Distance Estimation in Virtual and Real Environments using Bisection

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Abstract

Systematic error in judging distances in virtual environments is one of the most interesting problems in perceptual studies of virtual environments. The causes of this error are not known. This paper presents an experiment designed to investigate distance perception in virtual environments using the method of distance bisection (fractionation). Most other studies of distance perception in virtual environment rely on measures involving motor responses or time judgments. Unlike these, the method used in this study depends purely on visually perceived distances. Our experiment compares distance bisection judgments in virtual environments, bisection judgments in the real-world, and bisection judgments in the real-world with limited field of view. We also perform the judgments in two environmental contexts, an outdoor environment and an indoor environment. We find evidence that nonlinear distance compression occurs in virtual environments, but judgments in real-world conditions are accurate. We do not find an effect of environmental context.

CR Categories: I.3.m [Computer Graphics]: Miscellaneous—Perception

Keywords: Virtual reality (VR), distance perception, distance bisection, fractionation

1 Introduction

Virtual environments (VEs) allow the simulation of real-world events in a controllable and re-usable environment. Such simulations for complex real-world events can provide learning and training opportunities that would be expensive or impractical in the real world. Creating veridical simulations of size, scale, and distance in VEs remains a challenging task that is the subject of active research.

In particular, systematic error in perceiving distances is one of the most interesting issues in perceptual studies of VEs. Such error usually revolves around the perception of egocentric distance, i.e., absolute distance from one's self. Prior studies, e.g., [Waller 1999; Loomis and Knapp 2003; Thompson et al. 2004] have found that people underestimate distances in virtual environments when using a stereoscopic head-mounted display (HMD). Plumert et al. [2005], however, found no distance compression when the virtual environment was presented using a large-screen immersive display system (LSID). We do not know the reason for the different findings, but note that the response measures differed, i.e., Plumert et al. [2005] measured estimated time-to-walk, while others have typically employed blind-walking judgments. Another characteristic of a virtual environment presented through an LSID as compared to an HMD is that the field of view (FOV) is typically much larger in an LSID, although Knapp and Loomis [2004] argue that the FOV of most HMDs by itself is not the cause of distance compression in HMDs.

The work presented in this paper is motivated by two observations about the prior body of work in studying errors in distance perception in VEs. The first observation motivating the design of the study involves the dependent variable. Earlier methods used to assess egocentric distance perception in VE involved motor responses or time estimates, whereas the perceptual bisection judgments used in the present study depend only on visually perceived distances. The second observation motivating the design of the study involves adding variations in the environmental context as an independent variable.

Prior work on measuring ego-centric distance has used blind walking (e.g., [Willemsen and Gooch 2002; Interrante et al. 2006]) and time-to-walk estimates [Plumert et al. 2005] as the method of measuring distance. The reason for this difference in measuring techniques is that blind walking, a reliable method for real-world measurements [Loomis and Knapp 2003], cannot easily be incorporated into an LSID. While Plumert et al. [2005] showed that time-to-walk estimates are generally reliable, there is much less literature on their use in distance perception. In addition, blind walking involves perception and action. Time-to-walk estimates involve perception and imagination.

This study presents distance estimation experiments using a measure that relies only on visual perception, that of distance bisection. In distance bisection, subjects are asked to determine the midpoint of a distance interval between them and a target using the method of adjustment. Purdy and Gibson [1955] showed that subjects could accurately bisect distances up to 270m in an outdoor real-world environment with an average error of approximately 3%. This result has been replicated by Rieser et al. [Rieser et al. 1990] for distances from 2-24m. To our knowledge this study represents the first use of a bisection task in a VE. Bisection does not give an absolute measure of egocentric distance, as the other measures do, but may provide some insight into the properties of visual space as represented in a virtual environment.

