Running head: DISTANCE PERCEPTION IN VE'S

Factors Affecting the Perception of Interobject Distances in Virtual Environments

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Abstract

Two experiments explored four factors that may influence people's judgments of exocentric (interobject) distances in virtual environments. Participants freely navigated in a simple virtual environment and repeatedly made magnitude estimations of exocentric distances. Distances were generally overestimated. An exponential model (Steven's power law) fit the data and exponent estimates were generally less than unity. Geometric field of view and the presence of feedback were found to have the strongest effect on accuracy. Display type (head-mounted vs. desktop) and the presence of additional perspective cues were less influential.

1. Introduction

In the last few years, major claims have been made about the potential efficacy of virtual environments (VE's) for training knowledge and skills (see Seidel & Chatelier, 1997; Winn, 1998). These applications generally require trainees to learn the spatial characteristics of a computer-generated environment and then to apply this knowledge to a real-world setting. Although there is an emerging body of evidence that VE's can allow users to form useful mental representations of large real world spaces (Witmer, Bailey, Knerr, & Parsons, 1996; Ruddle, Payne, & Jones, 1997; Waller, Hunt, & Knapp, 1998) there is also some evidence that VE's lead to distortions of spatial perceptions of distances (Witmer & Kline, 1998) and angles (Ellis, Smith, Grunwald, & McGreevy, 1991). Because large-scale spatial representations are presumably derived from these perceptions, determining the tasks and circumstances under which perceptions are systematically distorted in VE's is an important step in understanding the limits of VE's applicability to training spatial knowledge. This paper examines the influence of several factors on the perception of exocentric (interobject) distances in VE's. Before discussing VE's, I briefly review studies pertaining to real world distance perception.

1.1 Distance perception in the real world

Studies of human distance perception in the real world have shown that the relationship between actual distance (d) and judged distance (δ) is well described by Steven's power law:

$$\delta = k \cdot d^n$$

where the modulus k is a unit-dependent scale factor and the exponent n depends on the nature of the judgment (Stevens, 1975). Traditionally, most attention has focused on estimates of the exponent, which signifies the direction and degree of curvature of the psychophysical function; however, any measure of absolute accuracy in distance judgments must account for both modulus and exponent estimates (Montello, 1991). I will adopt a natural and often used measure of accuracy – the percentage of overestimation:

$$\%\,overestimation = \frac{100 \cdot (d - d)}{d}$$

The vast preponderance of studies of human distance perception have focused on modeling egocentric distances (those between observer and stimulus). These studies generally yield exponent estimates very close to one; however, the exponent can range between 0.8 and 1.1 depending on the nature of the estimation task and the properties of the viewing environment (for a review, see Wiest & Bell, 1985). Exponent estimations for models of egocentric distances are sensitive to manipulations of stimulus properties such as scale of the environment (Teghtsoonian & Teghtsoonian, 1970), stimulus orientation (Wagner, 1985) and available depth cues (Kunnapas, 1968; Worley & Markley, 1969) as well as by the response method by which data are acquired (Da Silva, 1982; Wagner, 1985; Stevens, 1975). As a broad generality, most studies find that in natural settings, egocentric distances between three and 90 meters are typically underestimated and yield exponents between 0.91 and 1.00 (Wiest & Bell, 1985).

Comparatively few studies have examined the perception of exocentric distance. Those that do generally have found that exocentric distances are less likely to be underestimated than egocentric distances (Gogel, 1977), and may actually be overestimated by 20% to 40% (Levin & Haber, 1993). Exponents for exocentric distance estimations of distances between seven and 100 meters have been estimated to be between .99 (Wagner, 1985) and 1.05 (Da Silva, 1982) and are rarely significantly different from one. Although generally more linear than estimated egocentric distances, estimated exocentric distances are also affected by stimulus properties, most notably by stimulus orientation with respect to the observer. Estimations of distances between objects are significantly influenced by the visual angle that they subtend (Levin & Haber, 1993), appearing much more compressed in the in-depth than the fronto-parallel plane (Wagner, 1985; Loomis, Da Silva, Philbeck, & Fukusima, 1996). Wagner (1985) has suggested that this compression effect is associated more with the modulus of the power function than with the exponent.

