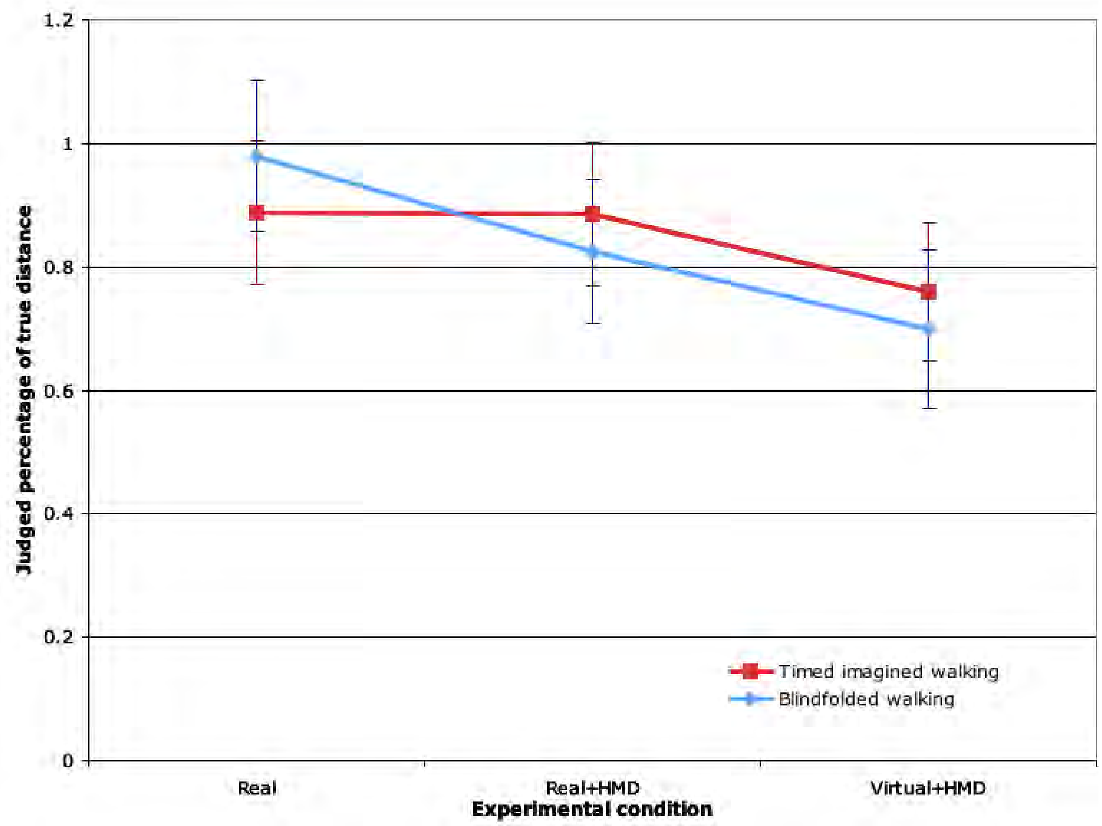


Figure 3.7: Comparison of measurement protocols: Mean expected judged percentages of true distances by experimental condition. Error bars correspond to 95% confidence intervals.

mating participants that were identified in the earlier analysis.

We compared the performance across the measurement protocols using a *Protocol(2)* × *Condition(3)* two-way ANOVA. We found that both the main effect of the *Protocol* ($F(1, 64) = 0.043$, $p = 0.837$) and interaction between *Protocol* and *Condition* ($F(2, 64) = 1.083$, $p = 0.345$) were not significant. The main effect of condition was significant ($F(2, 64) = 5.63$, $p = 0.006$). These results suggest that participants performed similarly in each of the three conditions whether they used the imagined walking or direct blindfolded walking. However, the timed imagined walking protocol yielded somewhat less accurate estimates in the Real condition and had noticeably lower precision (as evidenced by higher mean variable error).

The most important differences were in the relative performance of participants across the three conditions within each protocol. Participants significantly underestimated distance with both measurement methods in the Virtual+HMD condition relative to real world estimates. However, the difference between Real+HMD and Real conditions was only found with the blindfolded walking protocol. When participants viewed the targets in the real world through the HMD but imagined moving to the targets while standing in place, there was no difference between the Real and the Real+HMD conditions. When participants viewed the targets through the HMD and then actually walked to the targets, they underestimated distance in the Real+HMD condition relative to the real condition. Thus, the effect of the HMD encumbrance only influenced distance estimates when the participants were required to physically walk to the target. This may be related to a greater effect of the tipping torque or pull from the cables when walking as opposed to when standing still. Thus, it appears that the effect of wearing an HMD while viewing the real environment depends on the measurement protocol used to study distance estimation.

One limitation to the above direct comparison between the two protocols is associated with the potential presence of a systematic bias in the distance estimates produced by timed imagined walking protocol due to conversion of a directly measured value of time into an indirect measure of distance. The estimate of participant's speed required for this conversion was obtained by timing participant's sighted walking over a fixed distance. However, the data collected by Kunz, Creem-Regehr and Thomson [36] indicates that timed imagined walking produces systematically shorter estimates of time required to reach a target than the actual sighted walking. One explanation for this phenomenon is that the implied speed for the timed imagined walking is higher than the actual walking speed. Consequently our method for converting time to distance would lead to systematically shorter implied distances for timed imagined walking protocol.

3.6 General discussion and conclusions

The goal of this chapter's experiments was to compare a number of different visual presentation methods using two measurement protocols, while controlling for several other factors that could potentially influence distance perception. More specifically, we examined how distance estimation is influenced by the FOV and weight of an HMD, the protocol used to measure perceived distance, the display technology (i.e., HMD vs. LSID system), and the quality of rendering in an LSID system.

Our investigation confirmed earlier findings by Willemsen *et al.* [74] showing that the encumbrance of an HMD can cause underestimation of real world distance estimates. Specifically, we found that blindfolded walking distance estimates were significantly worse in the Real+HMD than in the Real condition. Further, the fact that performance in the Virtual+HMD condition was worse than the Real+HMD condition for both imagined timed walking and for direct blindfolded walking supports the conclusion that the restricted FOV and weight of the HMD cannot fully explain the degree of distance compression experienced in the virtual environments viewed through the HMD.

Our results do not fit quite as well with Jones *et al.* [31], despite the fact that the visual presentation conditions, as well as the HMD and tracking systems in Experiment 3b were the same as theirs. The most striking difference is the accuracy achieved in the AR condition. In their experiment, performance in the AR condition was comparable to performance in a real world condition. In our experiment, participants significantly underestimated distance in the AR condition.

What might account for the discrepancy in results? It seems possible that higher overall accuracy in Jones was also due in part to the combination of shorter distances and much shorter (in height) targets. This combination encourages subjects to incline their gaze downward and may more directly activate use of angle of declination cues to distance [54]. Second, Jones *et al.* [31] used a within-subjects design, whereas we used a between-subjects design. The smaller differences between conditions in their experiment can be partly attributed to the carry-over effects demonstrated by Ziemer et al. [81], which should negate some of the variation in performance between conditions even when the presentation order is randomized. Additional investigation is needed to determine the exact source of the observed differences in results.

The direct comparison between measurement protocols revealed that the effect of wearing an HMD while judging distances in a real environment depends on the protocol. This evidence of higher apparent robustness of the timed imagined walking with respect to physical encumbrances, its wider applicability, and the similarity of performance between the two protocols strengthens the argument [34] in favor of more general use of timed imagined walking.

Somewhat surprisingly, we found a similar level of accuracy when the virtual environment was displayed on the HMD and on the LSID. This result suggests that the ample differences between the two displays technologies do not lead to differences in distance perception, at least as measured by the timed imagined walking protocol. It is particularly striking in light of the fact that our LSID system lacks such important distance cues as motion parallax and stereopsis, both of which were present in the HMD. At this point, however, it is still not clear whether or not distance underestimation with the two display technologies is caused by the same factors.

We also found that the use of photo-based visual model did not substantially remedy distance compression experienced by the participants in the virtual environment displayed using a LSID system. This implies that an improvement in the quality of rendering would not help to decrease distance underestimation LSID systems, at least in those that lack stereo images and motion parallax support. This finding confirms earlier results by Thompson *et al.* [70], who found significant underestimation of distances in a photo-based virtual panorama environment displayed in an HMD. Anecdotally, we were somewhat surprised by this result because photo-based scenes appeared to give a much stronger impression of depth. Overall, our results reinforce the conclusion of Thompson *et al.* [70] and Messing and Durgin [45] that the quality of graphics does not significantly affect distance estimates in virtual environments.

This chapter's experiments directly compared distance estimation across several display systems and measurement protocols. Such comparisons have been difficult to make across prior studies of distance perception due to the wide variation in critical factors such as the visual targets and settings, the fidelity of the visual virtual model, and the range of distances examined. Our experiments were thus able to provide several new contributions:

1. Experimental evidence that wearing an HMD while viewing the real world does not cause compression when distance is estimated with imagined timed walking (in contrast to underestimation observed here and in previous studies for direct blindfolded walking)
2. A comparison between two commonly used experimental protocols for estimating distance: blindfolded walking and imagined walking
3. A direct comparison between distance estimation in HMD and LSID systems
4. A thorough investigation of the effect of the quality of graphics on distance estimation in LSID systems by comparing distance perception in the real world, photo-based, and virtual computer graphics rendered presentations.

CHAPTER 4
EFFECTS OF SCALE CHANGE ON DISTANCE PERCEPTION IN VIRTUAL ENVIRONMENTS

As presented in the previous chapters, a large body of work examining distance estimation in virtual environments has shown that distances are underestimated in virtual environments. An interesting question that has not been studied much is whether people who are trained in one VE can accurately perform the same task in a new environment. In this chapter, we address this via an experiment that examines whether experience making distance estimates in a virtual environment of one scale affects people's perception of the same distances in a similar environment of a different scale.

This chapter is a slightly updated version of work originally published as [50, 51].

4.1 Motivation and goals

Calibration of space perception across environments has been investigated by examining whether experience in the real environment affects distance perception in a virtual environment, and vice versa. Interrante *et al.* [28], for example, examined how experience in a real space influences participants' sense of presence and ability to estimate distance in a virtual space that was an exact replica of the real space. After a brief period of time in a real world space, participants were immersed in an identical virtual space. Participants who experienced the real world space immediately prior to viewing the virtual world replica were better able to judge distances than were participants who experienced the same virtual world replica without having seen the real world space. A follow-up investigation indicated that people were better at estimating distance in a novel virtual environment if they first experienced the virtual world replica and then transitioned to the novel virtual environment than if they did not experience the virtual world replica beforehand [69]. Along similar lines, Witmer and Sadowski [76] examined how experience in the real environment affected subsequent distance estimates in a virtual environment, and vice versa. Participants walked to targets while blindfolded in either a real hallway or a virtual environment model of a hallway. Though the effects were subtle, they found carryover from the first set of distance estimation trials to the second set. When participants judged distances in the virtual hallway first, they did slightly worse in their subsequent real world distance estimations. However, when participants judged distances in the real world hallway first, they showed less distance compression in the virtual hallway. Interestingly, the positive carryover from the real environment to the virtual environment was stronger than the negative carryover from the virtual environment to the real environment. Ziemer *et al.* [81] also found that the order in which people experience real and virtual environments impacts distance estimates. They asked participants to make two sets of distance estimates in one of the following conditions: 1) real environment first, virtual environment second; 2) virtual environment first, real environment second; 3) real environment first, real environment second; or 4) virtual environment first, virtual environment second. Both the distances and the spaces were identical across environments. When the second environment was the same as the first environment (real-real and virtual-virtual), participants' second estimates were underestimated in the virtual but not in the real environment. However, when the second environment differed from the first environment (real-virtual and virtual-real), participants' second estimates did not differ significantly across the two environments. Together, these studies show that experience in either a real or virtual environment can shift subsequent distance estimates.

Calibration of space perception across environments has also been investigated by examining whether recalibration of distance perception in a virtual environment transfers to the real environment. Richardson and Waller [61], for example, gave people experience with walking to and from targets in a virtual environment during an adaptation period of approximately five minutes. They compared pre- and post-adaptation distance estimates and found that people's average distance estimates were nearly accurate at post-adaptation (94%), representing a 50% improvement over pre-adaptation. Moreover, they found that the improvement generalized across both direct blindfolded walking and indirect (triangulated) blindfolded walking tasks. Additional work revealed that the recalibration of distance perception in the virtual environment carried over to the real environment; after a period of adaptation in the virtual environment, people significantly overestimated distances in the real environment [72]. In a similar investigation, Mohler *et al.* [46] examined how different kinds of adaptation experiences affect recalibration of distance perception in virtual environments. They had participants complete pretest and posttest distance estimates using either verbal report or blindfolded walking to targets 3-7m away in either a real hallway or a virtual hallway. Between pre- and posttest, participants experienced a 5- to 7-minute adaptation period in the virtual environment during which they walked to targets with either continuous visual feedback (walking with eyes open), terminal visual feedback (opened their eyes at the end of the estimation to see how close they were to the target), or verbal feedback (walked with eyes closed until experimenter told them they were at the target location). Like Waller and Richardson, they found that virtual environment distance estimates significantly improved after the adaptation period. However, they found that adaptation in the virtual environment had no effect on distance estimates in the real environment unless they altered the rate of optic flow in the virtual environment. When they altered the optic flow rate to be twice as fast as the normal walking pace during adaptation, participants showed significant underestimation in their later real world distance estimates. Together, these studies clearly show that experience in virtual environments leads people to recalibrate distance perception and that these recalibration effects can carry over to the real environment.

At present, little is known about whether spatial calibration in one virtual environment carries over to another virtual environment (for an exception, see Steinicke *et al.* [69]). For example, does the calibration achieved through interactions with a novel virtual world persist when a new virtual world is experienced? Answering this question is important because it is not yet known to what extent the recalibration that occurs is tightly linked to the specific characteristics of the adaption environment. A useful way to test the stability of the calibration is to make systematic changes from the adaptation environment to the new environment. Robust calibration of distance perception should be impervious to changes from the old to the new environment. Here, we looked at how scale changes from the adaptation environment to the new environment affected distance judgments.

At present, there are no direct comparisons of people's distance estimates when moving from an environment of one scale to an environment of another scale. However, there is some work suggesting that people perceive distances differently in real environments of different scales. For example, Compton and Brown [11] found that people who walked similar same-length routes in differently scaled urban settings judged their traveled distances quite differently. People who walked in a small village (i.e., a village in which many of the buildings were approximately seven-eighths as tall as normal village dwellings) judged their traveled distance to be two to three times greater than that of people who walked in a large city. Other work indicates that distance perception is also affected by scale-related factors such as average distance of objects in an environment [80]. Thus, it appears that environmental scale may play a role in distance perception in real environments.

The goal of this chapter's set of experiments was to examine how scale changes across virtual environments affect people's distance estimates. We first gave people experience with making distance estimates in one tunnel-like virtual environment with feedback (adaptation) and then asked them to make distance estimates in an identical, but differently scaled virtual environment without feedback (test). The same distances were used in adaptation and test. As in other work, we expected that people would become quite good at estimating distance by the end of the adaptation phase. Of particular interest was whether people's distance estimates remained accurate when they moved to another virtual environment that was different only in scale. If estimates remain accurate, this would suggest that the learning observed in the Waller and Richardson [72] and the Mohler *et al.* [46] studies is robust. If distance estimates become systematically less accurate, this would suggest that the learning is fragile. In this case, it is important to determine whether some types of scale changes are more disruptive than others.

We examined three types of scale changes: 1) changing the size of the tunnel, 2) changing the size of the targets, and 3) changing the separation of the targets. In Experiments 4a and 4b, we compared the effect of scaling only the tunnel with the effect of simultaneously scaling everything (i.e., the tunnel, targets, and target separation). We used joystick movement in Experiment 4a and blindfolded walking in Experiment 4b to determine whether the same effects on distance estimation were observed with different types of locomotion. In addition, we examined whether the direction of the scale change affected distance estimates by carrying out adaption in a small tunnel and test in a large tunnel, and vice versa. In Experiment 4c, we examined how changing both the size of the targets and the separation between the targets affected distance estimates via blindfolded walking. Finally, in Experiment 4d, we examined how changing either the size of the targets or the separation between the targets affected distance estimates via blindfolded walking.

4.2 Overview of experimental settings and procedure

4.2.1 Apparatus and materials

A head-mounted display (HMD) system was used to display the virtual environment (VE). The viewpoint of the virtual environment was adjusted for each participant's eye height. The HMD (NVIS nVisor ST) contained two small LCOS displays each with resolution of 1280 x 1024. The field of view is 40.5 vertical and 49.5 degrees horizontal. Participants translated through the virtual environment via a joystick (Logitech Cordless Precision game controller) or blindfolded walking. An Intersense Vistracker IS-1200 was fitted to the HMD to measure orientation and, in the case of blindfolded walking, position. The joystick directly controlled the speed of forward motion, with maximum deflection of the joystick corresponding to 1.5 meters per second.

Joystick conditions (Experiment 4a) were carried out in a dark room. Blindfolded walking conditions (Experiments 4b, 4c, 4d) were conducted in a large hallway. A black cloth was used to block out light around the sides and back of the HMD and a black piece of foam was attached underneath the HMD lenses to prevent participants from seeing the floor or their feet. Participants in the blindfolded walking conditions also wore headphones that transmitted a constant white noise. The headphones served a dual purpose of both blocking out some of the ambient noise of the hallway and as a guide for walking without vision. If participants deviated too far from the center of the hallway to the right, the white noise in the right ear headphone would get progressively louder. If participants moved too far to the left, the white noise in the left ear headphone would get louder. Differences in amplitude of white noise in the two ears allowed participants to self correct the direction of their travel while walking with their eyes closed. The experimenter demonstrated the white noise guiding tool to the participants at the beginning of the session and allowed them to step to the left and to the right to experience the difference in amplitude in each ear.

4.2.2 Virtual environments and targets

A large virtual tunnel (20m wide by 7.9m tall) and a small virtual tunnel (6m wide by 2.4m tall) were used to test the effect of changing the size of the tunnel on distance estimation (see Figure 4.1 and Figure 4.2). The two tunnels differed only in geometric scale. Specifically, the large tunnel cross-sectional area was approximately 11 times larger (3.3 times taller and wider) than the small tunnel. Both tunnels were 1000m long. The walls were texture-mapped with gray stone brick and the floor with a black asphalt-like texture. Texture scale remained the same in both tunnels; thus, the larger tunnel appeared to be made of many more bricks than the smaller tunnel.

The targets were pairs of poles placed in the tunnels at five different distances from the participants: 6, 9, 12, 15, and 18m. Three pairs of poles - large, small, and tiny - were used to test the effect of changing the size of the poles on distance estimation. Unlike the tunnels, the texture was scaled along with the size of the poles. The large poles were 4.95m tall by 0.99m wide, the small poles were 1.5m tall by 0.3m wide, and the tiny poles were 0.455m tall by 0.09m wide. Thus, the large poles were 3.3 times taller and wider than the small poles, and the small ones were 3.3 times taller and wider than the tiny poles. The lateral distance between the pole centers was proportional to the pole size. Thus, the large poles were separated by 4m, the small poles were separated by 1.21m, and the tiny poles were separated by 0.365m.

4.2.3 Procedure

The experiment consisted of two practice trials followed by an adaptation phase and a test phase. The whole session lasted an average of 25 minutes.

The practice trials were used to familiarize the participants with the distance estimation task. In each practice trial, two target poles appeared in front of the participants in the virtual tunnel. Participants were instructed to move forward with eyes open, and to stop when they were directly between the poles. Because of the limited field of view of the HMD, participants had to turn their heads 90 degrees to the left and right in order to make sure that they were exactly lined up with the two target poles. Pole distances of 9m and 15m were used for the practice.

Adaptation phase. During the adaptation phase, participants completed 20 distance judgments in the virtual environment, receiving feedback after each trial. Participants were tested on each of the five distances (6, 9, 12, 15, and 18m) four times during adaptation. The order of the target distances was randomized in blocks of all five distances. In each adaptation trial, the target poles appeared in front of the participant. Participants were instructed to look at the poles, but not to initiate travel. After 5s, the experimenter said, “Close your eyes, go.” Participants then moved forward through the virtual environment with their eyes closed via either the joystick or blindfolded walking. They said, “I’m done” when they thought they were lined up between the poles. To ensure that subjects did not receive any visual feedback during movement, the virtual environment was not displayed during the movement. The experimenter then pressed a button to make the environment and poles reappear, giving the participants feedback on how well they estimated the distance.

Test phase. After the adaptation phase, participants were instructed to close their eyes. They were then put in a differently-scaled virtual environment for the test phase. During the test phase, participants completed 10 distance estimation trials (two randomized sets of the five distances) but did not receive any feedback after finishing movement (i.e., the poles did not reappear when participants said "I'm done").

4.2.4 Measures

The software system recorded the distance traveled (in meters) for all adaptation and test trials.

4.3 Experiment 4a: How does scaling the tunnel versus everything (tunnel, targets, and separation) affect distance estimates via joystick movement?