The second motivation for this work, that of controlling for the environmental context, is a result of the recent finding of Lappin et al. [2006], who showed that in the real world, people tend to overestimate the position of the midpoint of the egocentric distance. They call this a phenomenon *anti-foreshortening*, to distinguish it from the foreshortening response that one might expect due to linear perspective (cf., [Gilinsky 1951]). Perhaps more interesting, though, is that [Lappin et al. 2006] found that errors in distance judgment depended on the *environmental context*, i.e., that subjects estimated distance differently depending on whether they were outdoors, in a hallway, or in a large indoor space. A replication of this finding in a VE could potentially provide some measure of presence or immersion as well as insight into the structure of perceived visual space. The possibility that distance judgments can be influenced by environmental context has not been systematically investigated for VEs.

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The present paper describes an experiment designed to replicate that of Lappin et al. [2006] in environments presented through an HMD. For purposes of control and comparison, we also conducted the experiment in the real-world, letting subjects have their natural field of view (FOV) as in [Lappin et al. 2006], and with an FOV that approximates that of the HMD used in the experiment. The remainder of the paper is organized as follows. Section 2 reviews in more depth the prior work. In Section 3, we describe our experimental methods. Section 4 presents the results of our experiments with a discussion; we conclude and present future work in Section 5.

2 Background

This paper continues our work on finding functional similarities and dissimilarities when people operate in virtual environments and real environments [Williams et al. 2007]. The present experiments are aimed at investigating similarities in the structure of visually perceived space. There have been systematic studies of the relation of perception and action in VEs, e.g., [Mohler et al. 2004; Mohler et al. 2005; Kay and Warren, Jr. 2001], as well as considerable investigation of the similarities in distance estimation between real and virtual environments [Proffitt 2006; Loomis and Knapp 2003; Thompson et al. 2004; Willemsen and Gooch 2002; Witmer and Sadowski 1998]. This work has usually found that subjects underestimate distances in virtual environments. The precise reasons for this are not known, but several factors have been examined. There have been discrepant empirical findings on how field of view in an HMD leads to an underestimation of distance. Wu et al. [2004] show that vertical FOV of 21° or less leads to an underestimation of distance. Knapp and Loomis [Knapp and Loomis 2004] found that a reduced vertical FOV similar to that of an HMD has no influence in the real environment. Thompson et al. [2004] show that distance perception in real and virtual environments is not due to the lack of realistic graphics. While these distance discrepancies exist in the virtual environment seen though the HMD, Plumert et al. [2005] found that time to walk estimates in real environment and virtual large-screen immersive display environment were highly similar.

The above work requires actions or imagination to compute a distance, and the present work instead focuses on differences in perception of distance in visual space. Although in geometry distance and direction do not necessarily depend on each other, in perception they can depend on each other, since perceived direction can depend on distance. For example, suppose that an object is located from an observer with a vector of 100m distance and 45° right direction. If the perception of near-far distances is compressed relative to left-right distances, as many have claimed (e.g. [Gilinsky 1951; Thompson et al. 2004]), then a 45 degree angle (to the observer's right) in the physical world would be perceived as even further to the right, because perception of the near-far distance would be compressed relative to the right-left distance. This motivation is another reason to learn more about how the perception of distances and scaling of distances in virtual environments compares to perception of physical environments.

3 Method

Two real-world settings and two replica virtual environments were used in this study. The real-world settings were an indoor hallway approximately 40m in length and a large lawn with a continuous grassy area approximately 50m by 50m. The virtual environments were replicas of these viewed through a full color stereo Virtual Research Systems V8 Head Mounted Display with 640 x 480 resolution per eye, a field of view (FOV) of 60° diagonally, and a frame rate of 60 Hz. The HMD weighs approximately 1 kg. An InterSense IS-900 tracker was used to update the participant's rotational movements around all three axes.