1.2 Distance perception in virtual environments

Although there are very few published studies of exocentric distance perception in VE's, there is some evidence that people's tendency to underestimate egocentric distances in the real world is exaggerated in VE's (Witmer & Kline, 1998; Lampton et al, 1994; Henry & Furness, 1993). In one of the most comprehensive studies of distance estimation in VE's to date, Witmer and Kline (1998) found that egocentric distances in a VE may be perceived as being less than half of their modeled distance. However, it has also been suggested that spatial information presented on any computer-generated display device will result in an apparent enlargement of distances (Roscoe, 1984). Many factors have been implicated in these effects, and the most intensely studied are those relating to aspects of the display or computer system. However, psychological variables almost certainly exert an effect on distance perception.

<u>1.2.1 System factors.</u> Several studies have examined aspects of VE's that affect spatial perception, and many of these factors are likely to affect judgments of exocentric distances. Variables such as display type (Eggleston , Janson, & Aldrich, 1996; Yeh & Silverstein, 1992; Henry, 1993), scene contrast (Eggleston, Janson & Aldrich, 1996), and navigational interface (Witmer & Kline, 1998) have been implicated in egocentric spatial perception. Additionally, Steven's exponent estimates and accuracy measures for egocentric distances can be affected by manipulations of texture and stimulus size (Witmer & Kline, 1998). Presumably, this is because textured VE's with objects of familiar size provide more depth cues, and thus allow more accurate distance perception. Because one of the most effective depth cues is linear perspective (Surdick, Davis, King, & Hodges, 1997), the first experiment reported below examines its effect on distance perception.

An important and unresolved issue in VE research concerns the utility of head-mounted versus desktop displays. Few studies have directly compared spatial perception in head-mounted displays (HMD's) to that of desktop monitors. Those that have typically find slight (or no) differences between viewing conditions (Wilson, 1997). Some research has indicated that HMD's may lead to greater than normal overestimations of perceived exocentric distances (Roscoe, 1991; Yang, Wade, & Proffitt, 1997; but see Henry, 1993). More recent evidence suggests that the accuracy of inferred relative distance estimations may be improved with HMD's as opposed to desktop displays (Ruddle, Payne, & Jones, in press). Further research on the perceptual differences between head-mounted and desktop displays is clearly necessary. The first experiment reported below examines the effect of the display type on the perception of exocentric distances by comparing the performance of participants in an immersive VE (HMD with 6 degree-of-freedom head tracking) with that of a group using a desktop system.

Another system factor that is related to spatial perception in VE's is the geometric field of view (GFOV) -- the visual angle depicted in the virtual scene. Distinct from the physical field of view (the angle subtended by the display device on the user's retina), the GFOV is a rendering parameter typically set by the VE designer. In general, wide GFOV's allow more of the VE to be portrayed, but may lead to scene compression and minification, and their attendant distortions in perceived distances, angles and shapes (McGreevy & Ellis, 1986; Barfield & Kim, 1991; Neale, 1996; see also Lumson, 1980). Narrow GFOV's may also produce misperception of distances (Neale, 1996; see also Hagen, Jones & Reed, 1978). Research that explores the effects of varying GFOV's allows VE designers to know the range of GFOV's that permit accurate spatial perception. For example, Barfield and Kim (1991) found that a GFOV of 60° yielded the greatest accuracy in exocentric azimuth judgments; however, the degree to which this finding applies to the perception of exocentric distances in VE's is unknown. It has been suggested that a relatively wide GFOV that matches the physical field of view of the display device will minimize perceptual distortions of distance (Witmer, personal communication) however, for many applications this is an expensive proposition. The second experiment reported below was designed to assess the role of the GFOV on distance perception in VE's.

1.2.2 An important cognitive factor: feedback.

Most of the research on spatial perception in VE's has focused on determining those aspects of the VE (as opposed to the user) that influence spatial perception. Clearly the technological issues associated with increased environmental and interface fidelity are important in allowing realistic and relatively error-free spatial perception. However, performance on many spatial tasks is driven much more by the representational power of the human mind than by the quality of the VE system. Humans are remarkably adept at deriving spatial information from environments with reduced cues. For instance, compared to VE’s, maps are very low-fidelity representations of an environment; however, they are able to allow nearly as good or better spatial understanding than VE’s (Bliss, Tidwell, & Guest, 1997; Satalich, 1995; see also Ruddle, Payne, & Jones, 1997). In many cases, leveraging the power of the human mind to inform spatial percepts and construct spatial representations is more cost-effective than investing in high-fidelity VE systems.