4.3.1 Experimental conditions

In the first experiment, we examined two different types and directions of scale change. In the two "Scale Tunnel" conditions, we performed an incomplete scale change by altering only the size of the tunnel between adaptation and test; the target poles remained the same size and distance apart. We examined the effect of this type of scale change when going from a small tunnel to a large tunnel (S-L), and when going from a large tunnel to a small tunnel (L-S) (see Figure 4.1). In the two

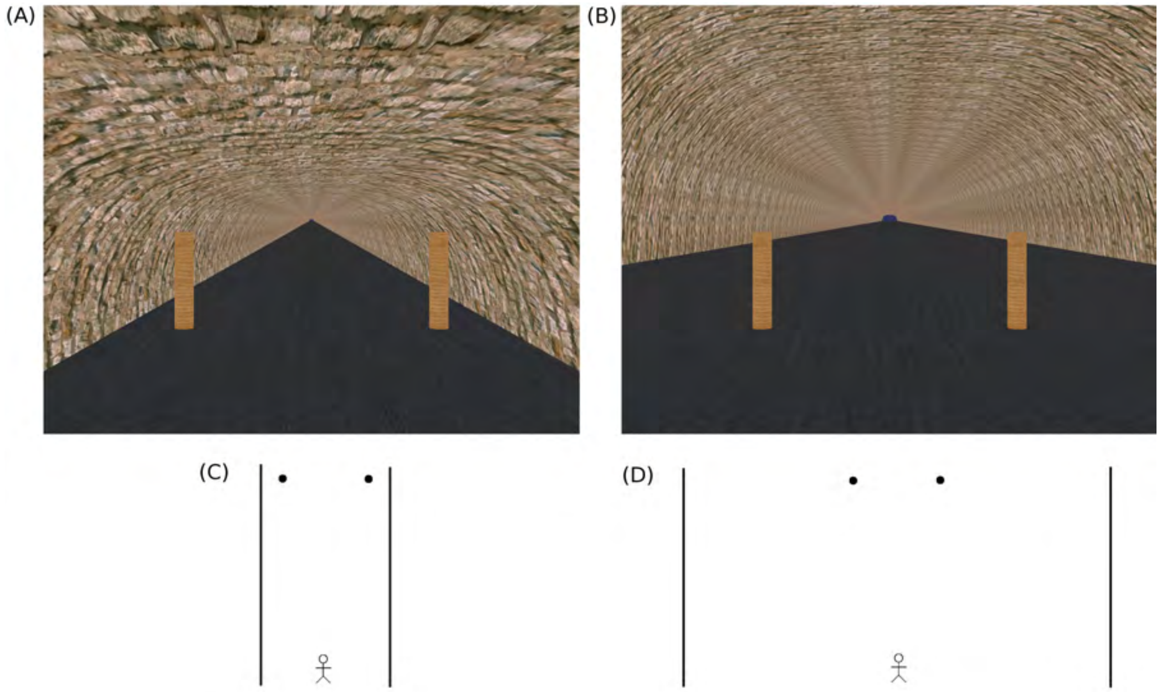


Figure 4.1: Small and large tunnels used in the Scale Tunnel conditions. The top panels show the viewer's perspective of the poles in the small (A) and large (B) tunnels. The bottom panels show a top-down perspective of the relationship between the viewer and the poles in the small (C) and large (D) tunnels.

"Scale All" conditions, we performed a complete scale change between adaptation and test by altering the size of the tunnel, the poles, and the separation between the poles. Again, we examined the effect of this type of scale change when going from a small tunnel to a large tunnel (S-L), and when going from a large tunnel to a small tunnel (L-S) (see Figure 4.2). In this experiment, participants used the joystick to move through the environment. Thus, there were four experimental conditions:

- Scale Tunnel S-L: adaptation in small tunnel with small poles, followed by test in large tunnel with small poles
- Scale Tunnel L-S: adaptation in large tunnel with large poles, followed by test

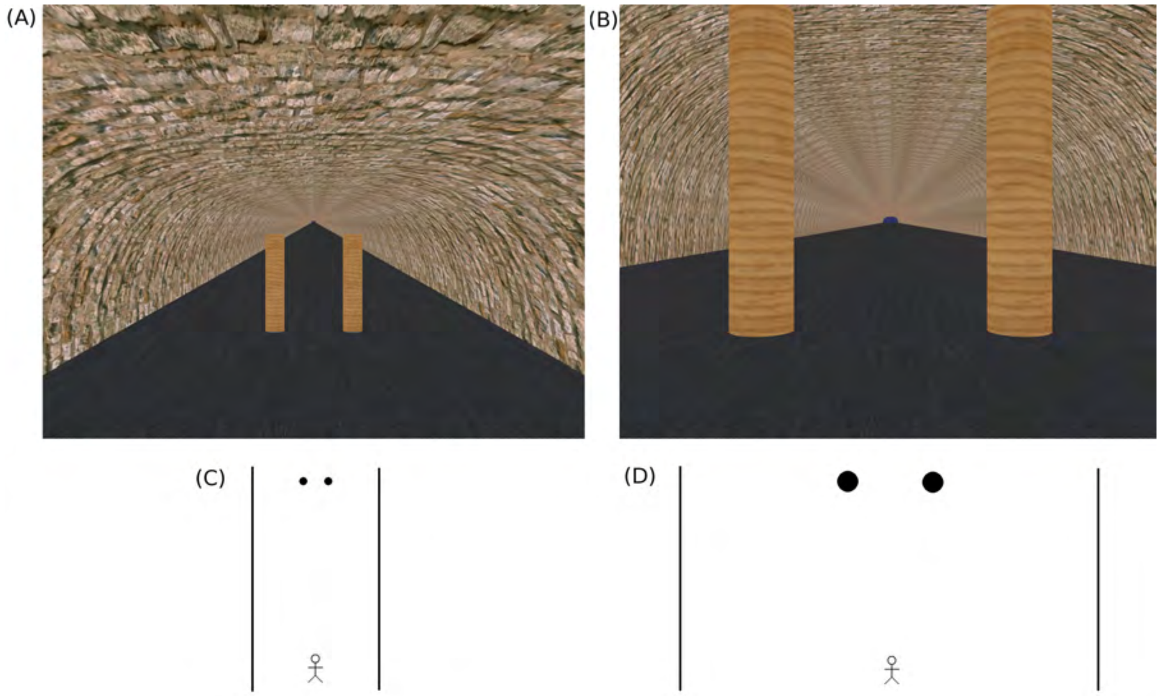


Figure 4.2: Small and large tunnels used in the Scale All conditions. The top panels show the viewer's perspective of the poles in the small (A) and large (B) tunnels. The bottom panels show a top-down perspective of the relationship between the viewer and the poles in the small (C) and large (D) tunnels.

in small tunnel with small poles

- Scale All S-L: adaptation in small tunnel with small poles followed by test in large tunnel with large poles
- Scale All L-S: adaptation in large tunnel with large poles, followed by test in small tunnel with small poles

4.3.2 Participants

Thirty-eight undergraduates participated for course credit. There were 20 females and 18 males.

4.3.3 Results and discussion

Figure 4.3 shows the mean percentage of the distance travelled in the four conditions for each distance and trial set. This figure shows that the accuracy of distance estimates increased gradually over adaptation. To determine whether there were differences between conditions over the course of adaptation, we compared the mean percentage of distance travelled during the first two and second two adaptation sets in a Condition (Scale Tunnel L-S, Scale Tunnel S-L, Scale All L-S, Scale All S-L) x Adaption Set (first two, second two) repeated measures ANOVA. (Distance was not included as a factor because there were only two observations at each distance for each adaptation set.) As expected, there was an effect of adaptation set, $F(1, 34) = 29.25, p < .001$, indicating that the mean percentage of distance travelled was smaller in the first two ($M = 74\%, SD = 13$) than in the second two ($M = 84\%, SD = 9$) adaptation sets. Thus, participants' estimates became more accurate over adaptation, though they underestimated distance even at the end of adaptation. There was no significant main effect of condition or interactions involving condition, indicating that distance estimates did not differ by condition during adaptation. The mean percentage of the distance travelled was 77% ($SD = 11$), 78% ($SD = 12$), 78% ($SD = 9$), 84% ($SD = 16$) in the Scale Tunnel L-S, Scale Tunnel S-L, Scale All L-S, Scale All S-L conditions, respectively.

Our primary question of interest was whether distance estimates changed after moving to a differently scaled environment. To address this question, we first calculated the percentage of the adaptation distance estimated at test by dividing

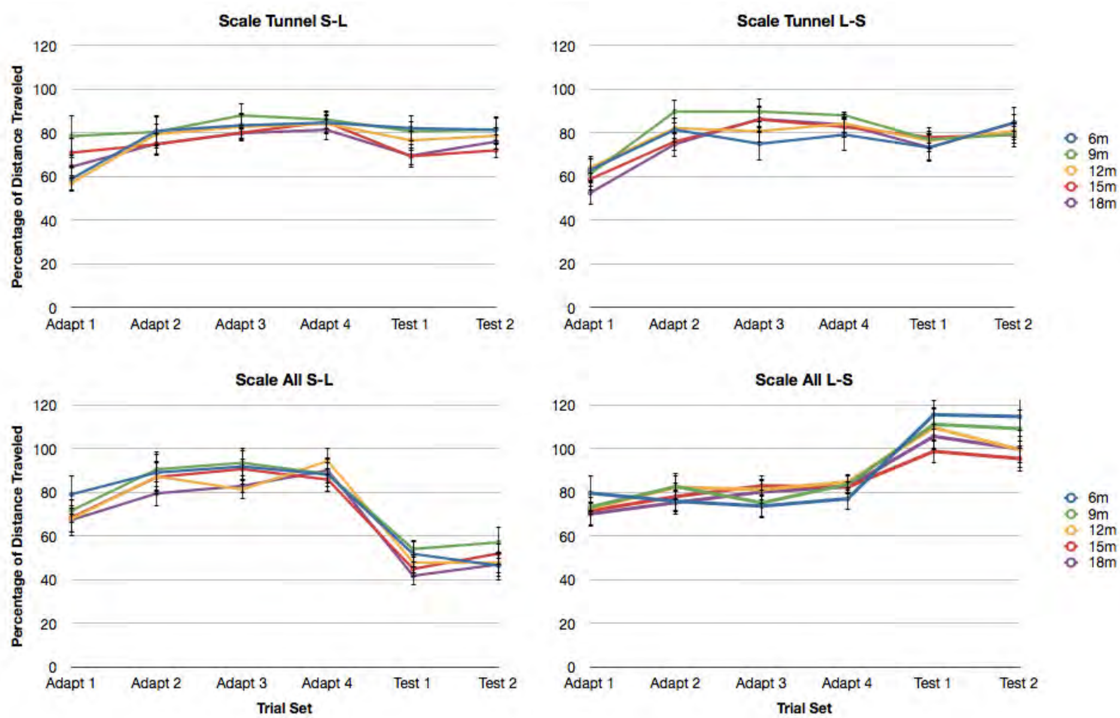


Figure 4.3: Mean percentage of distance travelled by target distance, trial set, and experimental condition in Experiment 4a (Joystick Movement).

the mean of the two test trials by the mean of the second two adaptation trials for each distance. We then averaged these percentages over the five distances to arrive at an overall percentage score for each participant. (Again, we did not include distance as a factor because there were only two observations at each distance for the adaptation and test sets.) Scores over 100% indicate that a participant made longer distance estimates at test than at adaptation, whereas scores under 100% indicate that a participant made shorter distance estimates at test than at adaption. Table 4.1 shows the mean percentages for each condition. We used separate one-sample t-tests to compare the overall percentage scores in each condition to 100%, the value expected with no change from adaptation to test. The scores for both the Scale All

S-L, $t(9) = 8.83, p < .001$, and Scale All L-S, $t(8) = 4.43, p < .01$, conditions were significantly different from 100%. Thus, participants exhibited significant change from adaptation to test when we scaled everything in the test environment. However, the percentage scores for the Scale Tunnel S-L, $t(8) = -1.76, p = .12$, and the Scale Tunnel L-S, $t(9) = .65, p = .54$, were not significantly different than the score expected with no change from adaptation to test.

To determine whether the magnitude of the percentage scores differed by condition, we entered these scores into a one-way ANOVA with condition as a between-participants factor. This analysis revealed a significant effect of condition, $F(3, 34) = 34.27, p < .0001$. Fisher's Protected Least Significant Difference (PLSD) follow-up tests indicated that all conditions differed significantly from one another except for the Scale Tunnel L-S and the Scale Tunnel S-L conditions.

Together, these results suggest that when all aspects of the test environment were scaled, participants going from the large to small tunnel perceived the same distances as longer during test than adaptation, and participants going from the small to the large tunnel perceived the same distances as shorter during test than adaptation. This pattern of results was not obtained when only the size of the tunnel changed from adaptation to test. These differences in how participants perceived the same distances after different kinds of scale changes suggest that not all types of scale changes affect distance perception similarly.

4.4 Experiment 4b: How does scaling the tunnel versus everything (tunnel, targets, and separation) affect distance estimates via blindfolded walking?

There were substantial differences in distance estimates when all aspects of the environment were scaled from adaptation to test in Experiment 4a. However, it is still unclear exactly what was being affected by changes in scale. Participants used a joystick rather than actual walking to "move" to the targets. Moving through a virtual environment via a joystick with one's eyes closed provides mostly timing information about distance (i.e., how long it takes to travel a given distance). Therefore, participants may have been using a timing strategy to complete the task, grounding their memory for distances in time rather than in actual movement through space. Furthermore, although the joystick speed was similar to normal human walking speed, it was not calibrated to individual participants' walking speeds. This may have led to an ungrounded perception of the environment, which was exacerbated by changing the scale of everything from adaptation to test. In Experiment 4b, we further tested the generality of people's responses to different types of scale changes by replicating Experiment 4a except that participants moved through the virtual environment via actual (blindfolded) walking. This allowed us to investigate whether people continue to show systematic over and underestimation of distance perception in response to scale changes when they are given the opportunity to physically walk to targets in a virtual environment.

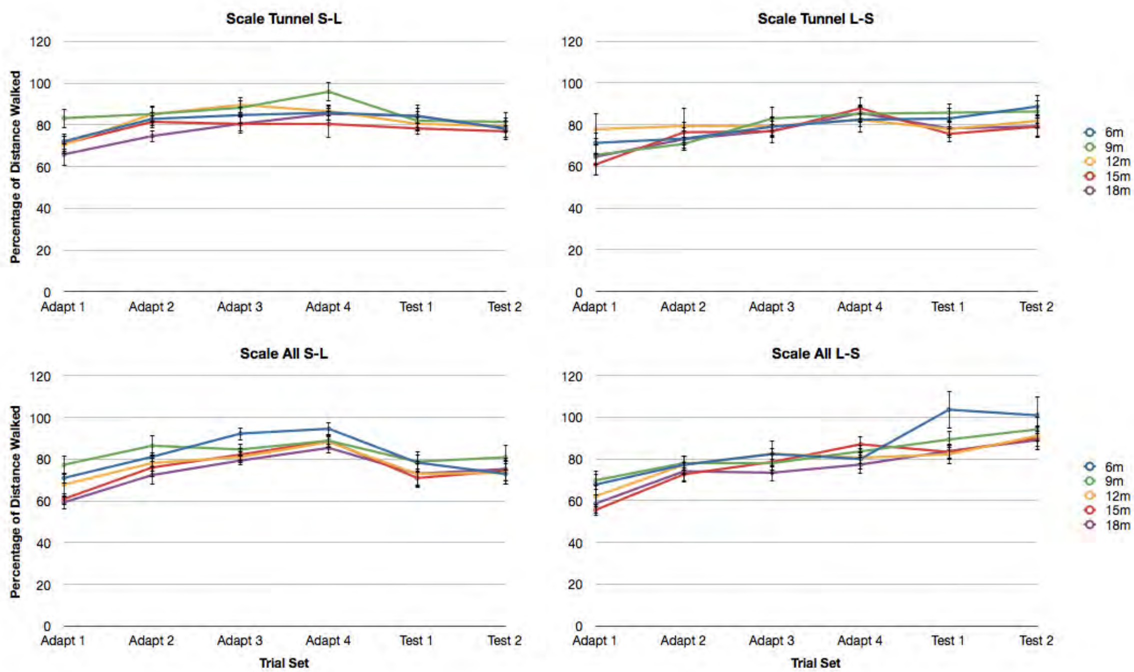


Figure 4.4: Mean percentage of distance walked by target distance, trial set, and experimental condition in Experiment 4b (Blindfolded Walking).

4.4.1 Experimental conditions

The experimental conditions and testing procedures were identical to those of Experiment 4a except that participants made distance estimates via blindfolded walking.

4.4.2 Participants

Fifty-three undergraduate students participated for course credit. There were 24 females and 29 males.

4.4.3 Results and discussion

Figure 4.4 shows the mean percentage of the distance walked in the four conditions for each for each distance and trial set. As in Experiment 4a, the accuracy

Table 4.1: Mean Percentage of Adaptation Distance Estimated at Test for Experiment 4a (Joystick Movement) and Experiment 4b (Blindfolded Walking).

Condition	**Experiment 4a**	**Experiment 4b**
Scale All S-L	56.0%* (16)	82.1%* (13)
Scale All L-S	134.5%* (23)	114.8%* (13)
Scale Tunnel S-L	92.7% (12)	95.4% (11)
Scale Tunnel L-S	97.1% (14)	100.8% (9)

Notes: Asterisks indicate that the score differed significantly from 100%. Standard deviations are in parentheses.

of distance estimates increased gradually over adaption. To determine whether there were differences between conditions over the course of adaptation, we compared the mean of the first two and second two adaptation sets in a Condition (Scale Tunnel S-L, Scale Tunnel L-S, Scale All S-L, Scale All L-S,) x Adaption Set (first two, second two) repeated measures ANOVA. As expected, there was an effect of adaptation set, $F(1, 49) = 115.25, p < .001$, indicating that mean percentage of distance walked was smaller in the first two ($M = 73\%, SD = 13$) than in the second two ($M = 84\%, SD = 11$) adaptation sets. Thus, participants' estimates became more accurate over adaptation, though they again underestimated distance even at the end of adaptation. There was no significant main effect of condition or interactions involving condition. The mean percentage of distance walked was 77% ($SD = 17$), 81% ($SD = 10$), 75% ($SD = 13$), 81% ($SD = 11$) in the Scale Tunnel L-S, Scale Tunnel S-L, Scale All L-S, Scale All S-L conditions, respectively.

Our primary question of interest was whether distance estimates changed after moving to a differently scaled environment. Table 1 shows the mean percentage of the adaptation distance walked for each condition. We used separate one-sample t-tests to compare the overall percentage scores in each condition to 100%, the value expected with no change from adaptation to test. The scores for both the Scale All S-L, $t(11) = 4.90, p < .001$, and Scale All L-S, $t(13) = 4.28, p < .001$, conditions were significantly different from 100%. Thus, participants exhibited significant change from adaptation to test when we scaled everything in the test environment. However, the percentage scores for the Scale Tunnel S-L, $t(11) = -1.42, p = .18$, and the Scale Tunnel L-S, $t(14) = .37, p = .72$, were not significantly different than the score expected with no change from adaptation to test.

To determine whether the magnitude of the percentage scores differed by condition, we entered these scores into a one-way ANOVA with condition as a between-participants factor. This analysis revealed a significant effect of condition, $F(3, 49) = 18.19, p < .0001$. Fisher's PLSD follow-up tests indicated that all conditions again differed significantly from one another except for the Scale Tunnel L-S and the Scale Tunnel S-L conditions.

The results of this experiment replicated those of Experiment 4a. Specifically, when all aspects of the test environment were scaled, participants going from the large to small tunnel perceived the same distances as longer during test than adaptation. Conversely, participants going from the small to the large tunnel perceived the same distances as shorter during test than adaptation. When only the tunnel was scaled at test, however, the effects were minimal.

Thus, it appears that these different kinds of scale changes affect joystick and physical movement through virtual environments similarly. It should be noted, however, that the effects of scaling everything in the test environment were attenuated when participants actually walked to the targets in the present experiment as compared to when subjects used a joystick to move to the targets in Experiment 4a. In the Scale All L-S condition, participants overshot distances relative to adaptation by an average of 34.5% (2.75m) in Experiment 4a, but only 14.8% (1.09m) in Experiment 4b. Likewise, in the Scale All S-L condition, participants undershot distances relative to adaptation by an average 44% (4.81m) in Experiment 4a, but only 17.9% (1.83m) in Experiment 4b. This suggests that the experience of walking to the targets led to a more effective grounding of distance perception.

4.5 Experiment 4c: Does scaling both the size of targets and the separation between targets lead to changes in distance estimates?

Together, the first two experiments suggest that not all types of scale changes affect distance perception similarly. When all aspects of the test environment were scaled, participants going from the large to small tunnel perceived the same distances as longer during test than adaptation. Conversely, participants going from the small to the large tunnel perceived the same distances as shorter during test than adaptation. When only the tunnel was scaled at test, however, participants perceived the distances as essentially the same from adaptation to test. These differences in how participants perceived the same distances after different kinds of scale changes were similar for both joystick and physical movement through virtual environments, although the effects of scale changes were attenuated with actual physical movement in the VE.