In this experiment subjects were asked to adjust a person or avatar ("adjustment person") at the midpoint between themselves and a target person or avatar. Subjects were instructed to base the midpoint on their perceptions and asked not to use strategies such as counting paces or markers that might be present in the environment. A between-groups experiment was run under three conditions using the procedure described below. In the first condition, subjects performed the experiment in the virtual environments. In the second condition, subjects were situated in the real world and bisected the distance with their natural FOV. In the final condition, subjects were situated in the real-world but wore goggles that approximated the FOV of our HMD.

We constructed goggles that approximated the FOV of our HMD by measuring the diagonal field of view the HMD presented in the virtual world and then building a pair of goggles with this diagonal FOV. HMD devices have more complicated fields of view than we have modeled, since the optics introduce notable pincushion distortion, and we have neglected that in our construction. Additionally, the HMD allows the intra-ocular distance of the eye projectors to be adjusted by each subject, while our goggles do not. Thus, these goggles only approximate the FOV of the HMD. Our goggles do not match the inertial properties of our HMD as done in [Willemsen et al. 2004], who found only minor effects due to the mechanical properties.

In each condition, 16 subjects performed a bisection judgment 16 times. Eight trials were performed in the outdoor environment and eight in the indoor environment ("environment"). Within each environmental context, each subject performed four trials at 15m and four at 30m ("distance"). At each distance, each subject performed two trials at one of two viewing directions, the ends of the hallway or lawn. ("viewing direction"). At each viewing direction, distance, and environmental context, each subject made one bisection with the adjustment person walking from the target person towards the subject, and one bisection with the target person walking away from the subject towards the target person ("walking direction"). The order of the two environmental contexts and the order of conditions within each context were counter-balanced across subjects, with trials blocked by the environmental context.

For a given trial, the subject was positioned at the correct viewing direction with the adjustment person in the appropriate location (with the subject or target person). In the real world, the target person positioned themselves at the correct distance using a laser measuring device. In the virtual environments subjects and avatars were positioned automatically. This distance could not be changed as subjects in the virtual environment could not change their position; they did, however, possess rotational degrees of freedom and could look around. In the real world, the adjustment person then walked away from or toward the subject until instructed to stop by the subject. Subjects were allowed to adjust the position of the adjustment person until they were comfortable that the adjustment person was at the midpoint. In the virtual environments, the procedure was repeated except the avatar walked under control of the subject through a joystick. The avatar walked using a motion-captured gait and could naturally turn and adjust their position depending on the position of the joystick. When the subjects indicated that the adjustment person was at the midpoint, the distance between the adjustment person and subject was recorded, and the subject was asked to take a step or two forward or backward (randomly, depending the experimenter) for the next trial. Likewise, in the virtual environment, the subject's position was jittered by a random amount between one and three meters for each trial. The target intervals were shifted in this way to make it difficult for subjects to use a constant feature of the environment as the judged

Figure 1: Physical environments (left) and the corresponding virtual environments used in the experiments (right).

midpoint.

4 Results and Discussion

We analyzed our results in terms of systematic error and random error. Systematic error (SE, sometimes called constant error) occurs when subjects adjust the midpoint consistently too close to themselves (consistent with foreshortening) or too far from themselves (consistent with anti-foreshortening). Random error (sometimes called variable error) is a measure of the precision with which subjects judge the same interval and is computed as the root-mean square standard deviation (RMS SD, the square root of the sum of the variances of each subject's four trials at a given environment and distance) expressed as a percentage of the correct midpoint distance.

We consider three predictions about our results, all based on judgments of distance in the real world. First, one might expect that subjects may make bisection judgments so that the further section was adjusted to be larger than the near section as predicted from the "foreshortening errors" reported by Gilinsky [Gilinsky 1951]. Second, one might expect that subjects adjust the near and far intervals to be about the same size without systematic error, as predicted by Purdy and Gibson [Purdy and Gibson 1955]. Finally, one might expect the results to vary by environmental context, so that subjects adjust the intervals veridically in an outdoor context but exhibit "anti-foreshortening errors" (where the further section is adjusted to be smaller than the near section) in an indoor context, as predicted by Lappin et al. [Lappin et al. 2006].