One very simple, though rarely studied, psychological factor that may influence the accuracy of distance perception in VE’s is the presence of error corrective feedback. To my knowledge, none of the experiments that examined distance perception in VE’s gave participants feedback about the accuracy of their responses. Although denying feedback allows researchers to investigate people’s initial percepts, it is possible that if given proper feedback early in their training, people could learn to mediate their perceptions by higher-level cognitive information. Real world studies of the effect of feedback on egocentric distance estimations have shown that it exerts a profound and immediate effect, improving accuracy and reducing the variance of people’s estimations (Gibson & Bergman, 1954; Gibson, Bergman, & Purdy, 1955). One would hypothesize that feedback is similarly effective in VE’s. In the second experiment reported in this paper, the effect of feedback was assessed directly by withholding it from one group of participants and comparing their performance with that of a comparable group that received feedback.

The two experiments reported here assess the influence of immersion, perspective cues, GFOV, and feedback on exocentric distance perception in VE's. Because gender influences spatial ability (McGee, 1979) and spatial knowledge acquisition in VE's (Waller, Hunt, & Knapp, 1998), it is also examined for a possible effect. By examining exocentric distance perception -- a task at which people are generally better than they are at estimating egocentric distances -- the present studies hope to isolate more easily those variables that exert an effect on the perception of VE's.

2. Experiment One

To date, studies of the perception of exocentric distances have almost exclusively used stationary viewpoints and static stimuli, thus eliminating potentially important depth and distance information derived from motion (Ellis, Menges, Jacoby, Adelstein, & McCandless, 1997; Crvarich, 1995; also see Toye, 1986). In general, these studies have allowed researchers to isolate the cues responsible for spatial perception; however, their ecological value is dubious. Many would argue that motion and interactivity are necessary requirements for VE's. For the present study, users were encouraged to navigate freely through the environment, as they might in most VE applications, using the dynamic interactive nature of the medium as they explored the stimuli from different perspectives of their own choosing. A standard distance was shown to participants before beginning their first trial. Perceived distances were then measured from participants' magnitude estimations.

2.1 Method

2.1.1 Participants. 59 undergraduate Psychology students from the University of Washington Psychology department's human subject pool participated in a short screening study that taught the rudiments of VE navigation with an electronic mouse. The first 16 men and 14 women in this study to reach criterion performance on a mouse navigation task were asked to participate in the distance estimation experiment. From this group, twenty people (10 men) ranging in age from 18 to 25 (M = 19.81, SD = 1.60) eventually completed the distance estimation experiment. Participants were paid $10 per hour.

2.1.2 Stimuli and apparatus. The virtual environment was a dark gray cubic room measuring 300 world-units on each side. On half of the trials, a rectangular grid was superimposed on the walls, floor, and ceiling of the room. The meshing of the grid (approximately 10 units) was fine enough to preclude participants from using counting strategies to determine distances on most trials. At the beginning of each trial, two small boxes, one red and the other green, were placed at random locations in the room (see fig 1).

This environment was modeled in World Up® by SENSE8® and run on a Pentium® Pro 200 using an Oxygen™ 102 graphics accelerator board. The GFOV of the world was set at 80°. Participants assigned to the desktop condition viewed the VE while sitting 38 cm from a 35 cm x 26.5 cm monitor with a resolution of 1152 x 900 (32K colors, 76 Hz refresh). Viewing distance was controlled by a hood placed around the monitor that also served to shield participants' peripheral view. The frame rate for this system was approximately 8.61 frames per second.

Participants in the immersive condition interacted with the VE by moving in a 1.83 m x 1.83 m curtained enclosure in the real world. Head movements were tracked with a six degree-of-freedom tracker (Polhemus Fastrak®). The sensitivity of the tracker was calibrated so that collisions between the virtual viewpoint and the walls in the VE corresponded to collisions between the participant's body and the curtains of the real room. These collisions were signaled with a tone. Immersed participants viewed the VE in a VR4 HMD from Virtual Research, which provides approximately a 60° horizontal field of view with 742 x 230 resolution. These participants told their distance estimates to the experimenter who entered them into the computer. Participants in the desktop condition navigated by means of mouse commands that provided six degrees-of-freedom of movement. Desktop participants entered their distance estimates directly into the computer.

2.1.3 Procedure. Equal numbers of participants were randomly assigned to both the immersed and the desktop condition. Participants took part in three one-hour experimental sessions conducted on three different days. Each session was composed of five ten-minute blocks of trials separated by a two-minute break. These breaks were used to reduce the chances of immersive participants experiencing symptoms of simulator sickness. In fact, none of the participants complained of such symptoms.