One question these findings raise is whether participants will continue to exhibit systematic changes in distance estimates when the target size and target separation, but not the tunnel size, are changed from adaptation to test. In Experiments 4a and 4b, we saw substantial effects of scaling all aspects of the environment from adaptation to test. In addition, we saw minimal effects of scaling when the tunnel size changed but the target size remained the same. This suggests that the changes in peoples distance estimates were driven by changes in target size and/or target separation. However, because we scaled the tunnel along with the targets and separation between the targets, we cannot completely rule out the possibility that target size and separation interact in some way with tunnel size. To begin to tease apart these factors, we conducted a third experiment in which the tunnel size was unchanged from adaptation to test, but the target size and separation changed from adaptation to test. Because the effects of going from small to large were somewhat larger than those of going from large to small, we chose to examine the effects of changing target size and separation from small (adaptation) to large (test). In the large tunnel condition, participants viewed small poles with a small separation during adaptation and viewed large poles with a large separation during test, whereas in the small tunnel condition, participants viewed tiny poles with a tiny separation during adaptation and viewed small poles with a small separation during test. Carrying out the same relative scale change in two differently sized tunnels with different sized poles allowed

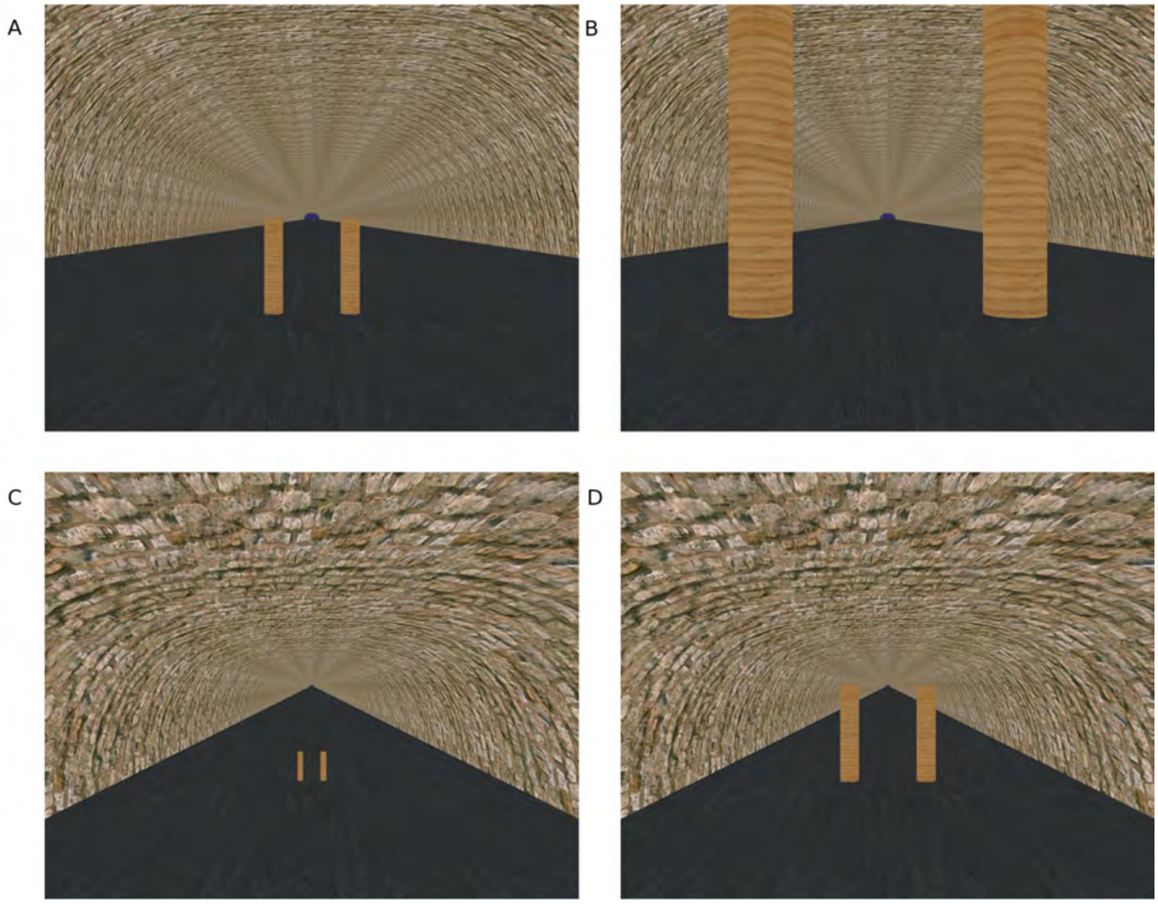


Figure 4.5: Poles and tunnels used in Experiment 4c. The top panel shows the poles in the large tunnel at adaptation (A) and test (B). The bottom panel shows the poles in the small tunnel at adaptation (C) and test (D).

us to determine whether the effects generalized across different tunnel and pole sizes.

4.5.1 Experimental conditions

There were two conditions:

- Scale TargetSizeAndSeparation S-L: adaptation with small poles and small separation, test with large poles and large separation, all in large tunnel.
- Scale TargetSizeAndSeparation T-S: adaptation with tiny poles and tiny separation, test with small poles and small separation, all in small tunnel.

The procedure was the same as that used in Experiment 4b. Again, participants made distance estimates via blindfolded walking.

4.5.2 Participants

Twenty-eight undergraduate students participated for course credit. There were 16 females and 12 males.

4.5.3 Results and discussion

Figure 4.6 shows the mean percentage of distance walked in the large and small tunnel conditions for each distance and trial set. As in the other experiments, the accuracy of distance estimates increased gradually over adaptation. A Condition (Large Tunnel S-L vs. Small Tunnel S-L) x Adaption Set (first two, second two) repeated measures ANOVA on the first two and second two adaptation trials revealed a significant effect of adaptation set, $F(1, 26) = 58.18, p < .0001$, indicating that mean percentage of distance walked was smaller in the first two ($M = 69\%, SD = 8$) than in the last two ($M = 80\%, SD = 10$) adaptation sets. Thus, participants' estimates became more accurate over adaptation, though they again underestimated distance even at the end of adaptation. There was no effect of condition or interactions with condition. The mean percentage of distance walked in the Large Tunnel S-L and Small Tunnel S-L conditions was 77% ($SD = 12$) and 72% ($SD = 10$).

Our primary question of interest was whether distance estimates changed from adaptation to test when the tunnel size remained the same (i.e., large or small), but the poles and separation between them increased in size. One-sample t-tests comparing the mean percentage scores to 100% revealed that participants significantly

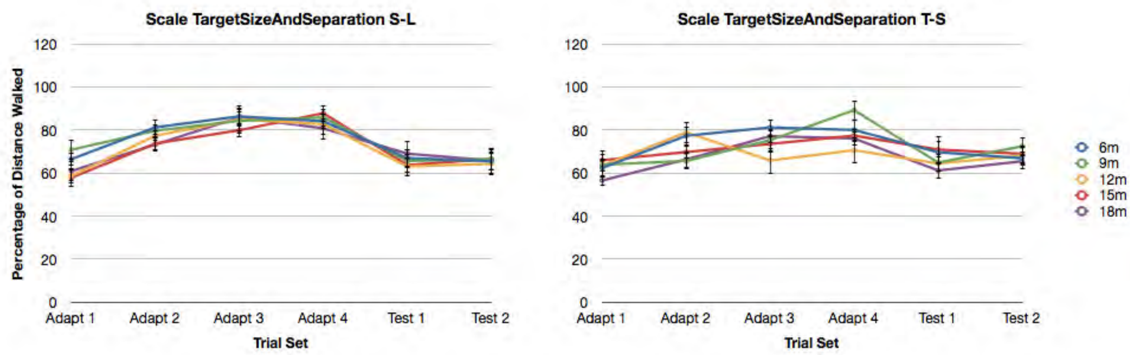


Figure 4.6: Mean percentage of distance walked by target distance, trial set, and experimental condition in Experiment 4c.

underestimated distances at test relative to adaptation in both the large tunnel, $t(13) = -5.56, p < .0001$, and in the small tunnel, $t(13) = -2.76, p < .05$. The mean percentage change scores were 78.1% ($SD = 15$) and 89.9% ($SD = 14$) in the large tunnel and small tunnels, respectively. In addition, a one-way ANOVA with condition as a between-participants factor yielded a significant effect of condition, $F(1, 26) = 4.84, p < .05$, indicating that the percentage of adaptation distance walked at test was significant smaller in the large tunnel than in the small tunnel.

These results clearly show that scaling the size of the target poles and the separation between them without scaling the size of the tunnel led to changes in distance estimates at test. Regardless of whether distance estimates were made in the small or large tunnel, participants significantly underestimated distance when the target size and separation increased from adaptation to test. Interestingly, there was more underestimation in the large tunnel than in the small tunnel. Although the source of this difference is unclear, it may be that distance estimates are more grounded in spaces closer to people's typical experience. That is, due to the size of the small tunnel, the distribution of distances in the scene is closer to that of everyday experience (i.e., it has a maximum probability near 3m), which is hypothesized to play a role in people's judgment of distance [80]. Overall, these findings offer further support for the idea that people were responding to changes in target size and/or separation rather than changes in the tunnel size. However, given that both target size and separation were scaled simultaneously, it is possible that changes in the two together are required to produce changes in distance estimates. To separate these two factors, we conducted a fourth experiment in which only target size was scaled in one condition and only target separation was scaled in the other condition.

4.6 Experiment 4d: Does scaling either target size or target separation alone lead to changes in distance estimates?

4.6.1 Experimental conditions

There were two conditions:

- Scale TargetSize S-L: adaptation with small poles and large separation, test with large poles and large separation, all in large tunnel.
- Scale TargetSeparation S-L: adaptation with small target separation, test with large target separation, all with small poles in large tunnel.

Again, all aspects of the procedure were the same as in Experiments 4b and 4c.

4.6.2 Participants

Twenty-four undergraduate students participated for course credit. There were 12 females and 12 males.

4.6.3 Results and discussion

Figure 4.8 shows the mean percentage of the distance walked in the target size and target separation conditions for each distance and trial set. A Condition (size vs. separation) x Adaption Set (first two, second two) repeated measures ANOVA on the mean of the first two and second two adaptation sets again revealed a significant effect of adaptation set, $F(1, 22) = 39.30, p < .0001$, indicating that mean percentage of distance walked was shorter in the first two ($M = 70\%, SD = 13$) than in the second two ($M = 83\%, SD = 14$) adaptation sets. There was no effect of condition or interactions with condition. The mean percentage of distance travelled in the target size and target separation conditions was 78% ($SD = 13$) and 75% ($SD = 16$).

Our primary question of interest was whether distance estimates changed from adaptation to test when 1) the size of the tunnel and the target separation remained the same, but the poles increased in size, and 2) when the size of the tunnel and the poles remained the same, but target separation increased. Separate one-sample t-tests comparing the mean percentage scores to 100% revealed that participants in the target size condition significantly underestimated distances at test relative to adaptation, $t(11) = -2.58, p < .05$. This was not the case for participants in the target separation condition, $t(11) = -.13, p = .90$. The mean percentage scores were 92.1%($SD = 11$) and 99.5%($SD = 14$) in the target size and target separation

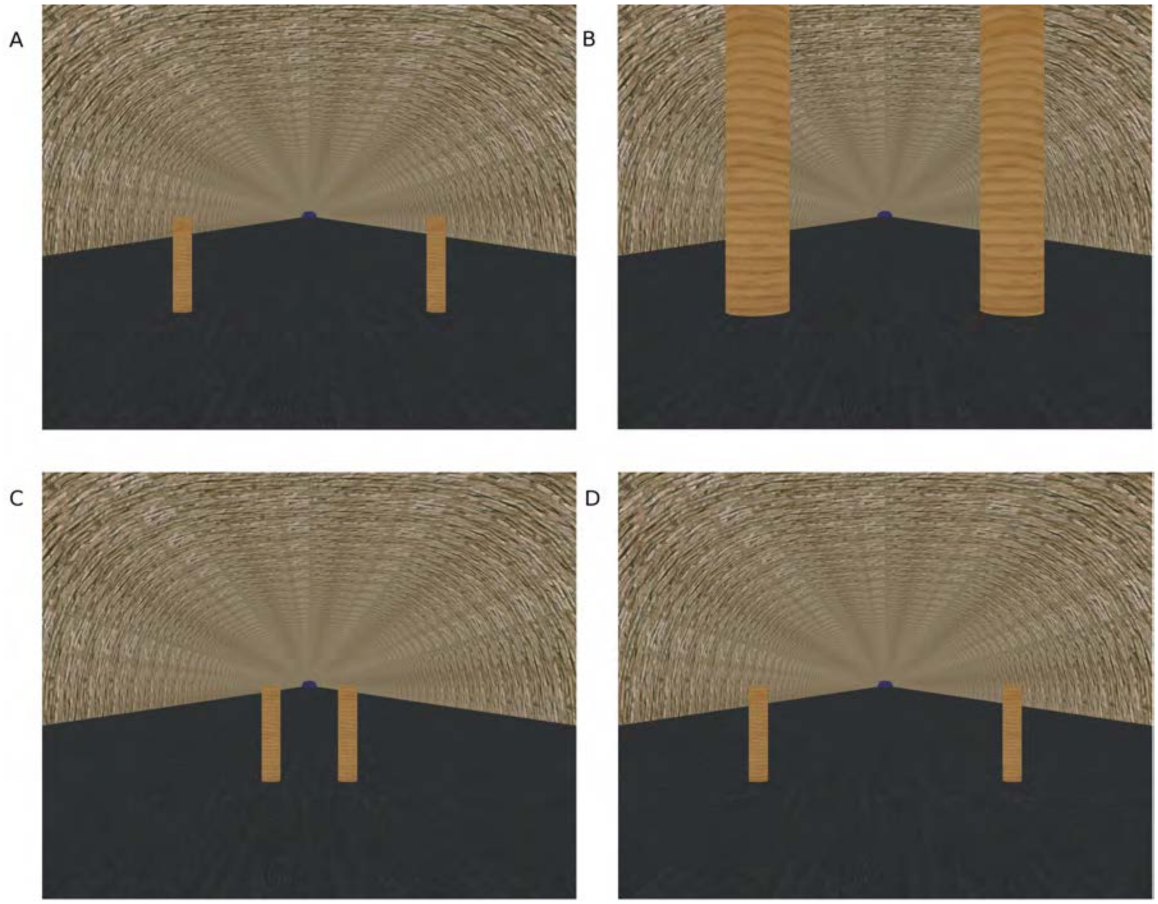


Figure 4.7: Poles and tunnel during adaptation (A) and test (B) in the Scale Target-Size S-L condition. Poles and tunnel during adaptation (C) and test (D) in the Scale TargetSeparation S-L condition.

conditions, respectively. However, a one-way ANOVA with condition as a between-participants factor yielded no effect of condition, $F(1, 22) = 2.19, p = .15$, indicating that the percentage of the adaptation distance walked at test did not differ between the size and separation conditions.

To help round out our investigation of the impact of changes in target size and separation on distance estimates at test, we also conducted a cross-experiment comparison of percentage scores in the target size condition from Experiment 4d

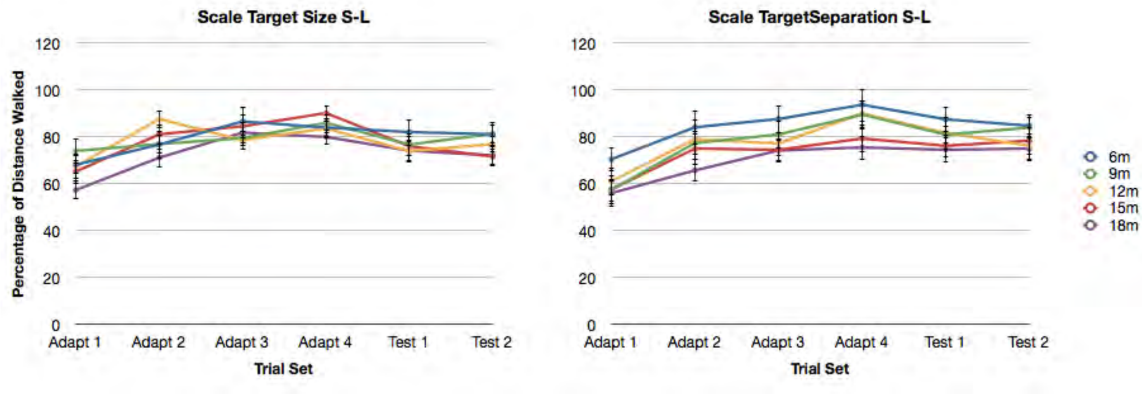


Figure 4.8: Mean percentage of distance walked by target distance, trial set, and experimental condition in Experiment 4d.

and in the target size and separation condition from Experiment 4c (large tunnel). All aspects of the two conditions were the same, except that the Experiment 4c condition involved changing both target size and separation at test, whereas the Experiment 4d condition involved changing only the target size. A one-way ANOVA with condition as a between-subjects factor yielded a significant effect of condition, $F(1, 24) = 7.54, p < .05$, indicating that participants underestimated distances more at test when both target size and separation changed ($M = 78\%, SD = 15$) than when only target size changed ($M = 92\%, SD = 11$).

Together, these results indicate that change in target size, not separation, is a critical factor leading to changes in distance estimation from adaptation to test. When target size changed but the target separation remained the same, participants significantly underestimated distance. However, when the target separation changed, but the target size remained the same, participants exhibited no significant change in their distance estimates from adaptation to test. Note, however, that the amount of underestimation when only the target size was changed from adaptation to test was relatively small. The implications of these findings are discussed in further detail below.

4.7 General discussion and conclusions

The goal of this investigation was to examine the influence of scale changes on distance perception in virtual environments. Of particular interest was how people responded to changes in the size of the surrounding environment (a tunnel in our case), the targets (two poles), and the separation between the targets. We discovered that distance judgments at test were largely unaffected by an eleven-fold increase in the cross-sectional size of the tunnel. Thus, the calibration of distance achieved during adaptation was stable in face of a significant change in the scale of the surrounding environment at test. Distance judgments were also unaffected by changes in the separation of the two targets. However, changing the size of the targets had significant and systematic effects on distance estimates. When the target poles became larger from adaptation to test, participants undershot distances at test relative to adaptation. Conversely, when the target poles became smaller from adaptation to test, participants overshot distances at test relative to adaptation. These results are summarized in Table 4.2.

Together, these results indicate that changes in the retinal size of the targets had a strong influence on the perceived distance to the targets. For objects with constant physical size, the size of the object on the retina is a well-established cue to distance. One manifestation of the perceptual encoding of the relationship between

Table 4.2: Summary of Experimental Conditions and Results.

Experiment	Scaling Conditions and Results	
Experiment 4a	Scale everything, move via joystick	Scale only tunnel, move via joystick, small poles
Small-to-large	56.0%*	92.7%
Large-to-small	134.5%*	97.1%
Experiment 4b	Scale everything, move via blind walking	Scale only tunnel, move via blind walking, small poles
Small-to-large	82.1%*	95.4%
Large-to-small	114.8%*	100.8%
Experiment 4c	Scale targets and separation, large tunnel only, small-to-large poles	Scale targets and separation, small tunnel only, tiny-to-small poles
	78.1%*	89.9%*
Experiment 4d	Scale target size, large tunnel only, small-to-large poles	Scale target separation, large tunnel only, small-to-large poles
	92.1%*	99.5%

Notes: The means represent distance estimated at test, expressed as the percentage of distance estimated at adaptation. Asterisks indicate that the score differed significantly from 100%.

retinal size and distance is the ability to judge absolute distance to well-known objects on the basis of their familiar size. Classic studies have shown that familiar size is a particularly powerful cue to distance when other cues are unavailable or attenuated [14, 29]. For example, if people view off-size playing cards (e.g., twice as large or small as a normal playing card) at the same distance in a darkened room, they will judge the smaller card as farther away and the larger card as closer. While the objects used in our experiments were not familiar to the participants prior to the experiment, participants became familiar with their size throughout the adaptation trials. They viewed the poles at the beginning of each adaptation trial and stood close to them at the end of each adaptation trial, providing them with extensive experience with size-distance relationships. Change in size can also be a cue for change in relative distance even if the actual size of the object is unknown. For example, objects that continuously grow in size on the retina can be perceived as moving on a trajectory approaching the observer (i.e., looming). Participants in our experiment could have been using either knowledge of absolute size or changes in relative size to make their distance judgments.

A complementary way to think about the link between size and distance is the ability to perceive objects as having a stable size despite changes in viewing distance. Object constancy refers to the idea that the same object is perceived as being the same size at different distances, even though the size of the image on the retina varies with distance from the observer. Many classic real-world experiments have shown that people accurately judge object size despite changes in distance [24, 26]. More recently, Kenyon *et al.* [33] examined whether people use size constancy in virtual environments. They found that when asked to adjust the size of a Coke bottle placed on a table at various distances in a rich virtual environment, participants accurately set the size of the bottle to correspond to the actual size of the object. Their work clearly shows that people maintain size constancy in virtual environments, although they have difficulty doing so in impoverished virtual environments (i.e., when cues to distance are removed). While our experiment did not explicitly examine the perception of object size, a tendency to perceive objects as having a stable size may underlie the pattern of distance judgments we found. Thus, when objects became larger, they were perceived as closer and when they became smaller they were perceived as further away.

Although object size appeared to play an important role in distance estimation, participants' adjustments of their distance estimates were only a small proportion of the 3.3 factor by which object size was increased or decreased. This suggests that distance estimates were based not only on perceived object size, but on information integrated from multiple distance cues. Unlike the classic perception studies in which participants viewed objects in cue-impoverished, darkened rooms, the virtual environments we used were fully lit and contained many other distance cues such as motion parallax, angle of declination, and linear perspective. Based on the results of the first couple of adaptation trials, when subjects could not have known the absolute size of the targets, we know that participants could estimate distance equally well with the large and small poles (albeit they underestimated distance for both sets of targets). Thus, it seems likely that participants were relying on cues other than size during adaptation such as the angle of declination. When the target size changed at test, those other cues conflicted with object size cues. In the face of conflicting cues, participants may have integrated the information from multiple cues and arrived at an estimate that was a weighted average of the conflicting sources of information. Other work indicates that cue weightings in virtual environments can shift depending on factors such as object distance [22].

Participants made greater adjustments when both the size of the poles and the separation between them changed from adaptation to test (Experiments 1-3) than when only the size of the poles changed (Experiment 4d). This pattern of results can be explained by a cue weighting model that puts confidence in cues that are consistent with a stable world view, the presumption that the physical attributes of and spatial relations among objects in the world tend to be stable [22]. A coupled change in pole size and separation is consistent with an explanation that the changes are caused by a change of viewpoint in a stable world. That is, if the size and separation of the poles are fixed, then the retinal sizes of the poles and angles subtended by the poles both grow or shrink at viewpoints closer or further away from the targets. Thus, scaling only poles size (Experiment 4d) would produce retinal images that could not solely be explained by a change in viewpoint. Notably, distance judgments were significantly less influenced in this condition. Likewise, distance judgments were not significantly influenced by changes in only the separation of the poles. This pattern of results suggests a preference for explanations that preserve the stability of object size over the stability of spatial arrangements.

Further work is needed to determine how the properties of the targets and the environment influence distance perception. For example, simple changes to the features of the poles (e.g., color, shape, or texture) between adaptation and test may be sufficient to override the perception that poles that get bigger are closer and poles that get smaller are farther away. If so, this would suggest that people dynamically re-weight distance cues in response to other perceptual information about targets.