Table 1 shows the systematic errors (SE - midpoint) expressed as a percent of the correct midpoint distance (Weber fraction) for the average over observers in the real-world conditions. This table also shows the random error. For comparison, we include the analogous results from [Lappin et al. 2006]. Figure 2 presents the systematic error results graphically.

An analysis of variance (ANOVA) on the systematic errors with one between-subject factor (condition, i.e., VE, real-world, real-world with limited FOV) and the other factors (environment, distance, viewing direction, walking direction) within-subject was performed on the systematic errors. We find a main effect of condition ($F(2,45) = 4.9$, $p = .01$) and of distance ($F(1,45) = 26$, $p < .01$). There were significant interactions of condition $\times$ distance ($F(2,45)=15$, $p < .01$), condition $\times$ environment ($F(2,45)=8.14$, $p < .01$), and a significant three-way interaction of condition $\times$ distance $\times$ environ-

	15m		30m	
	Lawn	Hall	Lawn	Hall
Virtual Environment				
AVE SE/Mdpt	2.6%	5.3%	-10.4 %	-11.9%
RMS SD/Mdpt	9.3%	7.4%	9.8%	10.0%
Real-World, Unlimited FOV				
AVE SE/Mdpt	1.0 %	0.8 %	3.4 %	1.9 %
RMS SD/Mdpt	6.1 %	7.0 %	5.5 %	6.0 %
Real-World, Limited FOV				
AVE SE/Mdpt	2.1 %	2.5 %	1.4 %	-3.7 %
RMS SD/Mdpt	5.0 %	7.0 %	5.6 %	5.5 %
Comparison to Results from [Lappin et al. 2006]				
AVE SE/Mdpt	3.6%	9.7%	2.8%	6.2%
RMS SD/Mdpt	3.7%	6.3 %	4.4%	8.1%

Table 1: Systematic (SE) and random errors (RMS SD) expressed as a Weber fraction for the three conditions of our experiment: real-world with natural FOV, real-world with limited FOV, and in virtual environments. Results from Lappin et al. [2006] are included for comparison.

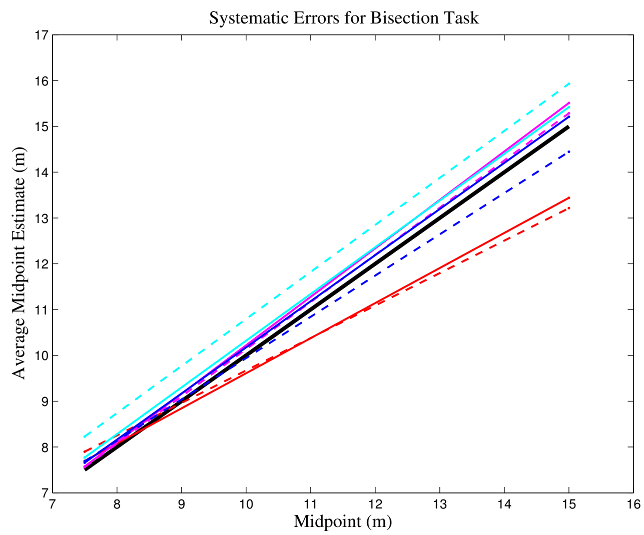

Figure 2: This figure shows the average midpoint estimate versus the midpoints for all conditions of our experiment. The black line shows the baseline of perfect perception; the red lines show the lawn and hall midpoint estimates for the virtual environments; the magenta show the real-world estimates with unlimited FOV; the blue show the real-world with limited FOV; the cyan show the Lappin et al.[2006] results. Results for the lawn environment are shown as solid lines and results for the hall environment are shown as dashed lines. The blue line below the black line at 15m corresponds to the hall environment.

ment ($F(2,45)=7$, $p < .01$). Subjects were better in both real-world conditions than in the VE. Subjects were more accurate at 15m than at 30m, although the sign of the error changed accounting for the two-way interaction. Subjects were better in the outdoor environment than in the indoor environment, except in the real world condition with natural FOV. The three-way interaction results from the finding that errors changed differently with respect to distance and environment in each of the three conditions.