At the beginning of the experiment, participants were told that they would be repeatedly placed in a virtual room that measured 300 x 300 x 300 units and to make their distance estimates with this scale in mind. They were told that the researchers were interested in their initial estimates of the distances between the two blocks and were instructed not to spend too much time with any one trial. At the beginning of each trial, the participant's virtual viewpoint was set in the corner of the room at a height that modeled their real-world height. The participant then navigated through the room, examining the two blocks from as many vantage points as he or she felt necessary to make an accurate estimate of the distance between them. When ready, the participant made his or her estimate and then was given feedback about the correct distance, whereupon the next trial began.

2.2 Results

Participants completed an average of 139 (SD = 44.08) trials during all three sessions. For the analyses that follow, mean percent overestimation, estimated model parameters, and model fits (R^2) were calculated separately for each participant in each trial type (grid present and grid absent). These dependent variables were then subject to separate 2 (grid present/absent) x 2 (desktop/immersed) x 2 (male/female) mixed effects univariate ANOVA's. To ensure comparability between model fits, all models were fit using non-linear regression. All statistical tests employ a two-tailed alpha level of .05.

2.2.1 Percent overestimation.

Across all twenty participants, overall percent distance errors ranged from -9.23% to 9.82% (M = 0.31%, SD = 4.78). The mean was not significantly different from zero (t(19) = 0.298, p = .78). The presence of the grid had a significant, though slight, effect on overestimation. The between-subject variables -- display mode (desktop vs. immersed) and gender -- had a less powerful effect on accuracy.

Participants tended to overestimate distances more when the grid was absent (M = 3.26%, SD = 3.79) than when it was present (M = 1.91%; SD = 3.44). A 2 (grid present/absent) x 2 (desktop/immersed) x 2 (gender) ANOVA revealed a significant main effect of the grid (F(1, 16) = 5.73, p = .029). No other main effects or interactions were significant at the .05 level, although the difference in overestimation between immersed (M = 1.55%, SD = 5.03) and desktop (M = 3.63%, SD = 4.12) participants was notable (F(1, 16) = 2.06, p = .17). The effects of the grid and immersion are illustrated in figure 2.

Effect sizes (η^2) of grid presence, gender, and immersion on overestimation were estimated at .26, .13, and .11 respectively.

2.2.2. Model selection. A more general version of the power model (with an additive constant) was fit to each participant's data for both the grid present and grid absent conditions:

$$\delta = a + k \cdot d^n$$

Because the presence of the grid did not have a significant effect on any of the parameter estimates or model fits (R^2), all models were subsequently fit collapsing over the grid conditions. Median parameter estimates and model fits for four versions of the more general power model are given in table 1. In general, the simple power model (with the parameter a constrained to equal zero) provided the most parsimonious fit for participants' data, explaining on average just under 70% (SD = 0.10) of the variance in their estimates. For every participant, the simple power model explained slightly more variance than the linear model (with n constrained to equal one). The addition of the additive constant parameter provided a significantly better fit to the data for only one of the participants.

2.2.3 Steven's exponents and power model fit. Exponent estimates for the twenty participants (collapsed over grid conditions) ranged from 0.71 to 1.02 (M = 0.88, SD = 0.08) and were significantly less than one ($t(19) = 6.44$, $p < .0001$). For ten (50%) of the participants, the 95% confidence interval of the exponent estimate did not contain one. A 2 (grid) x 2 (display mode) x 2 (gender) ANOVA revealed a significant main effect of gender ($F(1,16) = 5.31$, $p = .04$), such that exponents for men (M = 0.92, SD = 0.07) were significantly higher than those for women (M = 0.85, SD = 0.07). No other main effects or interactions were significant. The effect of display mode approached significance (F(1,16) = 4.27, $p = .055$), with exponents estimated from desktop performance (M = 0.85, SD = 0.08) being slightly lower than those from the immersed condition (M = 0.91, SD = 0.08). Figure 3 illustrates the effects of gender and immersion on exponent estimates.

Averaged over all participants, the estimated modulus (M = 2.03; SD = 0.96) was significantly greater than one (t (19) = 4.81, $p < .001$). Estimates of the modulus (k) were highly correlated with exponent estimates (r(18) = .97, $p < .001$), and the effects of the independent variables on the modulus were the same as for the exponent.

R^2 values from the simple power model were not significantly affected by gender, immersion, or the presence of the grid. A 2 (grid) x 2 (display mode) x 2 (gender) mixed effects ANOVA revealed no significant effects or interactions on participants' R^2 values. However, again, the effect of immersion approached significance (F(1,16) = 3.87, $p = .07$) with the simple power model fitting better for immersed participants (M = .74, SD = 0.09) than for desktop participants (M = .65, SD = 0.10).