A final issue concerns whether perceptual-motor recalibration during adaptation is necessary to produce scale change effects at test. The improvement in distance estimates over the course of adaptation shows that participants calibrated perception and action in our virtual environment (see also Mohler *et al.* [46]; Waller and Richardson [72]). Clearly, people learned about the relationship between the perceived visual size of the poles and movements produced to reach the poles during adaptation. Furthermore, the retinal changes in the size of the poles and the angle subtended by the poles at the beginning and end of each adaptation trial may have increased the salience of size cues. However, it is also possible that perceptual-motor recalibration is unnecessary to produce effects of scale change on distance perception. The fact that distance estimates during adaptation did not differ depending on whether participants saw large or small poles indicates that the critical factor is the change in size from adaptation to test. One way to test whether perceptual-motor recalibration plays a role in producing scale effects is to expose people to the poles at the different distances during adaptation without asking them to make any kind of distance judgment (e.g., blindfolded walking or simply giving no feedback). If people show systematic patterns of distance estimation at test depending on whether the poles become larger or smaller, then we can conclude that perceptual-motor recalibration is not necessary to produce these effects. At present, the role of purely visual experience in producing scale change effects on distance estimation is not known.

In sum, the large effects of scale changes on distance perception lend further support to the conclusion that people have difficulty accurately perceiving egocentric distance in virtual environments. The distances were the same from adaptation to test, and yet people thought the poles were farther away when the targets became smaller, and closer when the targets became larger. This occurred despite the fact that quantitative cues such as the angle of declination remained the same for a given distance. Further work is needed to better understand how space perception is calibrated in virtual environments. It would also be valuable to test whether scale changes like those investigated here have effects in the real world and how those effects compare to the effects in VEs.

CHAPTER 5
EFFECT OF MEASUREMENT SETTING IN JUDGING TRAVELED DISTANCE: ADDITIONAL EVIDENCE FOR UNDERESTIMATION OF DISTANCE IN VIRTUAL ENVIRONMENTS

In the two previous chapters, we investigated the factors influencing estimation of distances in VEs, and examined the effect of scale change on distance estimation. To prepare for traveled distance estimation studies covered in Chapters 7, 8, 9, we conducted a pilot experiment involving a simple traveled distance estimation task. In the experiment presented in this chapter (and initially presented as [49]), participants walked without vision a distance and then made estimates of the walked distance in either a virtual or a real environment.

Our primary goal was to examine the effect of measurement setting — virtual or real environment — on the traveled distance estimates. Although the participants' explicit task was to estimate traveled distance, our experiment was not designed to assess accuracy of traveled distance estimates. It was also not designed to compare traveled distance estimates made by participants who moved in real versus those who moved in virtual environments. Instead, in our experiment, all participants walked without vision in the real world. After this travel, they expressed their estimates in different measurement settings, virtual or real. The experiment was designed to assess effects of these different measurement settings. Expressing traveled distance estimates within a measurement setting required participants to make implicit distance-to-target estimates. For this reason, we hypothesized that participants who used the VE measurement setting would make *larger* traveled distance estimates than

Figure 5.1: The real hallway (left) and the virtual hallway (right) with poles at 18m.

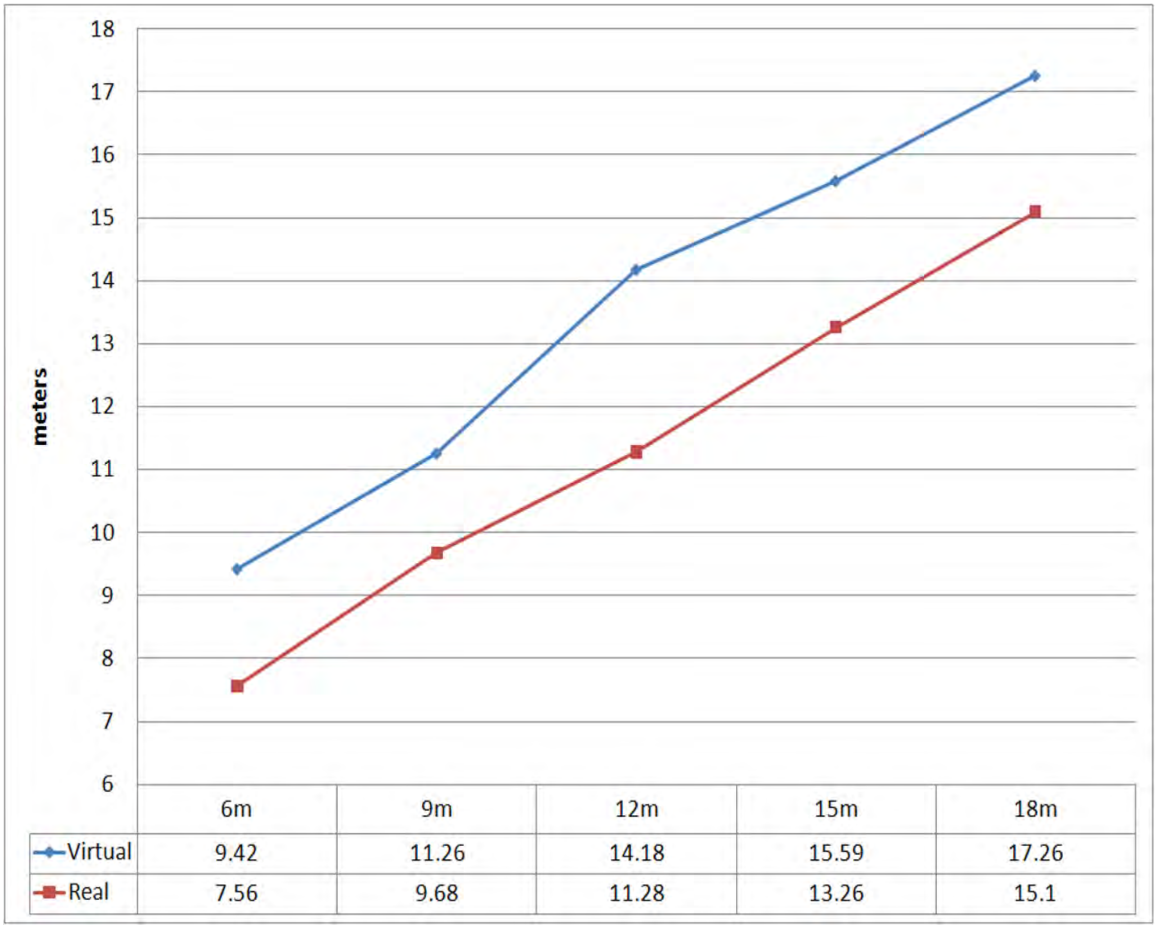
those who used the real world setting.

5.1 Experimental methods

The experiment was carried out in a hallway. To minimize exposure to the environment before the experiment, we escorted the participants (8 male, 8 female) to the hallway without vision (with either a blindfold or head-mounded display in place). To familiarize participants with visionless walking, we first directed them to walk along the hallway until instructed to turn around and walk back to the starting point (approximately 40m total). If participants deviated too much and approached hallway walls, we tapped the appropriate shoulder with a foam stick.

The experiment consisted of two practice and 15 test trials. The two practice trials, conducted at $9m$ and $15m$, were used to familiarize subjects with the procedure. The test trials consisted of three sets of all five distances, with distances randomized within sets.

Participants, wearing either the blindfold or HMD (NVIS nVisor ST equipped



	6m	9m	12m	15m	18m
Virtual	9.42	11.26	14.18	15.59	17.26
Real	7.56	9.68	11.28	13.26	15.1

Figure 5.2: Mean estimates of traveled distance vs. actual walked distance.

with an Intersense Vistracker IS-1200 six degree-of-freedom tracking system), first sat on a wheeled chair and were rolled to one of five distances ($6m$, $9m$, $12m$, $15m$ and $18m$). After turning the chair, we instructed subjects to stand and begin walking, still without vision. When they reached the starting point, we told them to stop and turn around. Participants were told to focus on their own walking, not the chair movement, as the cue for traveled distance.

The experiment had two conditions (see Figure 5.1). In the Real Setting condition, participants adjusted the position of a pair of real $0.3m$-wide by $1.2m$-

tall cylindrical poles from an initial position $10.5m$ away to the position where they believed they started walking. Participants removed the blindfold, and repeatedly stated whether they wanted the poles farther away or closer. Two experimenters (out of participants' view) moved the poles by manipulating strings connecting the poles and pulleys at the ends of the hallway. In the Virtual Setting condition, participants moved identical virtual poles (in an accurate model of physical hallway) by pressing up or down on the d-pad of a Wii Remote.

5.2 Results and discussion

Mean traveled distance estimates are plotted in Figure 5.2. We performed a $Setting(Real\ vs.\ Virtual) \times Distance(6, 9, 12, 15, vs.\ 18m)$ mixed model ANOVA and found that judged traveled distances were significantly different between the Virtual and Real conditions ($F(1, 14) = 4.86, p = 0.0448$). Overall, short traveled distances were overestimated and long traveled distances were underestimated. This was due to a measurement bias created by always starting the poles at $10.5m$.

As stated above, however, the goal of our experiment was to compare effects of measurement settings rather to test accuracy of estimates. Estimates in the Virtual condition were approximately 20 percent higher than those in the Real condition. We believe that a small part of this difference might be attributable to the encumbrance of the HMD causing Virtual condition subjects to believe they walked farther than Real condition participants did. Overall, however, we believe that the results are consistent with and provide further evidence for underestimation of perceived distance in virtual environments compared to the real world. When adjusting poles, participants needed to implicitly estimate the distance from themselves to those poles. Thus, to represent an estimate of a walked distance, we would expect a participant to place virtual poles farther away than real poles.

The primary result of this chapter's experiment was once again on the distance estimation problem covered in the first half of this thesis. The experiment also provided valuable initial experience with the traveled distance estimation problem, which is the focus of remainder of the thesis.

CHAPTER 6
BACKGROUND: TRAVELED DISTANCE ESTIMATION

This chapter reviews research about traveled distance estimation. We first present the overall problem of traveled distance estimation, then work that has been done in real environments followed by work done in virtual environments.

6.1 The traveled distance estimation problem

In the previous chapter, we conducted a pilot experiment that involved both distance estimation and traveled distance estimation. Traveled distance estimation is a different problem from distance estimation. It is to answer the question "How far did I just travel?" instead of "How far away is that thing?". It has received far less attention and there are many not-yet-answered questions about how well do people estimate traveled distances in virtual and real environments? Do they under- or over-estimate the distances? What the factors influence traveled distance estimation? What are the roles of optic-flow, vision, body-based cues, scale of environments, surrounding environments, etc.? Are there any differences in people's estimates between virtual and real environments?

Throughout much prior research on distance and traveled distance estimation, there has not always been a clear distinction between the two problems. In fact, some people seem to consider them much the same problem; e.g. Mossio *et al.* [47] states that "distance estimation should rather be seen as an estimation of traveled distances", because many of the methods popularly used to indicate distance estimation, such as blindfolded walking, triangulated walking, imagined walking, involve traveled distance estimation in some form. And in Frenz and Lappe [17, 39], the authors also treat a distance estimation task as a traveled distance estimation task.

However, from our experience and results that will be presented in Chapters 7 through 9, we believe that they are related but substantially different problems. In a traveled distance estimation task, the participant must integrate information sensed over a period of time to estimate how far she has traveled; this is a one-dimensional version (walking straight and ignoring orientation) of the "path integration" problem [16]. The participant is not given an explicit visual preview of the end position of the walked distance nor is allowed to look back from the end point to the starting point. Participants must form their estimate of traveled distance based entirely on information gathered during the walk; distractions and failures of memory and other factors can significantly impact this process [13]. In a distance estimation task, on the other hand, people are explicitly shown targets and perceive target distances in an instant or over a very short time. The process of *expressing* estimates of the perceived distances can happen either quickly (e.g. verbal report or throwing) or over a substantial period of time (e.g. blindfolded walking or timed-imaged walking), depending on the experimental protocol. But a key difference remains; in TDE, the "perception" of the traveled distance takes place over substantial time, while in DE the distance is perceived almost instantly.

In a number of experiments, the two problems seem confounded, involving both distance estimation and traveled distance estimation. Many distance estimation experiments use blindfolded walking or similar protocols to express estimates. In one experiment, for example, [39], the authors interpreted participant's undershooting movement toward previously seen targets as evidence for overestimation of traveled distance. Because the targets were seen and thus distances perceived immediately, we believe this experiment instead provides evidence about distance estimation, not traveled distance estimation. Of course, the two are intertwined in these kinds of experiments. When expressing the distance estimate via a protocol that involves real or imagined walking, the path integration process that is part of TDE is invoked. However, we speculate the previously seen goal provides a focal point for attention that makes the path integration process somewhat easier and potentially less susceptible to environmental or other distractions than it is in the case of a TDE task.

6.2 Traveled distance estimation in real environments

Sadalla *et al.* [65] evaluated the role of information retrieval in estimating traveled distances. In this study participants walked a 18-meter route consisting of two nine-meter segments perpendicular with each other. One segment contained seven intersections and the other contained eight intersections. The first walk was carried out in a lab. Participants then walked an additional 2.2m segment, and the second walk was carried out in a hallway outside of the lab. After the second walk, participants then were given a sheet of paper with a three-centimeter line representing the 2.2m walk. Participants estimated the distance of their initial walk by drawing another line proportional to the three-centimeter line. Next, they carried an additional task which was either recalling the names of fifteen intersections, or recognizing the names of fifteen intersection from a set of thirty names. Participants wore a special headpiece during the initial walk so that when they looked down, they could only see the one-meter area in front of their feet. Participants were also instructed to keep their gaze down to this one-meter area so that they did not see the whole traveled route instantaneously. The authors found that when the route consisted of fifteen easy-to-remember names, participants gave significantly larger traveled distance estimates compared to when the route consisted of fifteen hard-to-remember names. They also found that, for the recall task, participants with easy-to-remember names accurately recalled many more names than participants from the other condition. For the recognition task, however, no recognition performance difference was found between conditions. Thus, the authors suggested that the process of retrieving route information might influence traveled distance estimation. To further verify this hypothesis, a second experiment was designed in which participants were put in two conditions. In the first condition, participants were given five categories and fifteen intersection names (three names for each category), while the other group did not receive this information. The design and procedure was the same as the first experiment. If the hypothesis holds, we would expect that participants in the first condition would give larger estimates than those in the second condition because the given five categories would facilitate the recall task but not the recognition task. The results of the second experiment clearly showed that it was indeed the case, that participants in the first condition gave much larger estimates than participants in the second condition. Taken altogether, the authors suggested that retrieving route information influences the estimation of route length.

Sadalla *et al.* [63] investigated how the number of turns affects people's estimation of traveled distance. In the first experiment, participants first walked a 200-foot path, then walked a 100-foot path. After the walk, participants were presented with a sheet of paper that had a line on it. There were two points, X and Y, representing the length of the second walk. Starting with X as one endpoint, their task was to mark on the line the second endpoint so that the distance represented the length of the first walk proportionally to the length of the second walk. There were two different routes for the first walk: they had the same length but the one had seven right turns and the other had only two right turns. The route for the second walk was a straight line. The results from the first experiment showed that participants' estimates of the route with seven turns were significantly longer than those of the route with two turns. In the second experiment, participants first walked a 185-foot path, and then were supposed to reproduce that distance on a path with a different number of turns. There were two conditions. In the first condition participants' first walking path had seven turns, and their second walking path had two turns. In the second condition, their first path had two turns and their second path had seven turns. The results showed that participants' second walk was significantly longer when they experienced the seven-turn path first than when they experienced the two-turn path first. Taken together, the results from these two experiments suggested that the number of turns is an important factor in traveled distance estimation.

Sadalla *et al.* [64] investigated the effect of number of intersections along the route in estimating the route length. Two experiments were conducted, the first one in a laboratory and the second one outdoors in a city. In the first experiment, participants first walked a 28-foot path, then walked a five-foot path and were given a sheet of paper that contained a five-centimeter line. The line was to represent the five-foot path and their task was to draw another line to indicate the length of the first walk proportionally to the second walk. There were three types of first path: one with one intersection, one with four intersections and one with seven intersections. Each participant experienced all three types of path and gave estimates of traveled distance after each walk. The results clearly showed that participants' estimates of traveled distance increased as the number of intersections increased, and there was a significant difference between participants' estimates of each type, which indicated that the number of intersections influenced people's estimates of traveled distances. One noticeable thing was that the actual time it took for participants to finish the first walk was the same for all three types; thus, travel time did not seem to be the primary cue in this task. The second experiment was a replica of the first experiment in a real city. Participants first walked one of two roads, then estimated the length of the road by drawing onto a sheet of paper a line proportional to another line which represented the distance between two known intersections. The two roads had equal length (1.7 miles) but different number of intersections (one had six while the other had two). The result of the second experiment again showed that people gave larger estimates for the one with six intersections than the one with two intersections. The authors also noted that in fact the road with six intersections took longer time to walk than the one with two intersections because of the traffic lights, but since the time was not an important factor as shown in Experiment 1, it's probably not an important factor in the second experiment. Therefore the author suggested that the number of intersections is an important factor in traveled distance estimation.

Lee [42] investigated the effect of direction to the city on people's estimates of walking distances. In this study, participants estimated the length of 11 pairs of familiar-to-them walking paths ranging from 0.17 miles to 0.85 miles. Each pair contained one outward-from-the-city path and one inward path. Participants indicated their estimates by marking on a ruler having increments of 0.25 miles up to 2 miles. The results showed that estimates for outward distances were significantly longer than estimates for inward distances. The authors suggested that the observation could be explained by a "valence" hypothesis, which said that the more favorable the route, the shorter it appeared to be. So the destination of the route seems to be an important influence in estimating traveled distance.

Crompton [10] found that estimates of distances up to two miles in a crowded street in Manchester were correlated with the length of time that participants had known the street. They had first year, second year and third year students estimate the walking distance from a fixed location to twenty different places along the road. The students gave out written estimates without looking at a map or actually walking. The author found that on average one mile was estimated as 1.24 miles by first year students, 1.33 miles by second year students, and 1.45 miles by third year students. The author suggested that an explanation for this phenomenon could be that, overtime, the continuous accumulation of detail and richness of the route makes it become longer and longer in people's mind. This suggests that the route content may be an important factor in traveled distance estimation, and that the more details the route has, the longer it might seem to be.

Crompton and Brown [11] investigated the estimation of traveled distance in environments of different scale. In this experiment, participants either walked in Manchester or in Portmeirion - an antique Italianate town where all the buildings are about seven-eighths of normal buildings. After traveling the distance of approximately 0.31 miles, their task was to mark on a ruler the distance they had just traveled (the ruler had increments of 0.1 miles up to 1.5 miles). The results showed that people who walked in Manchester overestimated the distance by about 50% (their average estimate was 0.5 miles), but people who walked in Portmeirion overestimated by almost 200% (their average estimate was 0.91 miles). The author suggested that the differences in the scale of the environment was likely the cause of the difference of people's estimates, and that traveled distance in a small-scaled village environment seems to be much larger than traveled distance in an urban environment.

Ohno [53] conducted an interesting set of experiments investigating people's perception of traveled distance (and underground depth) in the Tokyo subway system. Among their results was the finding that participants estimated traveled distances in wider or more open spaces to be relatively shorter than distances in narrower, more confined spaces.

Berthoz *et al.* [4] examined whether people could reproduce traveled distances by using vestibular cues and body senses only. In this experiment, participants sat on a motorized robot with their heads restrained and with headphones on to block all audio cues. There were two phases. In the encoding phase, participants were passively transported forward by the robot. When the robot came to a complete stop, the testing phase began and participants used a joystick to control the robot to go forward the same distance as they had just traveled. Participants did not have vision during either travel period. There were five distances (2, 4, 6, 8 and 10m) appearing in random order. The results showed that participants estimates of traveled distance were only somewhat shorter than the real distances (about 86%), despite the fact that they did not have any auditory or visual cues. To rule out the possibility that participants used travel time as the main cue to estimate traveled distance, a second experiment was conducted. In the second experiment, the velocity of the robot in the encoding phase was accelerated and decelerated in a way that for all five distances the travel time was approximately the same (16 seconds). Participants from the first experiment participated in the second experiment again, without doing any retraining. The results showed that their estimates were approximately the same as the first experiment (89% of the distances), which suggested that travel time was not the primary cue used in this task. Altogether, the authors suggested that people seemed to underestimate traveled distance, and they could reproduce traveled distances by using vestibular and body-based cues without using any auditory and visual cues.

Glasauer *et al.* [20] investigated the role of travel time in a reproduction task.

In this study, participants first walked a predefined distance (encoding phase), then reproduced the traveled distance (reproduction phase) in three conditions: 1) Control condition in which no mental task was required (Control); 2) Mental task during encoding phase (MTE); 3) Mental task during reproduction phase (MTR). The mental task was counting down by sevens from a three-digit number given to participants at the beginning of the phase. In the first experiment, participants walked on a treadmill in both phases, and the distances were from 3.5 to 14 meters. In the second experiment, participants walked blindfolded in a large open space (100m x 17m). The distances were from 6.5 to 49 meters. The results from both experiments showed that participants' reproduction of traveled distances was fairly accurate in the control condition (103%, estimated distance/actual distance), but underestimated in the MTE condition (76%) and overestimated in the MTR condition (138%). By a series of analysis and computational model testing, the author suggested that participants tried to reproduce the duration of traveled distance in the encoding phase only, and the dual task made it more difficult for them to reproduce the time correctly. Thus, the authors suggested that travel time was an important factor in reproducing traveled distances.

In a more recent study [21], the authors also found that travel time was an important factor in a homing task(walk a pre-defined distance, then turn 180 degrees and walk back to the starting point) and in a blind-walking-to-target task (see a target, then walk to the target with eyes closed).

Campos *et. al.* [7] investigated the role of optic flow and body-based cues in distance estimation in the real world. In this study, participants saw a target (a human) at a distance, then turned 180 degrees and walked with vision a distance equivalent to the distance from self to the target. The optic flow was modified by using spectacle-mounted optical lenses. There were three pairs of lenses: 2.0X (magnification), 1.0X (unaltered) and 0.5X (minification). Each participant participated in two conditions. In the first condition (OM-view), participants wore each of the three pairs of lenses to see the target, then wore the 1.0X lenses during the walking phase. In the second condition (OM-view+walk), participants wore each of the three pairs of lenses to see the target, then wore the same pair of lenses during the walking phase. The distances were 6, 8, 10 and 12m. The author reasoned that if participants used optic flow only, in OM-view+walk condition, for the same distance there would be no difference in response in walking phase (because the optic flow was the same for both viewing and walking). And if participants used body-based cues only, the response for the same distance in two conditions would be the same regardless of the differences in the optic flow between two conditions. Therefore, from the experiment data, the authors could build a model to predict the contribution of optic flow and body-based cues in distance estimation. The results showed that the weight assigned to optic flow was 0.328, and the weight assigned for body-based cues was 0.672, which suggested that the brain gave body-based cues a weight twice as high as the weight assigned for optic flow.