An ANOVA on the random errors with one between-subject factor (condition) and two within-subjects factors (environment, distance) shows a main effect of condition ($F(2,45) = 7$, $p < .01$) and of distance ($F(1,45) = 52$, $p < .01$) and a significant interaction of condition $\times$ distance ($F(2,45)=5$, $p < .01$). Subjects were less variable in both real-world conditions. Subjects were overall less variable at 15m. Variability increased with distance in the VE condition but decreased with distance in both real-world conditions. This increase in random errors in VEs when compared to real-world conditions is consistent with other spatial learning tasks [Williams et al. 2007].

Examining these results for the case of the VEs presented over an HMD first, we see that qualitatively there is a difference between subject's bisection judgments at 15m and at 30m. At 15m meters the error is small in the direction of anti-foreshortening, while at 30m the error is larger in the direction of foreshortening. We consider two alternative explanations for these results.

First, the findings are consistent with the possibility that subjects' judgments were influenced by a running sum of their previous judgments. This bias is sometimes referred to as "regression to the mean judgment," and sometimes as an influence of Bayesian probabilities [Tversky and Kahneman 1974]. The hypothesis is that subjects, consciously or unconsciously, keep track of a running average of their previous responses and/or stimulus intervals. This running average then influences their judgments, within the limits of their uncertainty about a given judgment. In this way, their judgments of the 15m interval would be stretched out by the average of the 15m and 30m intervals, and their judgments of the 30m intervals would be shortened.

However, as shown in Table 1, the results of our experiment in the real world conditions do not support this hypothesis. Since the judgment task is the same in both virtual and real environments, it seems persuasive to us that regression to the mean should occur in all experimental contexts. It is possible that the higher uncertainty present in the VE, as evidenced by the higher random errors, leads subjects to emphasize certain distance cues (such as linear perspective) that result in systematic errors.

Second, there is the possibility that ground texture gradient affects the bisection judgments in the VE. Our HMD has a 38° vertical FOV and 480 vertical pixels of resolution The limited resolution and FOV of the HMD means that a 1.75m subject trying to estimate a distance at 7.5m does not have the acuity to judge texture gradients that vary more than about every 2cm, while at 15m the texture gradient can only be distinguished at a 5cm interval (see Figure 3). Gibson [1950] theorized that ground texture could play an important role in perceived distances. Sinai et al. [1998] induced systematic errors in distance judgments by varying the availability of ground texture and Wu et al. [2004] point out the importance of high-resolution scanning for determining distance.

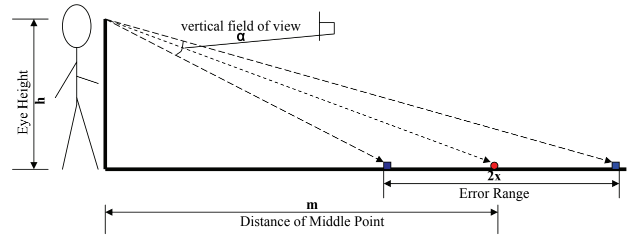

Figure 3: The size of one pixel on the ground plane. For an eye-height of 1.75m, a vertical FOV of 38° (matching our HMD), and vertical resolution of 480 pixels, the ground plane image of one pixel ($2x$ in the figure) is 2.0cm at 7.5m and 4.7cm at 15m.

5 Conclusion

This paper presented an experiment designed to investigate distance perception in virtual environments. In contrast to prior studies that have investigated this question, we did not use a measure that required a verbal report, e.g., [Loomis and Knapp 2003], motoric responses, e.g., [Loomis and Knapp 2003; Thompson et al. 2004], or an imagined calculation, e.g., [Plumert et al. 2005]. Our method used distance bisection to investigate distance perception. The advantage of our method is that it is purely perceptual, and does not require a secondary response. The disadvantage of our method is that it does not give us an indication of absolute egocentric distance.