2.2.4 The effect of feedback. Figure 4 illustrates participants' average percent of overestimation for the first ten trials. The figure suggests that after an initial tendency to underestimate distances slightly on the first two trials, participants overcompensate on the next few trials by overestimating the distances.

2.3 Discussion

The evidence from this experiment is consistent with the notion that the accuracy of distance judgments in VE's follows similar patterns as in the real world. As with real world studies, participants' exocentric virtual distance estimations were more accurate than previously reported egocentric estimates of virtual distances (Witmer & Kline, 1998), and were, on average, slightly overestimated. However, whereas Witmer and Kline (1998) found that egocentric distances were dramatically underestimated in VE's, the present study finds a more modest effect on exocentric distance judgments. It is likely that the ecological approach of allowing participants to navigate freely through the VE before generating an estimate accounts for much of this difference. Although differences in mean accuracy between egocentric and exocentric distance perception appear to behave similarly in VE's and the real world, it is worth noting that distance estimations in VE's are much more variable than in the real world. Real world studies of distance perception typically report coefficients of determination ($\underline{R}^2$) for Steven's power model to be well above .90 (Levin & Haber, 1993; DaSilva, 1982). The mean $\underline{R}^2$ of .70 obtained in experiment one illustrates the important and often-neglected fact that performance measures obtained in a VE are more variable than those obtained under similar circumstances in the real world. A worthy goal of future research is to examine the sources of the additional variance introduced by VE's.

Although estimates of Steven's exponents were significantly less than one for all conditions in this experiment, accuracy measures clearly indicated a general trend of distance overestimation. It can thus be inferred that much of the explanatory strength of Steven's law for modeling exocentric distance judgments in VE's comes from the modulus parameter. Modulus effects in real world psychophysics are uncommon, and are indicative of factors that affect judgments proportionally the same for all stimulus magnitudes. The larger than normal influence of the modulus on modeling virtual distance estimations may thus be due to factors that are unique to the perception of VE's. Such factors may include the combination of depth cues available from a VE, navigational metaphors, or task demands. At the very least, the influence of the modulus in this experiment serves as a clear example that exponent estimates cannot substitute for accuracy measures.

The effect of immersion repeatedly approached significance, with immersed participants being more accurate, more linear, and less varied with their estimates than participants who use a desktop display. That immersion was manipulated between (instead of within) relatively few participants is perhaps the main reason why it did not attain significance at conventional levels. Although HMD’s may be more helpful than desktop displays for allowing knowledge of inferred spatial relationships (Ruddle, Payne, & Jones, in press) the effect of immersion on perceptual processes is less clear. It is likely that the improved performance of the immersed participants in this experiment was due in large part to a more intuitive navigational interface – a head position tracker – and not the display characteristics of the HMD per se. More research is clearly warranted to disambiguate the roles of visual and proprioceptive/vestibular information on spatial perception and cognition.

3. Experiment Two

The previous experiment suggested that the direction and magnitude of participants’ accuracy varied systematically over the initial trials of the experiment (see figure 4). It is likely that this variation was due to the feedback that participants were given about the accuracy of their judgments. Experiment two examines this issue more directly by withholding feedback from one group of participants and comparing their performance to another group who receives it.

The effect of grid in experiment one, though significant, was quite small, yielding only a 1.35% improvement in estimation accuracy. For experiment two, the grid appeared on all trials and three levels of GFOV were manipulated within subjects.

3.1 Method

3.1.1 Participants. 24 undergraduate students (13 women) with a mean age of 21.74 (SD = 4.31) were recruited from the University of Washington department of Psychology human subject pool. All participants were given extra credit toward their Psychology class for their participation except for two who were paid $10 per hour.

3.1.2 Stimuli and apparatus. With few exceptions, the stimuli and apparatus used were exactly the same as the desktop portion of experiment one. On each trial, the computer randomly selected one of three geometric fields of view (50°, 80°, or 100°). At participants' viewing distance of 38 cm, the 50° GFOV presented identical physical and geometric fields of view. The 80° GFOV was the same as that used in experiment one. Figure 5 illustrates the appearance of the three GFOV conditions. Unlike experiment one, the grid was present on every trial, and the environment provided feedback only to people who were assigned to the feedback condition. The computer also recorded the amount of time taken to complete each trial.

All participants used the desktop system described in experiment one, although the resolution was changed to 640 x 480 (75 Hz. refresh) and a different graphics accelerator was used (Diamond Fire GL 3000). The frame rate for this system was approximately 24.18 frames per second.