6.2.1 Summary

Altogether, these and other studies have shown that estimation of traveled distance in the real world is influenced by the number of turns or intersections along the routes [63, 64], travel effort [3], travel time [20, 21], environmental features such as route segmentation [1, 2], scale of environments [11], and characteristics of the starting point and the destination [42, 10]. In much of the literature, it is suggested that people underestimate traveled distances in the real environment, and information from body-based cues are more important than information from visual cues. Secondary tasks also seem to have a significant influence on traveled distance estimation, and we speculate that the reason might be mental tasks affect people's estimate of travel time, which in turn affect their estimate of traveled distances.

6.3 Traveled distance estimation in virtual environments

Witmer and Kline [75] were among the first researchers to look at traveled distance estimation in VEs. They examined the effects of motion cues, methods of movement and speed of movement on estimating traveled distances. Participants saw the VE via an HMD and walked on a treadmill. The task was to move a distance (ranging from three to 100 meters), then give a verbal estimate of the traveled distance. Three methods of movement were investigated: joystick, treadmill and passive movement controlled by an experimenter. The speed of travel was either 1.2 mph or 2.4 mph (for treadmill condition, participants were prompted to walk faster or slower if their speed was out of the range +/- 10% of the pre-defined speed).

The result of the study showed that participants underestimated the traveled distance (their verbal estimates were about 67% of the actual distances), and there were no differences between the three methods of movements. The authors suggested that one possible explanation would be that even though people had information from their body-based cues, they also had to focus on responding to the prompt to walk at the right speed. This secondary task would distract them from focusing on the task and hence reduce their accuracy. There was a significant difference in participants' estimates between the two speeds in all three modes of travel, and people traveling with slower speed were significantly more accurate than those traveling with higher speed. The authors suggested that travel time might be responsible for this result, in a sense that participants might equate longer travel times to larger distances, and therefore made larger estimates.

Kearns *et al.* [32] investigated the role of optic flow and body senses in homing tasks in virtual environments. They used a triangle-completion task where participants walked to the first target with eyes open, then turned to see and walked to the second target, also with eyes open. After reaching the second target, they closed their eyes, turned and attempted to return to the starting position. Six types of triangles were investigated in this study. These triangles all had the same length first leg (4.25m), but varied in the second leg's length (2.25m or 4.25m) and the angle between the two legs (60, 90 or 120 degrees). In experiments 1 and 2, joysticks was used to move in the virtual environment. The results of the first two experiments showed that optic flow was an important cue for triangle-completion task, and the optic flow information from the floor texture was more important than the optic flow information from the wall texture. In the third experiment walking was used to move through the virtual environment, and the result showed that people can perform the task with information from optic flow when necessary, but normally rely on the information from body senses whenever it is available.

Popp *et al.* [57] investigated traveled distance perception in large-scale urban areas. The authors wanted to test whether there is a difference between actual walking in real environment and moving by computer mouse in a virtual environment, and whether the richness of surrounding environments is important or not. The real world was the campus of a university, and the virtual world was a model of the same campus projected onto a large curved display system with 180 degree horizontal FOV. To manipulate the richness of surrounding environments, they chose two routes on the campus such that one of them had a lot of trees and bushes on both sides while the other route did not. These two routes were also modeled in the virtual condition. The task was to walk or move 0.31 miles in the real or virtual environment (learning phase), then reproduce the distance they had just moved in the same environment but on a route with different surrounding richness (testing phase). The results showed that the reproduction distances in test phase were significantly larger than the distances in learning phase for both real and virtual environments, and there was no difference in the reproduction distances in test phase between real and virtual environments. However, there was no difference between estimates in testing phase whether participants went from rich- to low-surrounding or from low- to rich-surroundings. Thus, for these particular reproduction tasks, differences between real walking and moving with computer mouse did not seem to be important factors; and the surrounding environments of the route also did not seem to have a strong effect.

Redlick *et al.* [60] wanted to see if optic flow alone is enough to estimate traveled distances accurately. The virtual environment was a virtual corridor with time-varying textured wall and untextured floor and ceiling, and was displayed via an HMD without stereo. For each trial, a target appeared at one of four distances (4, 8, 16 or 32m). When the participant was ready, they pressed a button to make the target disappear and the optic flow begin. They pressed the button again when they thought that they had reached the location of the previously seen target. The optic flow moved with either constant speed (0.4 - 3.2 m/s) or constant acceleration (0.025 - 1.6m/s^2). The results showed that when the optic flow moved with constant speed or with acceleration less than 0.1m/s^2, participants stopped the motion before they reached the targets. The authors suggested that this implied that participants overestimated their traveled distances if their initial distance-to-target perception were correct. E.g. they traveled only 20m, but they believed that they had traveled to a target they thought was 32m away. But when the optic flow moved with acceleration larger than 0.1m/s^2, their estimates of traveled distances were fairly accurate. The authors therefore suggested that humans can use optic flow to estimate traveled distances. However, the errors in estimating traveled distances with constant motion speed or low acceleration implied that people could accurately judge traveled distance only when the appropriate motion information was provided.

Frenz and Lappe [17] tested if people could use optic flow to build up an internal representation of traveled distances, and then estimate them accurately. In this study, the virtual environment was displayed on a large screen, participants sat on a chair adjusted so that they all had the same eyeheight (1.6m), and there was no stereo or motion parallax. The scene was a ground with texture. In the first experiment, participants viewed the moving scene, then the motion stopped, and participants estimated the traveled distance by adjusting a line on the virtual ground so that the distance from that line to another fixed line (1.84m away from participants) was equal to the traveled distance. Traveled distances were from 1.8m o 4.6m. There were three conditions: textured ground plane, dot plane 1 (consisting of 3000 white light points), and dot plane 2 (consisting 150 white light points). The three different textures provided three different levels of optic flow. The authors observed that the dot plane 2 texture seemed to provide too little depth information to be useful and thus decided to provide texture movement during estimation phase as well. There was a control condition in which the textured ground plane was used and (like in the dot plane 2 condition) the scene moved during the estimation part. The results from the first experiment showed that people significantly underestimated traveled distances in all conditions: 49% with textured ground plane, 33% for dot plane 1, 24% for dot plane 2, and 28% for control condition. There was a strong correlation between the traveled distance and the estimate of traveled distance, which indicated that people could distinguish different traveled distances based on optic flow only. There also was a significant difference between people's estimates between the three conditions (basically, more flow yielded worse performance) implying that optic flow information affects people's traveled distance estimates.

The goal of the second experiment was to explain the difference between this first experiment's results and Redlick's results [60], since underestimation was found in this study but overestimation was found in [60]. With the same apparatus as experiment 1, the authors reproduced Redlick's study: participants first saw the interval distance, then the lines disappeared and the motion started, participants then stopped the motion when they thought they traveled the same distance. Two sub-experiments were conducted: in experiment 2A, the distances were the same as in Redlick's study (4 to 32 meters); in experiment 2B, the distances were the same as in the first experiment (1.8 to 4.6 meters). The results showed that people overestimated traveled distances in experiment 2A (slope of the regression line is 1.41), but underestimated traveled distances in experiment 2B (slope of the regression line was 0.64). Because this experiment involves first viewing the target to which participants will walk, we consider this to be more of a distance estimation study than a traveled distance estimation study; the implications for the traveled distance problem are unclear.

The third experiment was to investigate different methods for indicating traveled distances. Traveling was again done via simulated self-motion. Four methods were studied: 1) active reproduction of visual motion: participants traveled a distance, then tried to travel the same distance again; 2) interval matching: participant traveled a distance, then placed a line so that the interval distance between the line and another fixed line was the same as the traveled distance; 3) verbal report in number of eye-heights: participants traveled a distance, then made estimates by indicating how many eye-heights on a scale from one to nine; and 4) blindfolded walking: participants traveled a distance, then tried to walk blindfolded the same distance again. Distances were from 1 to 6.4 meters. The results from the third experiment showed that participants were pretty accurate in the active reproduction condition (slope of regression line was 1.03), but they underestimated in all other three conditions: slopes of the regression line were 0.65 for the interval matching condition, 0.79 for the verbal report condition, and 0.71 for the blindfolded walking condition.

These three experiments together suggested that optic flow provides useful information for estimating traveled distances, and people seem to underestimate short traveled distances in some circumstances.

Frenz *et al.* [18] investigated the importance of depth cues (disparity/motion parallax/figural cues) in estimating traveled distances. In earlier work of theirs [17], the authors found that people underestimated traveled distances by about 20% to 40%, so they wanted to see if adding depth cues to the virtual environment would help people improve their estimates. The virtual environment was displayed on a large screen and there was no head tracking or stereo. In the first experiment, they added motion parallax and pictorial depth cues by adding virtual poles into the scene. In the second experiment they added the depth of field of the view by extending the ground texture from 30m to 100m. In the third experiment, they added stereoscopy. In the fourth experiment they used a fully immersive virtual environment setting with a four-sided CAVE-like setting (three walls and a floor). The results from all four experiments showed that participants still underestimated traveled distances by the same amount (about 20% to 30%), which indicated that adding depth cues did not help people to improve their traveled distance estimates. Based on the results of both studies, the authors concluded that people's mis-estimation of traveled distances does not result from errors in perceiving the depth layout of the scene. They also suggested that the error might come from the fact that people do not have enough experience with self-motion in virtual environments to correctly estimate how far they have traveled.

Mossio *et al.* [47] investigated the contribution of optic flow to traveled distance estimation. A virtual environment (a long roadway with two walls) was displayed in an HMD and eyeheight was fixed at 1.7m. The task was reproduction of traveled distance, which consisted of two phases. In the encoding phase, participants saw the environment move 7, 9 or 12m. The speed of optic flow was constant at 1.2 m/s. In the testing phase, participants saw the environment move and then stopped the movement when they thought that they had traveled the same distance as in the encoding phase. There was a control condition where the speed of optic flow, the virtual environment and display settings remained the same as the encoding phase. In other conditions, elements of the testing phase were manipulated so that they all had some differences from the encoding phase. Dual tasks were introduced for most test phase conditions, including the control. In dual task conditions, while reproducing the distance, participants counted down from a random number between 40 and

60 that appeared on the screen. This was to try to prevent participants from using counting approaches for the reproduction. There was one non-dual-task condition called a reference condition. The results showed:

- The dual task strongly affected about 35% of participants — they overestimated by about 28%, while the rest of participants performed more accurately — they underestimated by about 6%. This suggested that two-third of participants were able to built a good representation of the traveled distance from the visual cues without using any counting strategy. The authors decided to exclude the data from participants who they believe relied on counting.
- Depth cues and texture regularity were not important in traveled distance estimation task. Manipulating depth cues (stereoscopic, motion parallax and perspective) and texture regularity in various ways did not affect the participants' performances. The authors concluded that depth cues and texture regularity had a little impact on people's estimation of traveled distances.
- The velocity profile of the motion mattered significantly. The authors found that the participants could be divided into two groups. One group consisted of people who were velocity independent, which meant they were able to accurately estimate traveled distances regardless of the changes in velocity. The other group consisted of people who were velocity dependent, which meant their estimates were strongly affected when the velocity of visual motion was changed from encoding phase to test phase.

Lappe *et al.* [39] tried to explain the reason Redlick *et al.* [60] reported overestimation of traveled distances, while Frenz and Lappe [17] found underestimation of a similar set of distances. The authors proposed a “leaky path integration” model. In this model, there is a state variable, typically distance from start, that is incremented during stepping but also gets reduced (i.e. leaks) by an amount proportional to its current value. To verify the model, two experiments were designed for the two tasks. In Experiment 1, two conditions were introduced. In the first condition, participants first saw the movement of the virtual hallway for a predefined distance, then adjusted a target in the hallway so that the distance from the participants to the target was the same as the traveled distance. In the second condition, participants first saw the virtual target at a predefined distance, then the target disappeared and the virtual hallway moved until being stopped by the participants when they think they had reached the same location of the target. The virtual hallway was displayed in a five-sided LSID, stereo was presented with shutter glasses, and head tracking was available. Predefined distances were from 2 to 64m, each distance was run with at least two different velocities: 0.5 m/s for distances between 2 and 16 meters, 1 m/s for distances between 2 and 32 meters, 2 m/s for distances between 4 and 32 meters, and 4 m/s for distances between 8 and 64 meters. The results showed that in the first condition, people on average gave an estimate of 0.9m for one meter of traveled distance. In the second condition, participants on average stopped the motion when they had traveled about 0.9m when they saw an object at one meter away. Lappe interpreted these results as indicating underestimation of traveled distance in the first condition, and overestimation of traveled distance in the second condition. From our perspective, however, the second condition is underestimation of distance to target.

The authors claimed that both results could be explained by the leaky path integration model as follows. In the first experiment, participants tried to compute the distance from self to target by integration, and the leak in integration made them put the target at a shorter distance than it should be. On the other hand, in the second experiment, participants tried to compute the remaining distance from self to target, and this time the leak would make them think that they were at the target's location while in fact they were not there yet. Thus, by redefining the state variable based on the task (distance from start or distance to target), the leaky path integration model can explain both underestimation and overestimation results found in traveled distance experiments. To further verify the model, a second experiment was designed with the hypothesis that if the leak in integration in the second experiment made people think that they were closer to the target than they actually were, then if participants were stopped part way and were asked to adjust the target so that it appeared in the same location, the target's new location would be over-proportionally decreased. The result from the second experiment supported the hypothesis, which suggested that the leaky path integration model is indeed a good model to explain and anticipate people's traveled distance estimates and distance estimates.

6.3.1 Summary

Overall, there has not yet been a great deal of research on traveled distance estimation in virtual environments. Results from the studies above suggest that people underestimate traveled distances in VEs. When a joystick is used to move in

VEs, optic flow is one of the most important cues [47, 60, 17, 18]. People integrate the amount of optic flow information that has passed to estimate distance traveled, and if we manipulate the optic flow information (by, e.g., changing the flow speed or reducing the quality of optic flow information) we can change people's estimates. And, people seem to use optic flow information from ground texture more than other surrounding texture. For example, Kearns *et al.* [32] showed that when only the wall optic flow was available, participants' estimates of traveled distances were significantly more variable than when only the floor optic flow was available. Depth cues such as stereoscopy, motion parallax, pictorial depth cues and perspective seem not to be important [18, 47]. However, when walking is used for movement in virtual environment, information from body senses (e.g. proprioceptive, vestibular and other movement-specific information) seems to dominate optic flow information [32, 7]. Lappe *et al.* [39] tried to explain the mis-estimation of traveled distances in virtual environments by the "leaky path integration" model. Their recent work also showed that the model can be applied in real environments [37, 38], and can be used to explain a pattern of underestimation of beeline distances after traveling a curvy path (longer curvy paths yield larger beeline underestimates than similarly shaped shorter curvy paths) [40].

CHAPTER 7
COMPARISON OF TRAVELED DISTANCE ESTIMATION IN VIRTUAL AND REAL ENVIRONMENTS

As stated in the previous chapter, there has not been much research comparing estimates of distances traveled in virtual and real environments. In this chapter, we present one of the first studies to directly compare estimates between virtual and real environments. Three modes of travel were studied: simulated, passive and active motion.

7.1 Motivation and goals

Research studies have shown that people underestimate traveled distances in both virtual and real environments. Some of the most important factors for estimating traveled distances are travel time, vision-based cues such as optic flow, and body-based cues such as vestibular and proprioception. Secondary mental tasks also influence how people estimate traveled time and distances.

However, there have been no direct comparisons of people's traveled distance estimates between virtual and real environments. Popp *et al.* [57] did a very first study comparing walking in a real environment and moving by a mouse in a virtual replica of the real environment, and found no significant difference in participants' estimates between the two environments.

We conducted two experiments to directly compare traveled distance estimate between real and virtual environments. In both experiments, participants first experienced motion in either real or virtual environment, then made estimates in a common

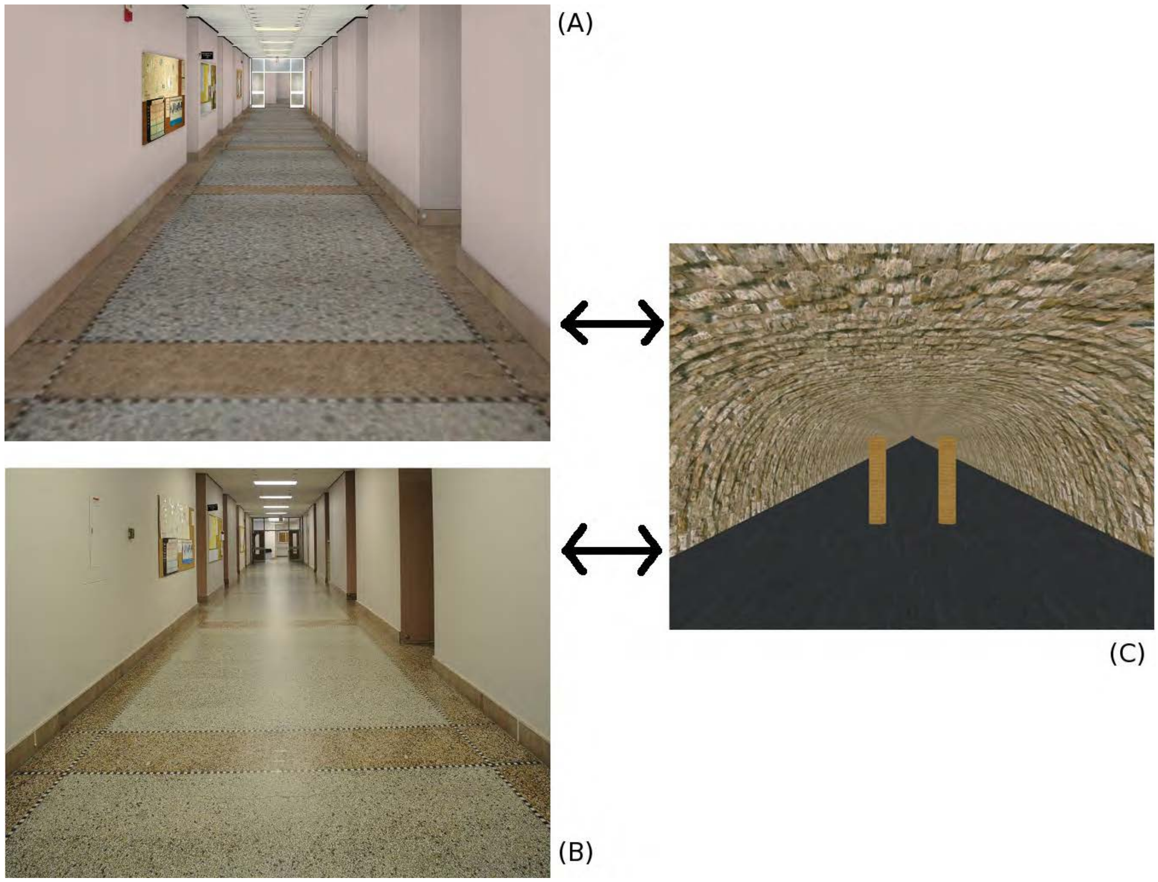


Figure 7.1: The virtual hallway (A), the real hallway (B) and the virtual tunnel with poles at 9m (C).

virtual environment.

7.2 Experiment 7a: Simulated and passive motion

In this experiment, participants either 1) were pushed through a real hallway; or 2) were pushed through a virtual hallway that was a high fidelity representation of the real hallway; or 3) experienced a simulated self-motion in the virtual hallway. Then they made their estimates of the traveled distance in another virtual environment, a virtual tunnel (see Figure 7.1).

7.2.1 Apparatus and materials

We used a head-mounted display (HMD) system to display the virtual environments. The nVIS nVisor ST HMD contains two small LCOS displays, each with resolution of 1280 x 1024 pixels. The field of view is approximately 60 degrees diagonal (40.5 degrees vertical and 49.5 degrees horizontal). An Intersense Vistracker IS-1200 6 DOF optical tracker was mounted on the back of the HMD to measure subjects' position and orientation in the hallway. A black cloth was used to block out light around the sides and back of the HMD and a black piece of foam was attached underneath the HMD lenses to prevent participants from seeing the floor or their feet.

We also used a height-adjustable and rollable chair to move participants through the environments.

7.2.2 Design and procedure

The experiment consisted of two practice trials followed by ten test trials. The whole session lasted an average of 20 minutes. The practice trials were used so that participants were familiar with the task and our instructions.

Each trial consisted of two phases. In the first phase, the participant experienced a movement through the virtual or real hallway. The first phase ended when the movement stopped. In the second phase, the participant was first shown an empty virtual tunnel. After a few seconds, a pair of poles appeared at a random distance in front of her. Then, she was instructed to estimate her phase 1 traveled distance by using a Wiimote D-pad to position the poles. In particular, she was told to move the poles to the location she believed was the same distance from herself as the distance she had just moved. When she was satisfied with the poles' location, she said "I'm done", then an experimenter pressed a button to record her estimates, switched her back to the hallway, and a new trial started. Participants wore the HMD in both phases.

Distances of 9m and 15m were used in practice trials. For the ten test trials, two sets of five randomized ordered distances (6m, 9m, 12m, 15m, and 18m) were used. The poles appeared at a random distance in the range of one-third to five-third of the true distance (e.g. for the distance 15m, the two poles appeared at a random distance in the range from 5m to 25m).

7.2.3 Experimental conditions

There were two passive and one simulated motion conditions: Real Pushing (RealPush), Virtual Pushing (VirtualPush) and Vision Only (VisionOnly). In RealPush condition, phase 1's environment was the real hallway, whereas in VirtualPush and VisionOnly conditions, phase 1's environment was the virtual hallway. In all three conditions, phase 2's environment was the virtual tunnel.