Our results support the assertion that distance perception in virtual environments differs from distance perception in the real world. We find evidence that nonlinear distance compression occurs in virtual environments, but judgments in real-world conditions are accurate. At 15m the distance bisection judgment in VE is close to distance bisection judgment in the real world and does not seem to have errors of the same magnitude as have been reported elsewhere, e.g., [Thompson et al. 2004]. The difference between 15m and 30m bisection judgments in VE is notable, however, and similar to the nonlinear distance compression reported by [Gilinsky 1951]. The random errors are significantly larger in VEs compared to the real-world, indicating that not only the accuracy but the precision of such judgments is worse than in the real world. As noted above, this finding is consistent with other spatial perception tasks in virtual environments [Williams et al. 2007]. Finally, we do not find an effect of environmental context.

Our bisection task may involve elements of exocentric distance perception as well as egocentric [Foley et al. 2004]. Exocentric distance perception has not, to our knowledge, been systematically explored in VEs. The bisection task was egocentric in that subjects were asked to view the distance from themselves to a target object and then judge the midpoint. The bisection task may be exocentric in that subjects were asked to compare the far segment to the near segment. Strong differences in egocentric and exocentric distance perception may result in differences between our results and work that uses purely egocentric methods, a subject we have not investigated.

Although our main concern is with VEs, we also analyzed the real-world data alone in a manner similar to that described above. We find a main effect of environment ($F(1,30)=6$, $p = .03$). There were significant interactions of condition $\times$ environment ($F(1,30)=24$, $p < .01$), distance $\times$ environment ($F(1,30)=11$, $p < .01$), and distance $\times$ viewing direction ($F(1,30)=4$, $p = .04$). In the real world, subjects were better in the indoor environment than in the outdoor environment. This finding may be due to the unconscious use of distance cues in the more textured indoor environment. We note that while Lappin et al. [2006] also found an effect of environmental context, their finding was the opposite of ours. The distance by viewing direction interaction is consistent with the explanation that subjects were better when facing east than when facing west, and all outdoor experiments were done in the afternoon, so subjects may not have been able to see as well with the sun shining in their face. The main conclusion from the real-world experiments is that distance bisection is accurate, as others have reported [Purdy and Gibson 1955; Rieser et al. 1990].

Our real-world results do not therefore reproduce the results of Lappin et al. [2006]. Possible reasons are that Lappin et al. [2006] included a third environment (a lobby) in their experiments that affected the results of the other two conditions. Lappin et al. [2006] did not control for order of the environments in their experimental design, and it is possible that one of the environments confounded distance estimation in the others. We are unable to compare their orders to any matching subset of our orders since the environmental order used in their experiments was not preserved.

We note that while distance is not a statistically significant factor in the real-world conditions, we possibly see a shift in the pattern of errors from the natural FOV to the limited FOV conditions. Although Knapp and Loomis [2004] demonstrated that FOVs based on manufacturer's specifications did not cause systematic errors in distance judgments in the real-world, HMDs have nonlinear optics, including pincushion distortion, that may reduce the "true" FOV to values close to those found by Wu et al. [2004] to cause distance underestimation. Better modeling of the FOV of HMDs is a topic of active inquiry.

An additional hypothesis for our results in VEs that we plan to investigate is the explanation advanced above that an interaction between limited FOV and limited resolution in the display device causes errors in distance judgments. To our knowledge this issue has not been explored before. Wu et al. [2004] point out the importance of near-ground information in making accurate distance judgments. It may be that the limited texture gradient visible with the resolution of the HMD and the restricted FOV cause systematic error in far-ground distance judgments. The issue of how resolution affects distance judgment has potentially important impact in the investigation of simulated environments for people with low vision, e.g., [Guth et al. 2005].

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