3.1.3 Procedure. Participants were trained on the rudiments of VE navigation with a mouse. They were then required to complete a 'virtual obstacle course' in less than four minutes before continuing participation. Participants were then randomly assigned to either receive feedback or not (subject to the constraint that equal numbers of participants appear in each feedback condition). As in experiment one, each trial began with a red and a green block being randomly placed inside the environment. Participants were instructed not to spend too much time on any one trial, but were also told that they should feel free to view the blocks from whatever perspectives they felt necessary to arrive at an accurate distance estimation. Participants made as many distance estimations as they could in the remaining time, taking breaks whenever they wished.

3.2. Results Participants completed an average of 87.46 trials (SD = 23.19), with roughly one-third at each GFOV setting. Percent overestimation, estimated parameters, and model fits were calculated separately for each participant and were subsequently used as dependent variables in separate 3 (GFOV) x 2 (feedback) x 2 (gender) ANOVA's.

3.2.1 Percent overestimation. Accuracy was clearly affected by both feedback and GFOV, but not by gender. In general, participants were more accurate when given feedback and when viewing the VE with the moderate GFOV's as illustrated in figure 6. An ANOVA confirms that main effects of GFOV ($F(2, 40) = 35.61$, $p < .001$) and feedback ($F(1, 20) = 9.50$, $p = .006$) are highly significant. No other main effect or interaction approached significance. Effect sizes (η^2) for GFOV and feedback were estimated at .64 and .32 respectively.

Participants tended to overestimate distances much more and to be more variable in their responses without feedback (M = 24.49%, SD = 26.55) than with (M = 0.80%, SD = 6.99). Figure 7 illustrates the percent of overestimation for participants in both feedback conditions across the first ten trials. By the seventh trial, the difference between the percent of overestimation for participants who received feedback (M = 6.38%, SD = 38.42) was significantly lower than for those who did not receive feedback (M = 41.06%, SD = 35.61) (t(22) = 2.29, p = .023).

Specific effects of GFOV were examined with pairwise contrasts. These revealed that accuracy was significantly different between the 50° GFOV condition (M_{feedback} = -11.19%; SD = 9.73; M_{none} = 14.09%, SD = 26.13) and the 80° GFOV condition (M_{feedback} = 0.82%; SD = 7.44; M_{none} = 23.45%, SD = 26.42) (F(1,20) = 38.115, p < .001). In fact, for the participants who received feedback, the underestimation of -11.19% in trials with a 50° GFOV was significantly less than zero (t(11) = 3.98, p = .002). Overestimation was also significantly reduced between the 100° and the 80° GFOV trials ($M_{\text{feedback, }100^\circ}$ = 6.47%; SD = 10.62; $M_{\text{none, }100^\circ}$ = 34.97%, SD = 29.58) (F(1,20) = 11.53, p = .003).

3.2.2 Time to complete trials and the effect of resolution. The GFOV significantly affected how long participants took to complete each trial, with narrow GFOV trials taking nearly 1.5 times as long as others. Contrasts in the 3 x 2 x 2 ANOVA on completion time confirmed that mean times for the 50° GFOV (M = 72.02 s, SD = 36.30) were significantly greater than those for either the 80° (M = 49.69 s, SD = 26.48) (F(1, 20) = 33.18, p < .001) or 100° (M = 48.51 s, SD = 25.69) (F(1,20) = 22.03, p < .001) GFOV's. No other factor or interaction of factors had a significant impact on participants' time to complete a trial.

For those participants who received feedback, trials with an 80° GFOV ($M_{\text{\% overestimate}}$ = 0.82%, SD = 7.44) were viewed under nearly the exact same conditions as those desktop participants in experiment one who judged trials on which the grid was present ($M_{\text{\% overestimate}}$ = 1.91%, SD = 3.44). The only differences between these two conditions were the resolution setting of the monitor and the frame rate, which had no significant effect on distance estimation accuracy (*t*(30) = 0.57, n.s.).

3.2.3 Steven's exponents and power model fit. The simple power model was fit separately to each participant's data for each GFOV condition. Across the 24 participants, exponent estimates from these model fits ranged from 0.54 to 1.03 (*M* = 0.80, *SD* = 0.12). The mean was significantly less than one (*t*(23) = 8.30, *p* < .001). For 11 (46%) of the participants, the 95% confidence interval of the exponent estimate did not contain one. R^2 values from these models ranged between .32 and .72 (*M* = .56, *SD* = 0.11). Neither exponent estimates nor R^2 values were significantly affected by GFOV, feedback, gender, or any of their interactions. However, the observed power to detect these effects was rather low, ranging from .05 to .43 (*M* = .19).