In the two pushing conditions, participants sat on a chair. The chair was adjusted so that their eye heights were the same as their actual eye heights (in practice, the chair had a max height of 0.85m, so for some very tall participants, sitting on the chair did lower their eye heights a bit). An experimenter pushed the chair at the speed of normal walking (about 1.1m/s). In the VisionOnly condition, the optic flow was constantly accelerated from 0.0m/s to 1.1m/s over the first 0.69 seconds of travel, then stayed at the speed of 1.1m/s, and then was constantly decelerated from

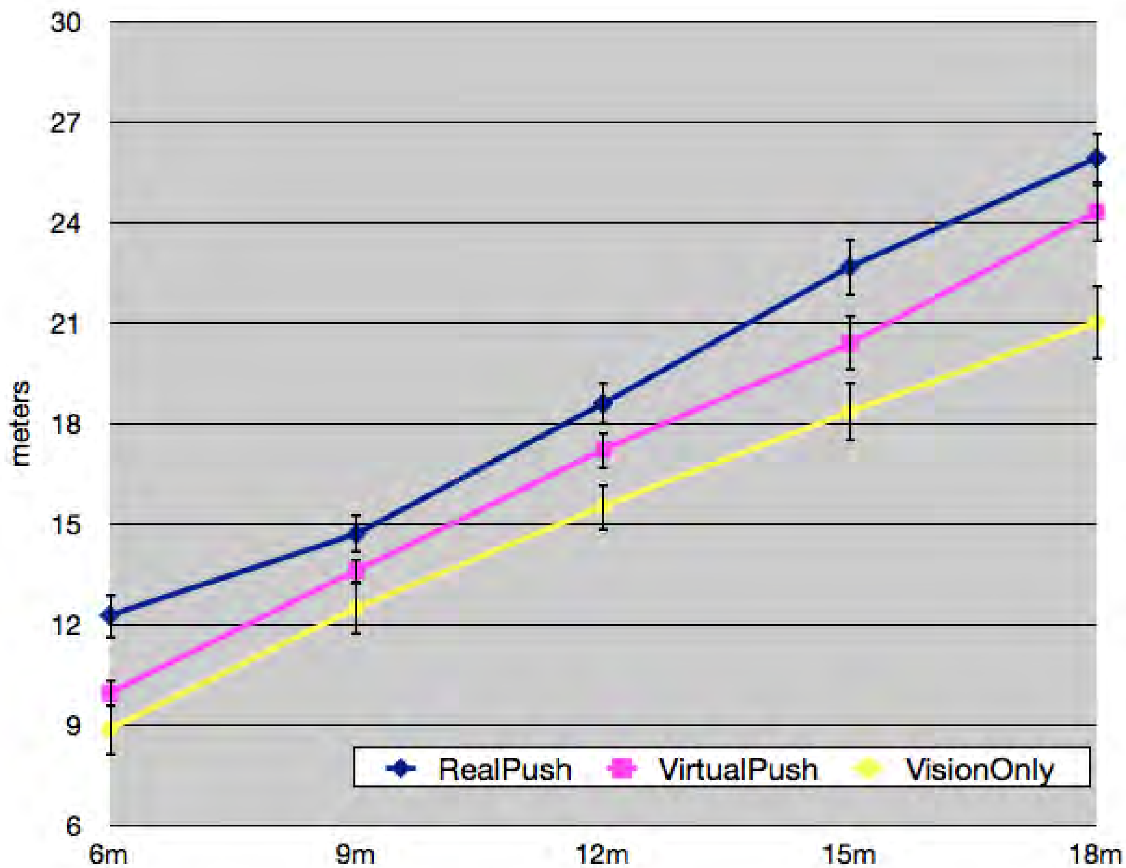


Figure 7.2: Mean estimates of three conditions in Experiment 7a.

1.1m/s to 0.0m/s over the last 0.69 seconds of travel. The total time was computed so that the predefined movement distance was achieved.

7.2.4 Results and discussion

Figure 7.2 shows the means of estimated distances, and Figure 7.3 shows the percentage of the means of estimated distances over the true distance for each of the five distances in all three conditions. From the figure, we can see that participants overestimated distances in all three conditions. To determine the significance, we divided an estimated distance by the true distance to get the estimate score, then

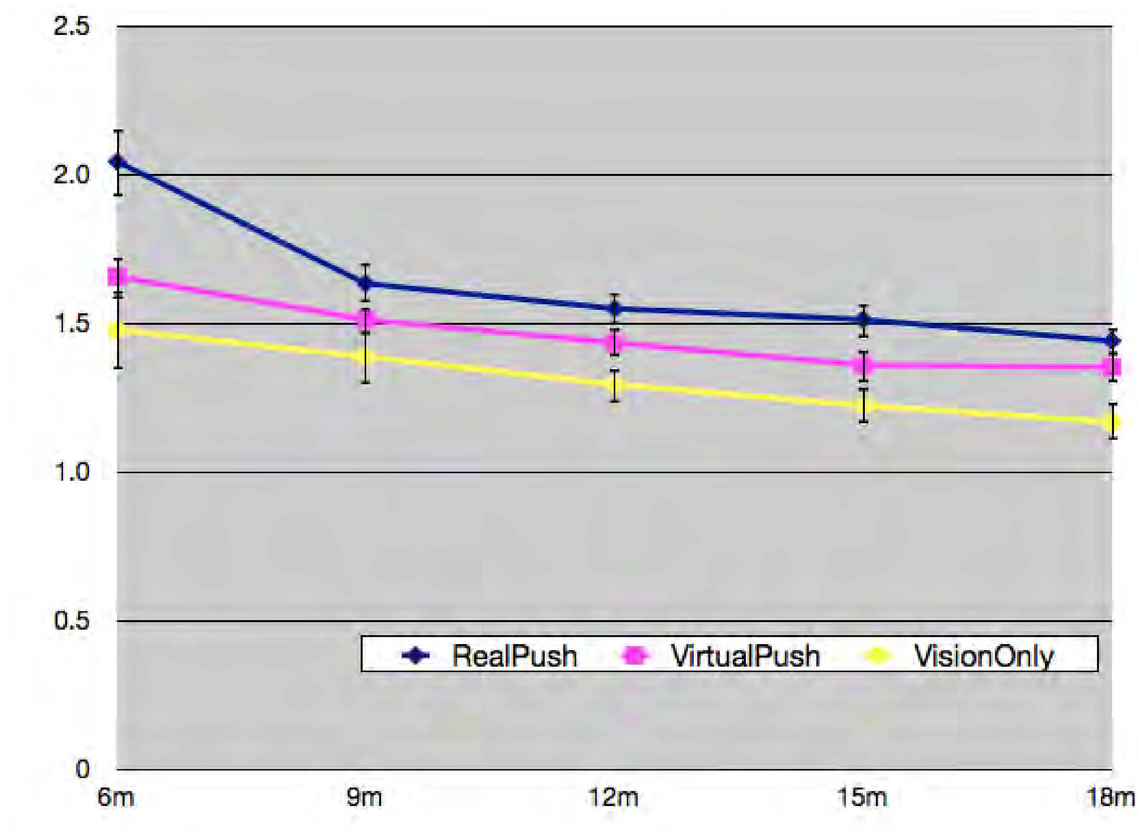


Figure 7.3: Percentage of mean estimates of three conditions in Experiment 7a.

averaged ten estimate scores to yield an overall score for each person. We then used separate one-sample t-tests to compare the overall scores in each condition to 1, the value expected if the estimates were correct. The scores for all three conditions differed significantly from 1, as shown in the Table 7.1.

This overestimation makes some sense. If people were 100% accurate in judging traveled distances, their estimates using this protocol should be overestimates because we know that people underestimate distances in VE; when the participant made a judgment in the second phase, she placed the poles too far away because she perceived them closer than they actually were. For example, if the participant

Table 7.1: Mean score and t-test result for all three conditions in Experiment 7a.

Condition	**Mean**	**t-test result**
RealPush	1.63 ($SD = 0.36$)	$t(47) = 12.20$, $p < .001$
VirtualPush	1.46 ($SD = 0.29$)	$t(51) = 11.37$, $p < .001$
VisionOnly	1.31 ($SD = 0.22$)	$t(19) = 6.33$, $p < .001$

believed that she had traveled 9m, she might place the poles at 12m because poles at 12m away in virtual environments seem to be 9m away. On the other hand, if people greatly underestimate traveled distances, their estimates using this protocol might end up being smaller than or equal to the actual distance, and if they overestimate traveled distances, their estimates using this protocol might end up being substantially overestimated. In Chapter 4, we used the same hallway for the distance estimation in the adaptation phase, so we can informally use the result of the first adaptation trial as a baseline for distance estimation accuracy with no feedback in the virtual tunnel corresponds to the phase 2's task of this study. The result of the first trial in Chapter 4 shows that participants underestimated distances from 30% to 40%. This suggests that participants in this experiment were likely to "overestimate" traveled distances by 40% - 60%. This is indeed about the range of overestimation we see here. Thus it is unclear from this experiment how accurate people's estimates were. The data is consistent with accurate estimates, but could also be consistent with modest under or over estimates.

Our main focus was not on absolute accuracy of travel distance estimates, but on whether there is any difference between people's estimates in real and virtual environment. So we ran an one-way ANOVA on the percentage scores of the three conditions, and found that there was a significant difference among the three conditions $F(2,119) = 8.54$, $p < 0.001$. In additional, Tukey's HSD Test showed that RealPush estimates ($M = 1.63$, $SD = 0.36$) was significantly larger than VisionOnly estimates ($M = 1.31$, $SD = 0.22$), and there was no significant difference between the RealPush ($M = 1.63$, $SD = 0.36$) and VirtualPush ($M = 1.46$, $SD = 0.29$), and between the VirtualPush ($M = 1.46$, $SD = 0.29$) and VisionOnly ($M = 1.31$, $SD = 0.22$) conditions. This implies that people pushed through the real hallway made larger estimates than people experiencing the simulated self-movement in the virtual hallway.

The fact that people's estimates in the RealPush condition were significantly higher than in VisionOnly condition, and that VirtualPush estimates were also higher (though non-significant) than the VisionOnly estimates suggests that vestibular information from the pushing experience has an important role in estimating traveled distances. RealPush estimates were higher than VirtualPush estimates (although not significantly). One possible explanation is that VEs are often perceived as smaller than they actually are, so the virtual hallway might look smaller than the real hallway, and hence people might feel they traveled less in the virtual hallway than in the real hallway.

One interesting fact is that the travel time was approximately the same for all three conditions, but people's estimates still differed among the three conditions, which suggests that travel time is not the sole factor used to make estimates when people passively move through the environment.

Differences between RealPush versus VirtualPush, and VirtualPush versus VisionOnly were not significant. One factor that could have contributed to making differences difficult to detect is that participants saw the real hallway before putting the HMD on. This might have "grounded" them and lessened the effects.

7.3 Experiment 7b: Sighted and blindfolded walking

In the first experiment, participants did not actively move through the environments. Campos *et al.* [7] showed that humans brain use a weighted combination of body-based cues and optic flow, and the weight assigned for body-based cues is twice as high as the weight assigned for optic flow cues. In another study, Ruddle *et al.* [62] showed that body-based information (gained via actual walking and turning) improved participants' performance significantly in navigation tasks in VEs.

So we conducted the second experiment which was similar to the first experiment, except that people actively walked in the first phase. We wanted to see how actual walking affected the traveled distance estimation in both virtual and real environments.

7.3.1 Apparatus and materials

The same HMD and tracking system were used as the first experiment.

7.3.2 Design and procedure

The design and procedure were the same as the first experiment.

7.3.3 Experimental conditions

There were three conditions: 1) Real Walking (RealWalk): participants saw the real hallway through the lenses of the HMD in the first phase; 2) Virtual Walking (VirtualWalk): participants saw the virtual hallway in the first phase; and 3) Blindfolded Walking (BlindWalk): participants wore an HMD but nothing was shown on screen in phase 1 and participants were told to keep their eyes closed.

In all three conditions, participants walked a pre-defined distance in the first phase, and then made estimates in the virtual tunnel. In order to stop the participant at a pre-defined distance, a string was attached to a belt around the participant's waist, and an experimenter held the string in place where the participant started walking, and said "Stop" when the pre-defined distance was reached (in practice, the experimenter said "Stop" just before the distance was reached, so that subject could stop just when the string was fully extended and didn't get a strong jerk).

In the first two conditions, participants walked with their eyes opened, whereas in the BlindWalk condition, participants walked with their eyes closed.

7.3.4 Results and discussion

Figure 7.4 shows the means of estimated distances, and Figure 7.5 shows the percentage of the means of estimated distances over the true distance for each of the five distances in all three conditions. Again, we see that participants overestimated distances in all three conditions, and the amount of overestimation was again in the same 40% to 60% range discussed in Experiment 7a. One-sample t-tests again confirmed that participants significantly overestimated all distances (see Table 7.2).

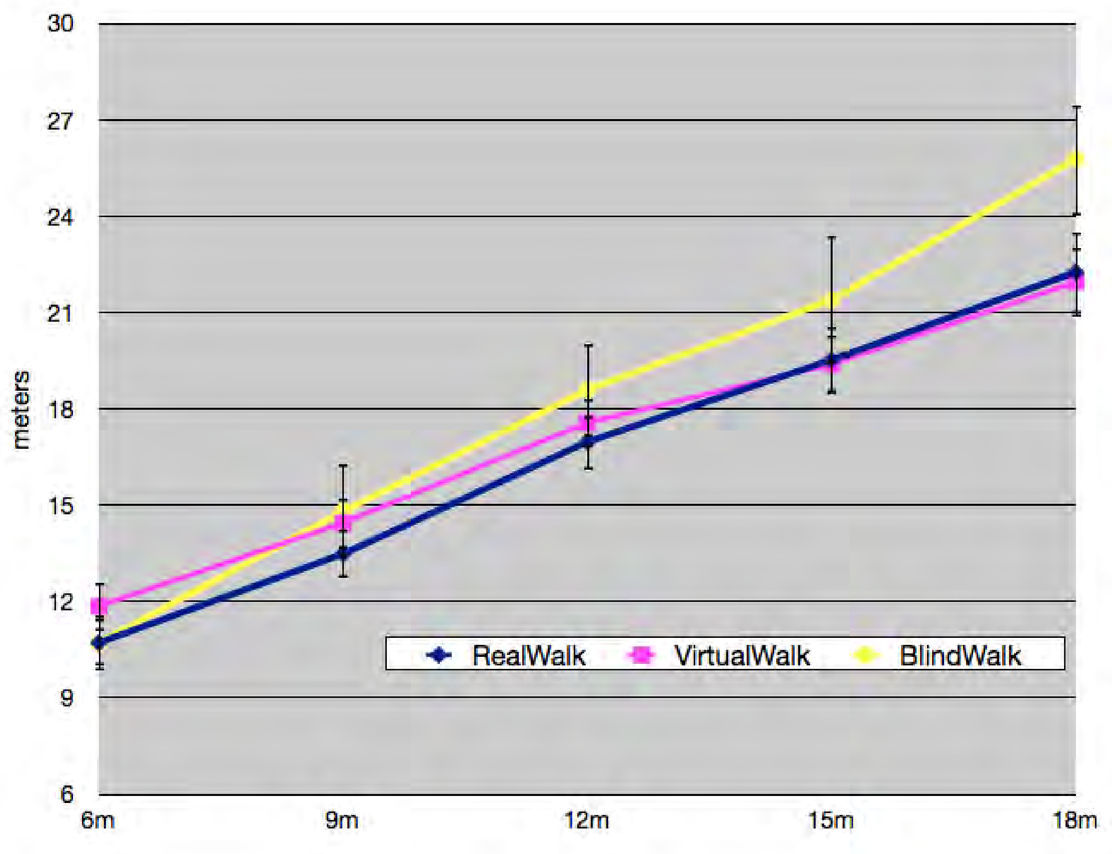


Figure 7.4: Mean estimates of three conditions in Experiment 7b.

To determine if there were significant differences between the three conditions, we ran a one-way ANOVA on the percentage scores of the three conditions, and found that there was no significant difference among the three conditions $F(2, 69) = 0.48$, $p = 0.62$ (ns). This result differed from the result of the first experiment. One possible explanation is that because participants had information from walking, and walking cues are much stronger than vision cues [7, 62], their estimates were more accurate and less varied.

One notable result is that estimates in VirtualWalk condition were larger than

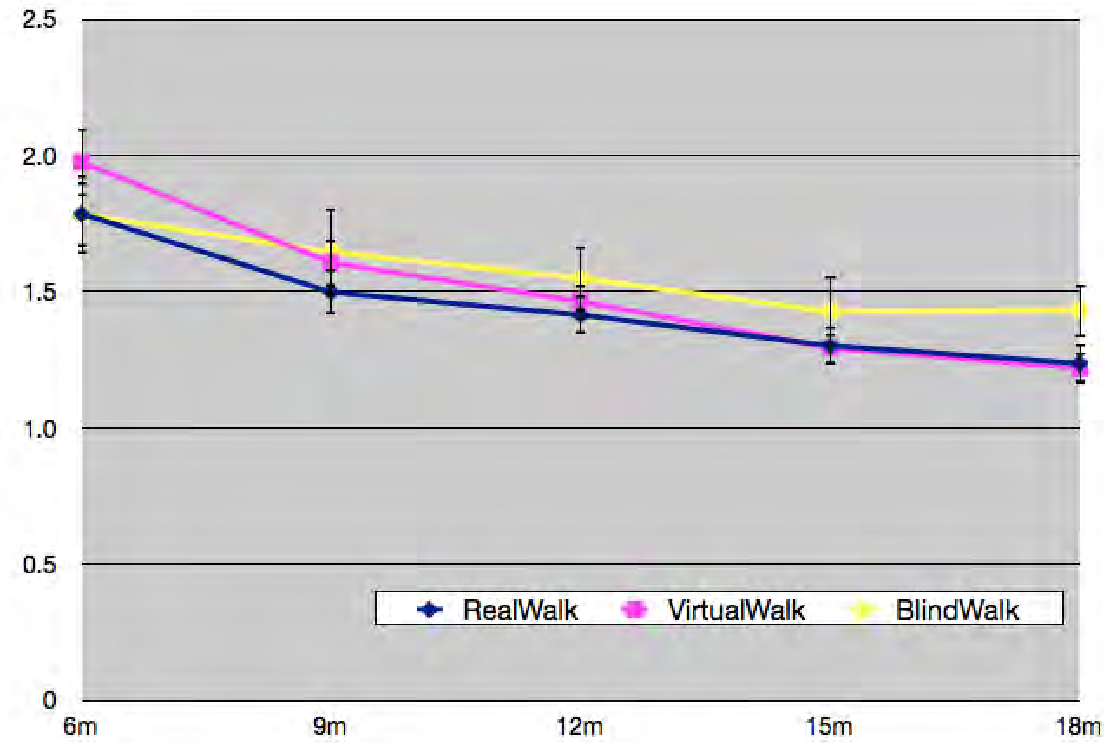


Figure 7.5: Percentage of mean estimates of three conditions in Experiment 7b.

those in RealWalk condition (although it is not significant). This conflicts with the result of the first experiment, in which estimates in VirtualPush condition were smaller than those in RealPush condition. We observe that even though the virtual environment was very realistic and the tracker was very responsive, people were still nervous when walking in the virtual hallway and they walked much slower than people in the RealWalk condition. A t-test analysis of the walking time show that participants walked significantly slower in the VirtualWalk condition ($M = 16.94$, $SD = 1.21$) than the RealWalk condition ($M = 13.58$, $SD = 2.25$), $t(50) = 3.78$, $p = 0.0016$. Since it took them longer to walk the same distance, they might have thought that

Table 7.2: Mean score and t-test result for all three conditions in Experiment 7b.

Condition	**Mean**	**t-test result**
RealWalk	1.44 ($SD = 0.35$)	$t(25) = 6.43$, $p < .001$
VirtualWalk	1.51 ($SD = 0.35$)	$t(25) = 7.54$, $p < .001$
BlindWalk	1.56 ($SD = 0.51$)	$t(19) = 4.95$, $p < .001$

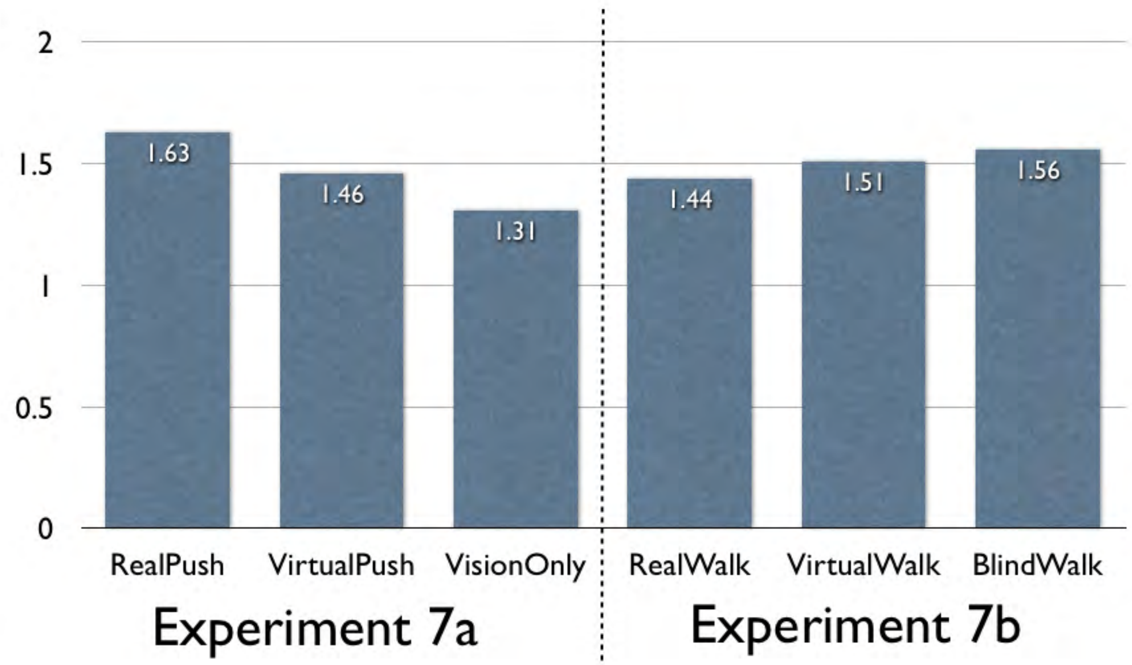


Figure 7.6: Percentage of mean estimates of all six conditions of the two experiments.

the distance they covered was larger than it actually was. This suggests that travel time and travel effort might play an important role in estimating traveled distances when walking is used to move through the environments.

7.4 General discussion and conclusions

The primary goal of this experiment was to compare traveled distance estimation between virtual and real environments, with three mode of travel: simulated self-motion, passive and active movement. We found that there was a significant difference between traveled distance estimates between being pushed through a real environment versus experiencing simulated self-movement through a virtual environment. There were no significant differences between seeing a real environment versus seeing a virtual environment versus having no vision when participants actively walked through the environments.

The findings in this study confirm earlier results of [4, 32, 60, 17, 47] which showed that vestibular and optic flow are quite important in estimating traveled distances when people don't physically move through the environment. But when walking is used as the mean of travel, body senses seem to dominate other cues such as optic flow.

Our results also suggest that travel time and travel effort could play important roles in estimating traveled distances when walking is used.

Again, the focus of this experiment was to compare estimates of distances traveled in real and in virtual environments. It was not designed to carefully assess the absolute accuracy of the estimates. But it is, of course, interesting to consider what the data might tell us about participants' accuracy. Overall, in raw numbers, the estimates in all conditions were substantially higher than the traveled distances (see Figure 7.6). But, as detailed in Section 7.2.4, participants made these using a distance-estimation-based pole-placement task that we know is subject a fairly large error; e.g. to express a distance of 10m participants will typically place the targets 13-14m away. In our view, then, the data from all six conditions of the two experiments, ranging from 1.31 to 1.63 percentage estimate ratios, are consistent with participants' actually having a fairly accurate sense of their traveled distances. In other words, the "overestimation" seems primarily due to large distance error inherent in the measurement protocol used in the experiment.

One other result of our experiment is that short distances were overestimated more than long distances in both experiments. One possible explanation is that because participants had a small FOV, they might not have paid attention to the first three to four meters immediately in front of them; this "missing" segment could contribute a constant value to all errors.

In conclusion, this was one of the first studies to directly compare traveled distance estimates in virtual and real environments, using three modes of travel: simulated self-motion, passive movement via pushing, and active movement via walking. In particular, the study:

- Demonstrated a significant difference in traveled distance estimates made by participants who were pushed through a real environment and participants who experienced simulated self-movement through a virtual environment.
- Provided additional evidence that body senses are stronger cues than vision.
- Suggested that traveled distance estimates are reasonably accurate (when the DE-based protocol error is "subtracted"), although confirmation will require further study.

Finally, this study also highlighted the difficulty of designing a good protocol for expressing traveled distance estimates. In a pilot study, we tried a numerical protocol: after traveling a distance, participants indicated their estimates in number of feet. This protocol did not work well. Females' estimates were substantially lower than males' estimates, and when asked how they estimated at the end of the study, many participants reported that they simply converted one step to one foot and then made the estimate equal to the number of steps taken. The current protocol is still challenging for participants because the test environment is somewhat abstract and unfamiliar. Most problematic, though, is that it requires participants to make an implicit distance estimate. We know people underestimate distances in VEs but we don't have a precise measure of the error. This makes conclusions about the absolute accuracy of participants' traveled distance estimates difficult.

CHAPTER 8
EFFECTS OF SCENE DENSITY AND RICHNESS ON TRAVELED DISTANCE ESTIMATION IN VIRTUAL ENVIRONMENTS: EXPERIMENT 1

In this chapter, we examined a different aspect of the problem of estimating traveled distance. In particular, we presented an experiment examining the effects of scene density and richness on people's estimates of traveled distance. Participants in this study first experienced a simulated self-motion in one of two different virtual environments, then were asked to reproduce the distance via walking in another virtual environment.

This chapter is a revised version of work initially published as [48].

8.1 Motivation and goals

As discussed in Chapter 6, previous work has shown that estimation of traveled distance is influenced by many factors, including the number of turns or intersections along the routes [63, 64], travel effort [3], travel time [20, 21], route segmentation [1, 2], scale of environments [11], characteristics of the starting point and the destination [42, 10], and optic flow [7, 47, 60, 17, 18]. Along similar lines, a recent study by Raghubir *et al.* [59] and Van De Ven *et al.* [71] found that people perceive trips from one place to home to take less time than a trip in the opposite direction. From some of these studies, it appears that the nature and density of nearby ambient features could play a role in estimating traveled distances in virtual environments.

The goal of the experiment reported here was to directly test whether scene

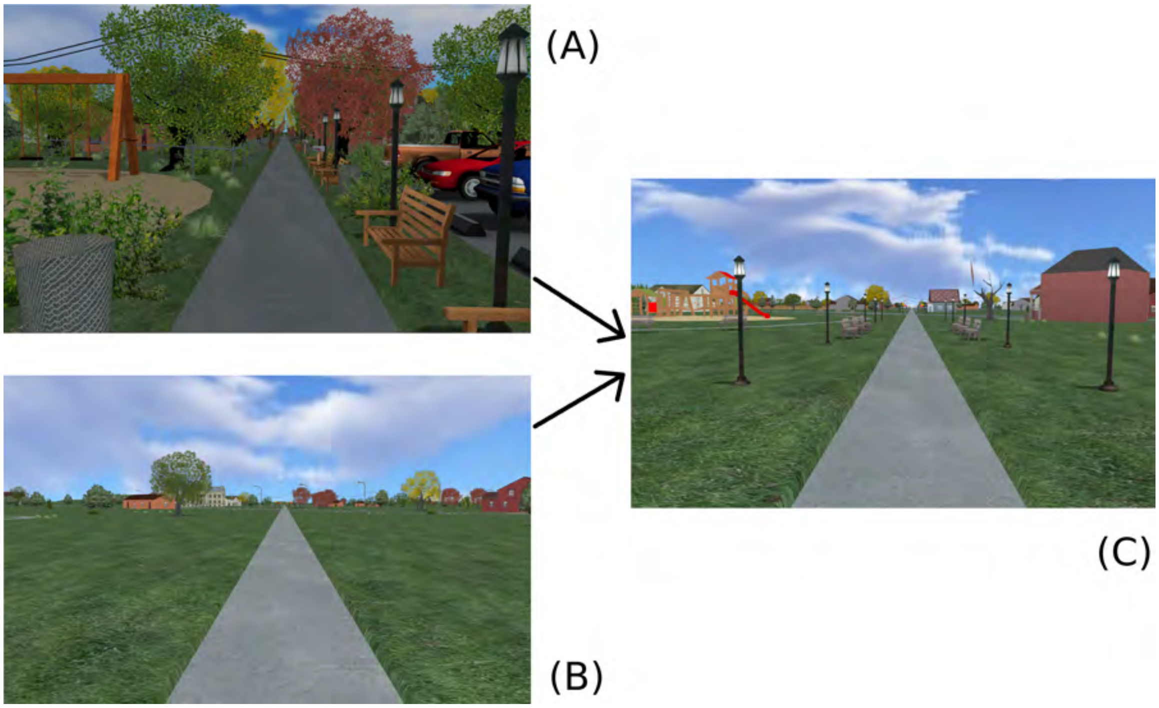


Figure 8.1: The feature-dense environment (A), the feature-sparse environment (B), and the neutral environment (C).

feature density and richness affect estimates of travel distances in VEs. More specifically, we test whether estimates made by people who travel in a feature-rich environment differ from those made by people who travel the same distance in a sparser environment.

8.2 Design and procedure

8.2.1 Participants

Twenty-eight Vietnamese undergraduates (16 females and 12 males) participated in the study. They were English, Mathematics and, Electrical Engineering majors at Hanoi University of Science and Technology. None of them was familiar with the building where we conducted the experiment. Data from three additional participants was dropped because these participants did not seem to understand the task well enough. Grubb's outlier tests also confirmed that their estimates were outliers.

8.2.2 Apparatus and materials

We used a head-mounted display (HMD) system to display the virtual environments. The nVIS nVisor ST HMD contains two small LCOS displays, each with resolution of 1280 x 1024 pixels. The field of view is approximately 60 degrees diagonal (40.5 degrees vertical and 49.5 degrees horizontal). An Intersense Vistracker IS-1200 6 DOF optical tracker was mounted on the back of the HMD to measure subjects' position and orientation in the hallway. A black cloth was used to block out light around the sides and back of the HMD and a black piece of foam was attached underneath the HMD lenses to prevent participants from seeing the floor or their feet.

8.2.3 Procedure

The experiment was carried out in a long hallway at Hanoi University of Science and Technology. Participants could be tracked accurately for walks of up to 110m in length (see Figure 8.2).

Before the experiment started, the participant adjusted the HMD so that each screen was centered on the corresponding eye. The HMD calibration procedure was similar to the one used in Chapter 3's experiments.

Then the participant was told to close her eyes and an experimenter would initialize the simulation. After being directed to open their eyes, the participant saw an egocentric view looking down a long straight sidewalk in a virtual town. The participant was encouraged to look around – up, down, left, and right – to get a feel

Figure 8.2: Participant wearing HMD in the Hanoi University of Science and Technology hallway.

for the VE and to know that she could move freely.

Next, the participant was told that she would see a simulated self movement in the VE (phase 1), and would afterwards be asked to express her estimate of the distance traveled by trying to reproduce that distance via physical walking (phase 2). The simulated self movement speed was 1.1m/s, but the participants were only told that the speed was similar to normal walking speed. We chose 1.1m/s because it was the average observed walking speed of HMD-wearing subjects in prior experiments in our lab.

The simulated self movement covered a distance of 65m. After the self-motion in phase 1 stopped, the participant was asked to close her eyes and the experimenter initialized a new simulation in a different virtual environment to start phase 2. The waiting time was approximately 30 seconds. In phase 2, the participant was asked to walk with eyes opened until she believed she had covered the same distance as in phase 1. Overall, participants seemed comfortable walking with their eyes open while wearing the HMD in phase 2; they walked straight without additional assistance. Each participant was given only one trial. The reason for having only one trial was that if there were multiple trials, participants might just use a counting strategy without paying attention to the surrounding environment after the first trial.

8.2.4 Experimental conditions

There were two conditions. In the Dense condition, the participant experienced phase 1 in a feature-dense environment containing numerous relatively interesting nearby objects (see Figure 8.1A), and then made their traveled distance estimate in phase 2 in a neutral environment (see Figure 8.1C). In the Sparse condition, the participant experienced phase 1 in a much sparser environment (see Figure 8.1B), and then made their traveled distance estimate in phase 2 in the neutral environment. A between-subject design was used in this study.

8.3 Results and discussion

Figure 8.3 shows the mean estimates for the two conditions. Participants' estimates were higher in the Sparse condition (M = 60.40, SD = 4.09) than in the Dense condition (M = 46.39, SD = 3.31). To determine whether the difference is significant, we used an unpaired t-test. The analysis shows that there is a significant difference between the two conditions, $t(26) = 2.69$, $p = 0.01$. To compare the

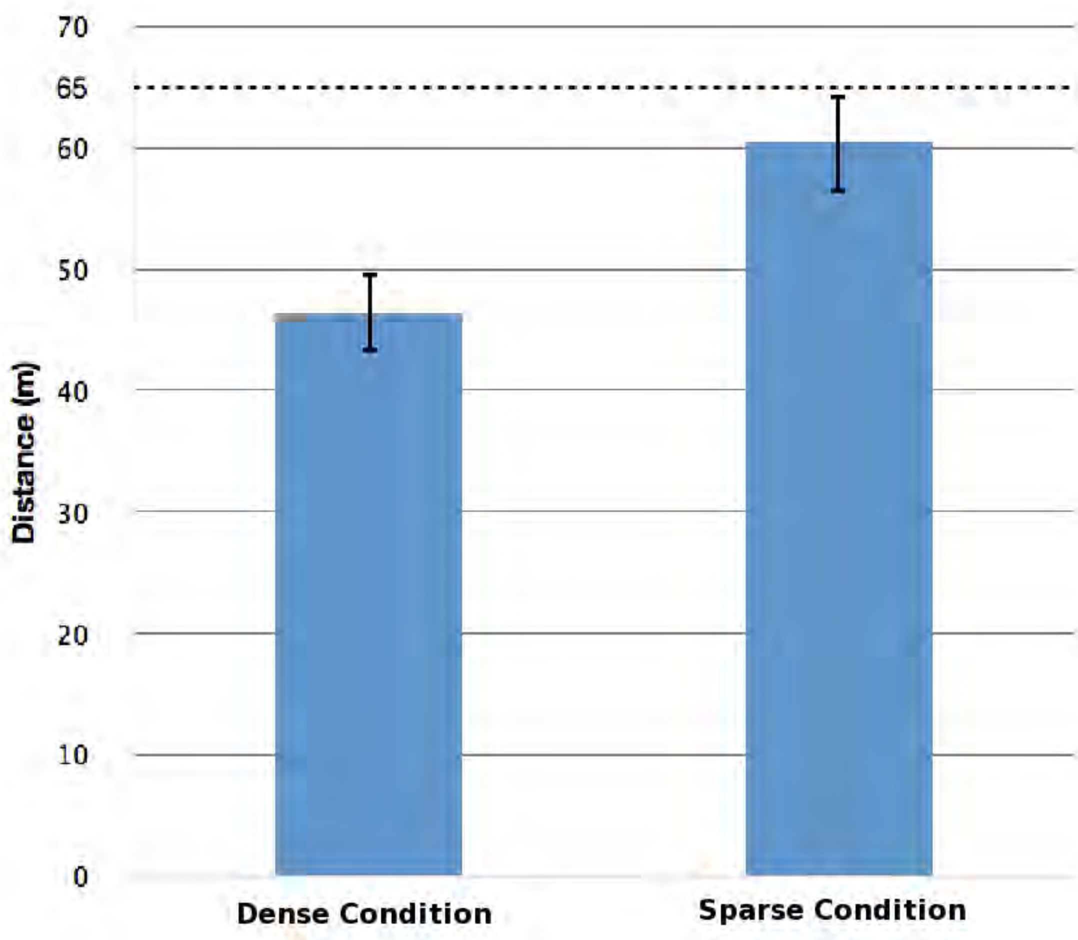


Figure 8.3: Average traveled distance estimates, in meters, for the Dense condition (feature-dense environment) and the Sparse condition (feature-sparse environment). Actual simulated self-motion distance was 65m and is represented by the dashed line.

estimates to the actual simulated travel distance of 65m, we divided the estimates in each condition by 65 and compared the percentages to 100% using one-sample t-tests. Results indicated that the Dense condition's subjects significantly undershot the distance, with average estimates only 71% of the actual 65m ($M = 0.71$, $SD = 0.20$, $t(14) = 5.62$, $p < 0.0001$). On the other hand, the estimates of subjects in the Sparse condition did not differ significantly from the actual distance ($M = 0.93$, $SD = 0.23$, $t(12) = 1.13$, $p = 0.28$).

The results of this experiment suggest that environmental feature density may affect judgments of traveled distance. In particular, distances traveled in environments dense with nearby features may seem shorter than in sparser environments.

As mentioned in the introduction, prior work has shown that many things can influence estimates of traveled distances. Major "segmenting" route features such as intersections and turns have well-established effects [63, 64]. But, to our knowledge, the experiment reported in this chapter provides some of the first evidence of an effect due to a basic ambient feature density. These initial results are intriguing but additional investigation is required to understand the underlying cause of the effect.

As detailed in Chapter 6, Glasauer *et al.* [20] showed that when participants' minds were occupied with secondary mental tasks, their estimates of traveled distances became shorter. A similar explanation is consistent with our results. In the feature-dense environment, people might pay more attention to the details of the environment, occupying their minds and shortening their estimates. This can also provide an alternative explanation for Crompton's finding [10] in which fourth year students' estimates route-length estimates were longer than those of first and second year students. Crompton suggested that (in accordance with the feature accumulation hypothesis), fourth year students over time took in more and more features of the route, making it seem longer. An alternative explanation, consistent with our results, is that the first year students found the not-very-familiar route more engaging; their occupied minds "lost track of time", resulting in shortened estimates.

Our result is not obviously consistent with the findings in Crompton and Brown [11], in which distances traveled in the feature-rich Portmeirion were judged to be far longer than the same distance traveled in Manchester. One potentially important factor in their result is that, after walking in Portmeirion or Manchester, the experimenters showed participants a map of the route they had just traveled and asked for their estimates. Participants clearly saw that they had traveled the whole Portmeirion town, but only a part of Manchester city. Given the potential to apply different scales to the city and town maps, and even different expectations for normal travels speeds, it is not entirely clear that the feature-richness of Portmeirion was the root of the long estimates.

Another possible explanation for our own results is that estimates in the second condition are more accurate than those in the first condition because the testing environment is more similar to the second condition's phase 1 environment. It is true that the "neutral" testing environment looks somewhat more like the feature-sparse environment than the feature-dense one. Future experiments should thoroughly examine the relationship between the treatment and test environment, and also assess the contributing roles played by optic flow versus feature density and salience. It is known, for instance, that people (and animals) use optic flow as a significant factor in estimating traveled distances [7, 47, 60, 17, 18, 15], and in our experiment, the optic flow is substantially different between the feature-dense and feature-sparse scenes. But the kinds of nearby features and "interesting-ness" of those features also differ between scenes.

In summary, this study is one of the first experiments to demonstrate an effect of the basic ambient feature density on traveled distance estimation in virtual environments. Participants judged simulated self-movement over the distance of 65m in a feature-dense environment to be significantly shorter than the same movement in a feature-sparse environment. The following chapter, Chapter 9, presents a follow-up experiment with more conditions, hoping to build upon this initial result by testing whether initial movements in three different environments — feature-dense, feature-neutral, and feature-sparse — yield three different estimate levels. We eventually would like to be able to develop a clearer computational notion of feature density; it would be interesting, for instance, to be able to automatically generate scenes that meet a designer's "feeling of size" goals.

CHAPTER 9
EFFECTS OF SCENE DENSITY AND RICHNESS ON TRAVELED DISTANCE ESTIMATION IN VIRTUAL ENVIRONMENTS: EXPERIMENT 2

This chapter presents the follow-up to the experiment in Chapter 8. The result of Chapter 8 was interesting, and suggested that the density, richness and/or interestingness of the environment affect traveled distance estimation. However, it had only two conditions, making it difficult to conclude much. To further investigate this problem, we designed and carried out a second experiment with four conditions and more complete data collection that allowed us to compare participants' walking speeds and times in addition to their distance estimates.

The previous experiment had feature-dense and feature-sparse environments in the first phase, and a feature neutral environment in the second phase. Here we add two more phase 1 environments. One is a "simple" feature-medium environment, whose density is somewhat between dense and sparse. If density or interestingness plays a important role as suggested in Chapter 8, we might expect that the traveled distance estimates after experiencing movement in the feature-medium environment will fall between the ones after experiencing movement in the feature-dense and feature-sparse environments. We also added a second feature-medium environment with signs to try to distinguish interestingness from density. The second feature-medium environment was the same as the first but with the additional of some signs designed to potentially attract participants' attention. We hypothesized that if interestingness was dominant, then estimates after the movement in the feature-medium with signs environment would be the same as ones after the movement in the feature-dense environment. On the other hand, if density was dominant, then estimates will be the same for both feature-medium environments.

9.1 Design and procedure

9.1.1 Participants

Sixty-one undergraduates (21 males, 40 females) participated in the study. Data from three additional participants was dropped because one participant did not seem to understand the task, and estimates from two other participants were outliers when testing by Grubb's outlier test.

9.1.2 Apparatus and material

The HMD and tracker system was the same as in Chapter 8.

9.1.3 Procedure

The procedure in this experiment was the same as in Chapter 8. In the first phase, the participant experienced a simulated self-motion of 65m in a virtual environment. Then in the second phase, she was in a different virtual environment and was asked to walk with eyes opened until she felt that she had traveled the same distance as in the first phase. Each participant was given only one trial, and a between-subjects design was used in this study.