3.3 Discussion

The presence of feedback yielded perhaps the most striking effect in this experiment, improving estimation accuracy by nearly 25%. Figure 7 illustrates that feedback began to exert this influence by the sixth or seventh trial. This result has clear implications for training. For VE applications for which the acquisition of metric spatial knowledge is important, a brief period of training with feedback may dramatically improve people's accuracy in estimating distances. On the other hand, it is important to recognize that although the presence of feedback had a profound influence on absolute accuracy, it did not have an effect on judgments of relative distances. Because Steven's power law fit participants' data equally well regardless of whether they received feedback, it appears that all participants were consistently using their own psychological scale. However, only those who received feedback were able to adjust their internal scale to the actual scale used in the environment. This suggests that topological information and ordinal spatial relations are accurately perceived in VE's whether or not feedback is given.

This experiment also corroborates previous findings that the GFOV is an important determinant of spatial perception, and that a GFOV between 50 and 80 degrees leads to more accurate perceptions. A low GFOV – even when it corresponded to the physical field of view – caused participants to spend a significantly longer time to arrive at significantly greater inaccuracies. Similarly, participants systematically overestimated distances with a very wide GFOV. It is likely that the effect on accuracy is due to the magnification (or minification) induced by a lower (or higher) GFOV. Lumsden (1980) has described the distortions in perceived distances due to magnification in photography, and it is likely that similar perceptual mechanisms operate in VE's. Alternately, it is possible that because the decreased GFOV made it less likely for both objects to be displayed together, the distance estimation task in the low GFOV condition was more likely to be inferential than perceptual. Because inferred distances are typically more underestimated than perceived distances (Wiest & Bell, 1985), an alternative explanation for the effect of GFOV on accuracy maintains that the GFOV altered the nature of the task.

4. General Discussion

The experiments reported in this paper provide compelling evidence that distances in VE's are not necessarily perceived as radically different than how they are perceived in the real world. Given proper feedback, a sufficiently wide GFOV, and the ability to move in the environment, participants were unbiased and nearly perfectly accurate in their estimations of interobject distances, as has been found with real world studies. These results contrast somewhat with those of Witmer and Kline (1998) who concluded that distance estimations in VE’s are less accurate than in the real world. These authors noted that estimations of perceived distances in VE’s were not made more accurate by the addition of textures or by more intuitive navigational devices. The present results indicate – at least for exocentric distances – that people can perceive distances in VE’s nearly as well as they can in the real world.

A crucial and unresolved question with this research concerns the role of distance perception in the construction of spatial representations. At some level, it is undeniable that large-scale spatial representations are composed of integrated sets of perceptions; however, it is not clear what perceptual aspects are needed to derive an accurate or useful cognitive representation of an environment. Many would doubt that accurate perception of metric distances is required for survey knowledge. The degree to which perceptual accuracy predicts representational accuracy is an important future research endeavor.

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Table 1

Four versions of the model: $\delta = a + k \cdot d^n$. Median parameter estimates and mean R^2 values averaged over the 20 participants from experiment one.

Model	**Constraints**	**Median Estimated Parameters***			**Mean R^2**
		a	k	n	
Proportional	a = 0 ; n = 1		0.99 (4)		.68
Linear	n = 1	13.86 (7)	0.92 (9)		.69 (8) †
Power	a = 0		1.71 (3)	0.89 (10)	.70 (10) †
Saturated	none	-59.46 (0)	7.81 (0)	0.65 (4)	.70 (1)‡

Note. * number in parentheses indicates the number of participants for whom the 95% confidence interval of the estimate does not contain the canonical value (a = 0; n = k = 1).

† indicates the number of participants for whom the model provides a significantly better fit than the proportional model.

‡ indicates the number of participants for whom the model provides a significantly better fit than the power model.

Figure Captions

Figure 1. Views of the VE used in experiment one. Participants freely navigated through the environment and estimated the distance between the two cubes. On half of the trials, the walls of the room were covered with a grid.

Figure 2. Mean percent overestimation (and standard errors) of distances in experiment one.

Figure 3. Mean estimated Steven’s exponents (and standard errors) for distance estimations in experiment one.