The experiment was carried in a long hallway in the basement of a building at the University of Iowa. The hallway was 80 meters long, and was fully tracked. Because we had a few participants who walked farther than 80m in the experiment of Chapter 8, we decided to implement a turning mechanism in this study: when a

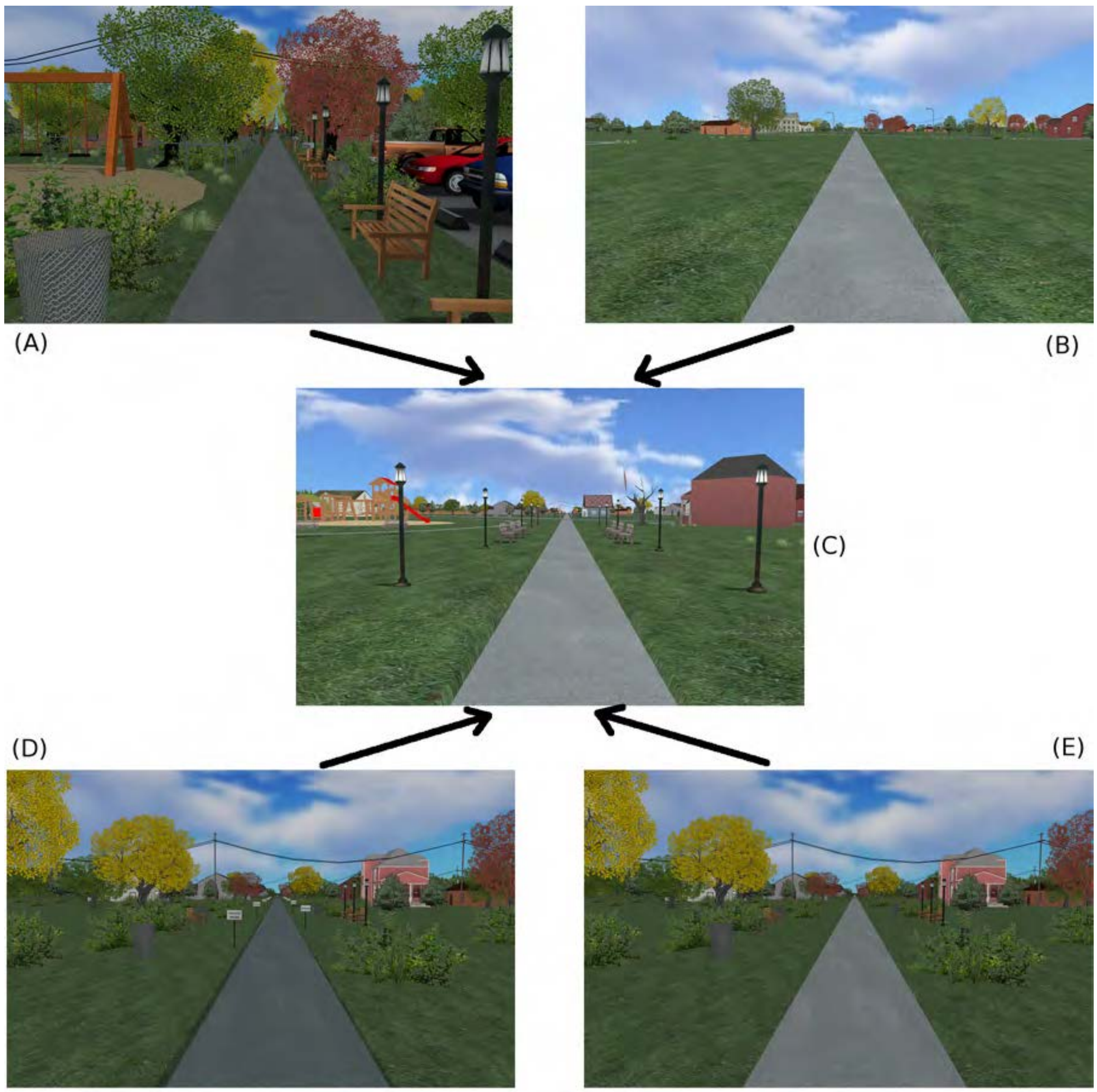


Figure 9.1: The feature-dense environment (A), the feature-sparse environment (B), the neutral environment (C), the feature-medium-with-sign environment (D), and the feature-medium-with-no-sign environment (E). A, B, D and E were used in phase 1, C was used in phase 2 for all conditions.

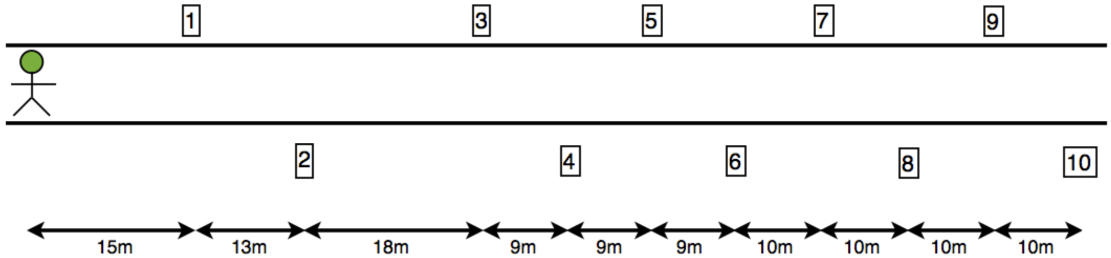


Figure 9.2: Layout of the signs in the feature-medium-with-sign environment.

participant was about to reach the end of the hallway, we told them to stop, close their eyes, and then turn around 180 degrees. While they were turning, we pressed a button to rotate the virtual world 180 degrees around the position of the participant so that when she finished turning and opened her eyes, she saw herself at the same virtual place, facing the same direction as before. We then instructed her to keep walking until she thought she had traveled the same distance as in the first phase. All participants who had to turn around in this manner expressed that they had no difficulty continuing their walk and that the turning did not bother them.

9.1.4 Experimental conditions

Two conditions which were identical to the ones in Chapter 8 were Dense (Figure 9.1A) and Sparse (Figure 9.1B). Two additional conditions were MediumSign (Figure 9.1D) and MediumNoSign (Figure 9.1E). The first-phase environment of the MediumNoSign condition was a modification of the feature-dense environment, in which we removed many near by objects (e.g. trees, trash cans), as well as some interesting landmarks such as the play ground. It gave a feel of being "medium-dense", which means that it was less crowded than the feature-dense environment, but not as empty as the feature-sparse environment.

The first-phase environment of the MediumSign condition was the same as the feature-medium-with-no-sign environment, except that we added a sequence of Burma Shave-style signs along the travel path. Each sign contained a line from a riddle or a short poem (see Table 9.1). The signs were placed alternatively on both sides of the path, following the pattern illustrated in Figure 9.2. With this layout, the simulated self-motion of 65m ends near the sixth sign. We included four extra signs beyond the sixth because we wanted to make sure that participants did not anticipate that the last sign indicated the stopping point. The reason for having the feature-medium-with-sign environment was that we wanted to see if the distraction of reading the signs would affect participants' estimates of the traveled distance. However, we did not tell participants to look at the signs or even mention their existence.

The second phase environment was the same feature-neutral environment as in Chapter 8 (see Figure 9.1C)

9.2 Results and discussion

Figure 9.3 shows the mean estimates of participants in all four conditions. Participants' estimates were the highest in the Dense condition ($M = 65.48$, $SD = 22.93$), slightly lower in the MediumSign ($M = 59.46$, $SD = 28.08$) and Medium-NoSign ($M = 58.99$, $SD = 16.19$) conditions, and the lowest in the Sparse condition ($M = 40.19$, $SD = 10.91$). To determine if there is any significance, we ran a one-way ANOVA analysis on the estimates of the four conditions, and found that there was a significant difference between them: $F(3, 59) = 4.7$, $p = 0.005$. In addition, Tukey

Table 9.1: Sentences for signs in the medium-with-sign environment.

Sign	Sentence
1	How do you fix a broken pizza?
2	With tomato paste.
3	I hide my dromedary
4	inside of our garage
5	my parents don't suspect it's there
6	it's wearing camel-flage
7	What is a bunny's favorite music?
8	Hip Hop!
9	What has four wheels and flies?
10	A garbage truck.

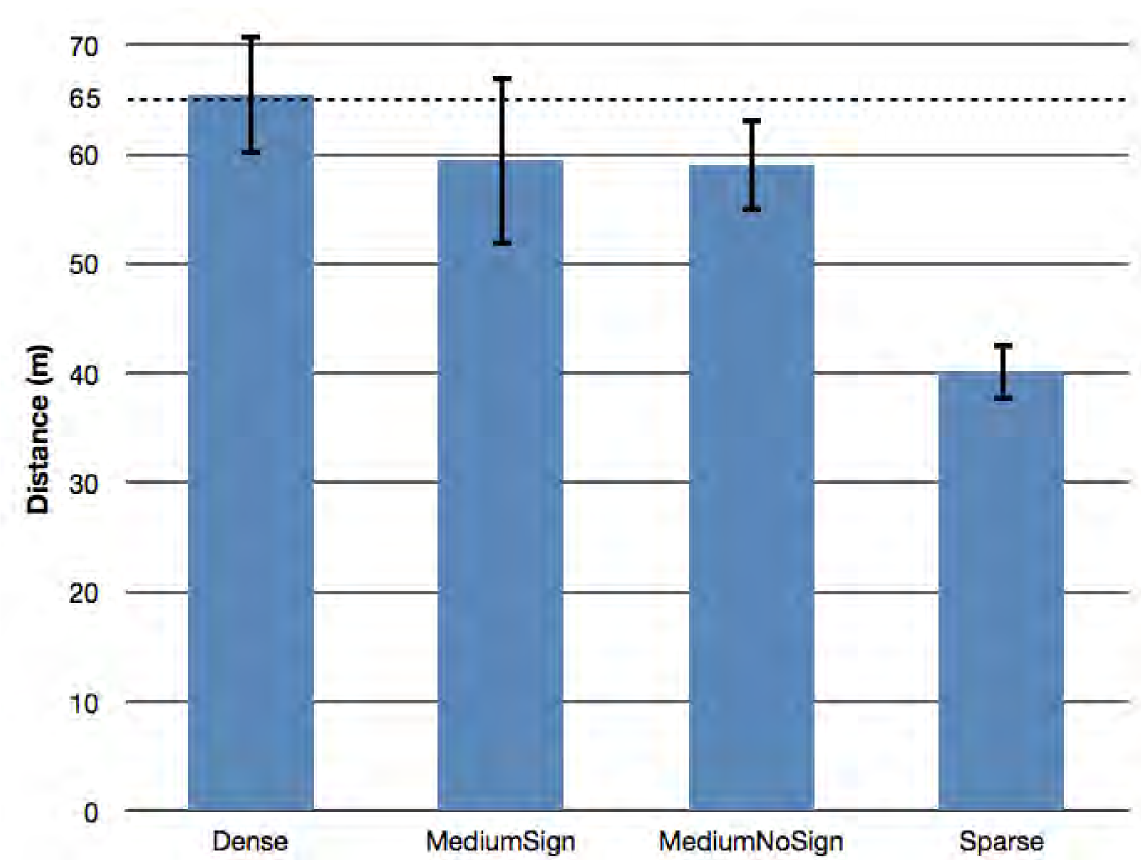


Figure 9.3: Average traveled distance estimates, in meters, for all four conditions. The actual simulated self-motion distances of 65m is represented by the dashed line.

Table 9.2: Mean estimates and t-test results for all four conditions.

Condition	**Mean Estimate (m)**	**t-test result**
Dense	65.48 ($SD = 22.93$)	$t(16) = 0.09$, $p = 0.93$
MediumSign	59.46 ($SD = 28.08$)	$t(12) = 0.71$, $p = 0.49$
MediumNoSign	58.99 ($SD = 16.19$)	$t(13) = 1.39$, $p = 0.19$
Sparse	40.19 ($SD = 10.91$)	$t(15) = 9.09$, $p < 0.001$

HSD tests indicated a significant difference between people's estimates in the Dense and Sparse conditions, but not between any other pair of conditions.

To compare participants' estimates to the actual simulated self-motion of 65m, we ran separate t-tests to compare each condition's estimates to 65 and found that participants in the Sparse condition significantly underestimated the distance. Estimates in the Dense, MediumSign, and MediumNoSign conditions were not significantly different from 65 (see Table 9.2).

So participants experiencing the feature-sparse environment made much smaller estimates than those experiencing the feature-dense environment, and having the signs in the MediumSign conditions did not significantly affect people's estimates of the traveled distance.

One might wonder if participants' walking speeds were different between the four conditions because of their different experiences in the first phase. To address this concern, we recorded the travel time for each participant, and used this number to compute the walking speeds. The results of one-way ANOVA analysis showed that there was no significant difference in walking speeds between the four conditions, $F(3, 57) = 1.81$, $p = 0.16$. We also ran separate one-sample t-tests to compare their

Table 9.3: Mean speeds and t-test results for all four conditions.

Condition	**Mean Speed (m/s)**	**t-test result**
Dense	0.76 ($SD = 0.15$)	$t(16) = 9.20$, $p < .001$
MediumSign	0.77 ($SD = 0.16$)	$t(12) = 7.22$, $p < .001$
MediumNoSign	0.87 ($SD = 0.21$)	$t(13) = 4.20$, $p < .001$
Sparse	0.72 ($SD = 0.19$)	$t(13) = 7.69$, $p < .001$

walking speeds to 1.1m/s - the speed of optic flow in the first phase - and found that participants' speeds were significantly smaller than 1.1m/s in all four conditions (see Table 9.3).

So participants' estimates were significantly different, but their walking speeds were not. This raised another question: were their walking times different? It could be possible that their walking speeds and walking times were not significantly different between conditions, but the two non-significant differences could add up to yield significantly different estimates. We ran a one-way ANOVA on the walking times of participants in the four conditions and found that there was a significant difference ($F(3, 54) = 3.54$, $p = 0.02$), and Tukey HSD tests showed that the walking time in the Sparse condition was significantly less than the walking time in the Dense condition, but no significant difference between any other pair of conditions. This result is consistent with the result of the analysis of traveled distance estimates (see Table 9.4); shorter estimates corresponded to shorter walking times.

9.3 General discussion and conclusions

A striking result is that the estimate differences between the Dense and Sparse conditions were opposite from the result of chapter 8. In chapter 8, Vietnamese par-

Table 9.4: Mean travel times for all four conditions.

Condition	Mean Time (s)
Dense	85.81 ($SD = 20.91$)
MediumSign	75.42 ($SD = 26.34$)
MediumNoSign	71.52 ($SD = 28.03$)
Sparse	57.68 ($SD = 21.37$)

ticipants made significantly larger estimates in the Sparse condition than in the Dense condition, whereas in this chapter, American participants made significantly larger estimates in the Dense condition than in the Sparse condition. The experimental settings, the environments and the task were identical, but the results of the two experiments were opposite. One possible explanation is that traveled distance estimation is more of a cognitive rather than a perceptual problem, and hence differences in population may significantly affect traveled distance estimates.

We do not expect that people's ability to accurately estimate *distances to targets* is greatly affected by environmental features (though see [41, 77] for evidence of some effects); people can focus on the target, readily ignoring features of the surrounding environment. The traveled distance problem, on the other hand, seems different; as discussed in the introduction to Chapter 6, people don't directly perceive traveled distance but process the travel experience over time, thinking, taking into account multiple sources of visual and body-sense information, and perhaps being influenced by factors such as familiarity of experienced surroundings (city versus rural dwellers) and speeds (e.g. usual mode of transportation - walking versus cycling versus automobile - and nature of traffic).

For the experiments of Chapters 8 and 9, the populations were similar in age and educational level and background. Probably the largest population difference, though, was that the Vietnamese participants were residents of a large, dense city, where the most common mode of transportation is motorbiking in relatively slow high-traffic situations. We believe that the American participants have, for the most part, much less experience in dense cities and also much more experience with high-speed automobile travel. Nisbett and Masuda [52] have demonstrated significant East/West differences on related phenomena (e.g. greater focus by Easterners on background context versus Westerners attention to focal objects). It certainly seems possible that significant population differences could affect people's reactions to the environments they experienced.

The second interesting and somewhat surprising result is that in three out of four conditions, participants were on average accurate (not significantly different from 65m) in estimating the traveled distance, despited the fact that their walking times and speeds differ significantly from phase 1 speed and time. This suggests that participants were able to build a good representation of the distance they traveled in the first phase, and were able to reproduce that distance without relying primarily on time. As far as we know, this is one of the first studies to find such accuracy for long action-space distances. Many prior studies seemed to find evidence of underestimation of traveled distances, but their measurement protocols were quite different from ours; for instance, they did not use actual walking or they used a distance estimation task in the protocol. Popp's measurement protocol [57] was comparable to ours and had comparable non-underestimation result.

On the other hand, estimates in the Sparse conditions were quite low, and significantly different from those of the Dense condition. This suggests that the surrounding environment did affect people's estimates. One possible explanation is that the Sparse environment was boring for American participants; little progress seems to be made during the first phase, leading participants to believe they had not traveled very far.

Signs had no significant effect, perhaps because people did not attend to them. We did not ask detailed questions about their experience afterward. We note, however, that the variance of estimates in the MediumSign condition was much larger than in the MediumNoSign condition, which suggests that reading the signs might have distracted some participants.

CHAPTER 10
CONCLUSION AND SUGGESTIONS FOR FUTURE EXPERIMENTS

This chapter summarizes this dissertation's contributions to distance estimation and traveled distance estimation research, and presents some ideas for future experiments.

10.1 Novel contributions

Through the six experiments presented in this thesis, we added new knowledge about distance estimation and traveled distance estimation, as well as provided additional supporting evidence to existing literature. The novel contributions of the work in this thesis are as follows.

10.1.1 Distance estimation

For the distance estimation problem, our first contribution is a direct comparison of several visual presentation methods using two measurement protocols. The key results of that comparison are:

- There is no significant difference in people's estimates when the virtual environment is displayed in an HMD or in an LSID. This is particularly striking in light of the fact that our LSID system lacks such important distance cues as motion parallax and stereopsis, both of which are present in the HMD system.
- When distances are estimated in a HMD based virtual environment, there is no significant difference between distance estimates from the blindfolded walking protocol and distance estimates computed from the timed-imagined walking

protocol. This evidence, in addition to the above evidence that imagined walking protocol is not affected by the encumbrance of an HMD, provides support for the wider use of timed imagined walking as an alternative protocol for the popular blindfolded walking protocol.

- Wearing an HMD while viewing the real world does not cause compression when distance is estimated with time-imagined walking, but does cause underestimation with blindfolded walking. This result implies that the effect of wearing an HMD while judging distances in a real environment depends on the measurement protocol.
- The quality of graphics (good quality 3D model versus photo-based model) does not significantly affect distance estimates in virtual environment, at least in an LSID system.

Our second contribution is the finding that people's perception in VEs is affected by certain kinds of scale changes, i.e. some scale changes had effects, but some did not. We discovered that changes in target size had a significant influence on people's estimates of the distance to the targets: when target poles became larger from adaptation to test, participants undershot distances at test relative to adaptation; and when the target poles became smaller, participants overshot distances at test relative to adaptation. Changes in the size of the surrounding environment or the separation between targets did not have such strong influence on people's estimates. This result lends further support to the conclusion that people are less well grounded and their perceptual systems are less robust in virtual environments than in real environments.

Finally, the result of Chapter 5 provides additional evidence of underestimation of distances in VEs through a novel context of a traveled distance estimation task.

10.1.2 Traveled distance estimation

For the traveled distance estimation problem, our first contribution is the direct comparison of traveled distance estimates between virtual and real environments, using three modes of travel: simulated self-motion, passive motion (i.e. pushing on a chair) and active motion (i.e. direct walking). The key results of the comparison are:

- There is a significant difference in estimates of traveled distance between being pushed through and seeing real environments and simulated self-movement in virtual environments. There were no significant differences when participants actively walk through the real or virtual environments. These results provide additional evidence that vestibular and optic flow are quite important in estimating traveled distances when people don't physically move through the environment. But when walking is used as the mean of travel, body senses seem to dominate other cues such as optic flow.
- Chapter 7's experiment provided some evidence that people are fairly good at estimating traveled distances. However, the measurement protocol required participants to make VE-based distance estimates, which added substantial error to their expressed traveled distance estimates. Although we have some data about the size of this error, our knowledge is not precise enough to know whether participants' actual sense of their traveled distances were accurate, or slightly high, or slightly low.

- It is not easy to find a good measurement protocol for traveled distance estimation. We piloted several protocols in addition those used in the traveled distance experiments; none seemed entirely satisfactory, especially for studies that could benefit by subjects completing multiple traveled distance trials. Future studies are needed to find a better measurement protocol.

Our second traveled distance contribution is the tentative finding that environmental richness and density affect traveled distance estimation. We discovered that:

- Under certain circumstances, participants seem to be accurate at estimating fairly long (65m) traveled distances.
- The density and richness of the surrounding environments seem to have a strong effect on traveled distance estimation. However, this effect seems to vary by population, probably due to the more cognitive nature of the traveled distance estimation problem.

10.2 Suggestions for future experiments

The findings of our experiments are intriguing, especially the effects of scale change on distance estimation and the effects of scene density and richness on traveled distance estimation, but represent only the initial step. Additional experiments will be required to fully understand the underlying causes of these findings.

To further increase understanding of the distance estimation problem, we suggest three experiments. First, it would be interesting to directly compare three settings: HMDs, stereoscopic, head-tracked LSIDs, and non-stereoscopic LSIDs. The results of Chapter 3 found no differences between estimates in HMDs and non-stereoscopic LSIDs. However, the experiment involved static objects in familiar settings. The use of less familiar and/or dynamic scenes could provide challenges that result in measurable performance differences between participants using these technologically quite different presentation settings.

A second suggested experiment is a more comprehensive investigation of distance estimation in an augmented reality setting. The experiment of Chapter 3 did contain an augmented reality component but no interesting significant results were found, perhaps because our HMD and tracking systems were not calibrated well enough. Not much research has been done in this area, even though it potentially has many valuable applications such as equipment maintenance or construction design.

We also suggest following up Chapter 4's experiment by investigating the effects of scale changes in the real world. More specifically, we would like to see if the same effect can be achieved in full cue (well-lit, familiar-sized setting) or reduced-cue real-world environments (that are reasonably similar to the virtual environment used in our prior experiment). We hypothesize that effects of scale change will be substantially less or insignificant in a full cue real-world environment. And we hypothesize that performance in the reduced cue environment will be, as in the virtual environment, more strongly affected, consistent with the notion that participants are less well ground in virtual environments and reduced-cue real environments.

For the traveled distance estimation problem, we also suggest three further experiments. The first is a traveled distance estimation study involving long distances (500m or longer) in both real and virtual outdoor environments. As part of this, it would be valuable to attempt to confirm results of Crompton's study [11] by comparing participant's estimates of traveled distances in two quite different outdoor environments. It would next be very interesting to compare these results with estimates of long actual walks in virtual models of the same outdoor environments. Although technology is quickly improving, the current difficulty of fast accurate large-range outdoor tracking makes such an experiment quite challenging.

A natural follow-up of the experiments in Chapters 8 and 9 would be a study directly designed to include two populations that we suspect might estimate traveled distances differently. In particular, such a study could examine whether people who are from dense, crowded cities make different traveled distance estimates than people from rural areas and, if so, under what conditions. This could help explain the differences between the results of Chapter 8 and Chapter 9.

Finally, we suggest another, different follow-up to the experiment in Chapter 9 using several different environments with "quantifiably" different levels of density and richness. Ultimately, we hope to be able to predict the accuracy of participants' estimates in a particular environment based on a computational model that accounts for the scene's feature density and richness.

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