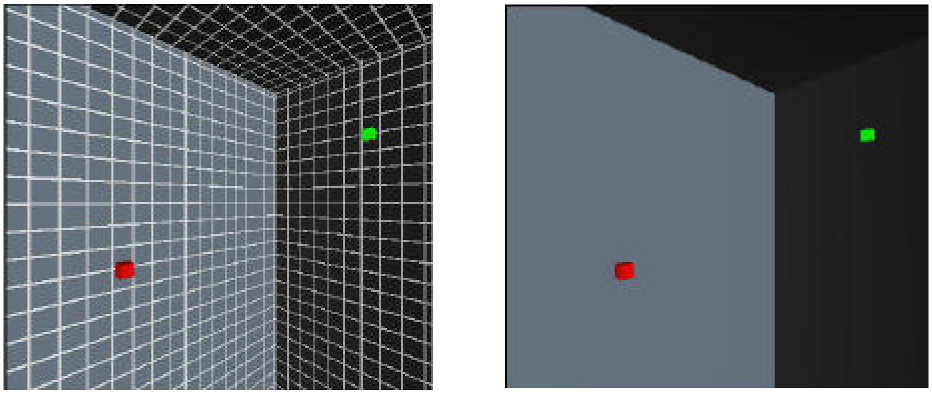
Figure 4. Mean percent overestimation (and 95% CI) of distances on the first ten trials of experiment one.

Figure 5. Three views of the same environment at the three GFOV settings used in experiment two. From left to right, the GFOV’s are 50, 80, and 100 degrees.

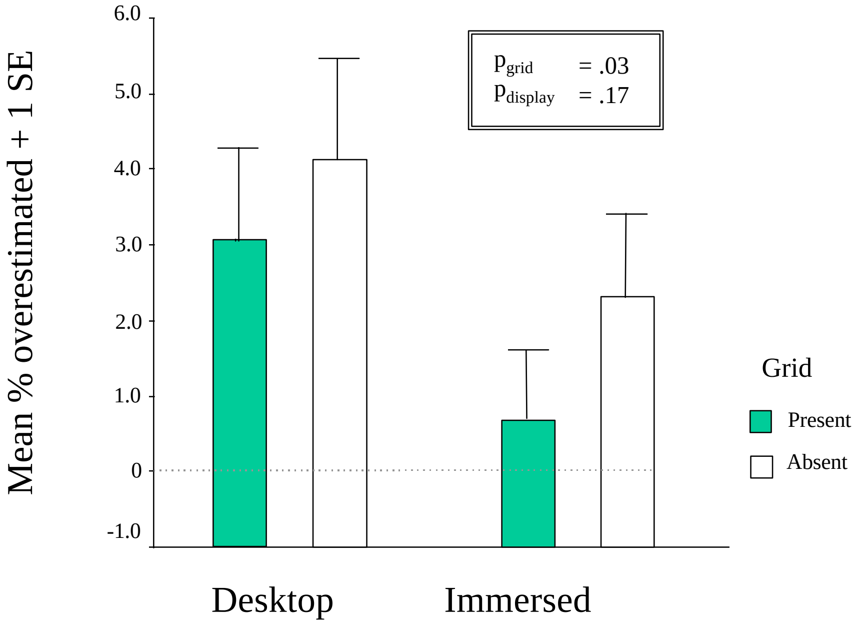
Figure 6 Mean percent overestimation (and standard errors) of distances in experiment two.

Figure 7. Mean percent overestimation of distances on the first ten trials for participants who did and did not receive feedback

Waller, Fig. 1



Waller, Fig. 2



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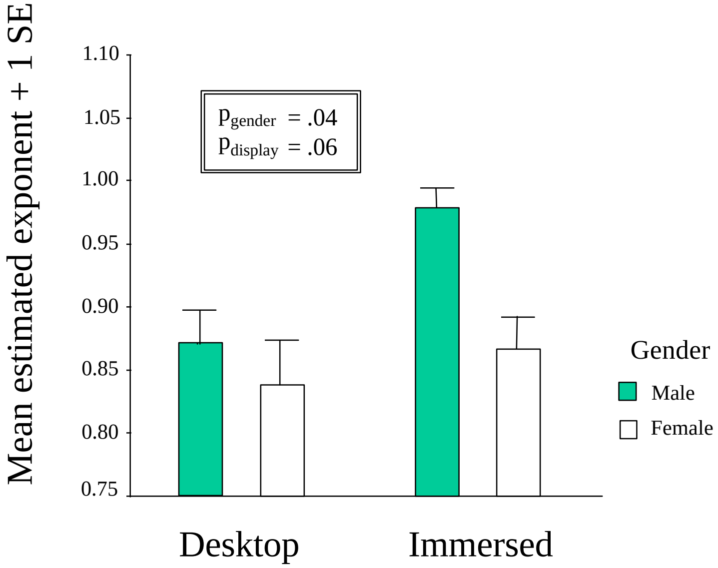

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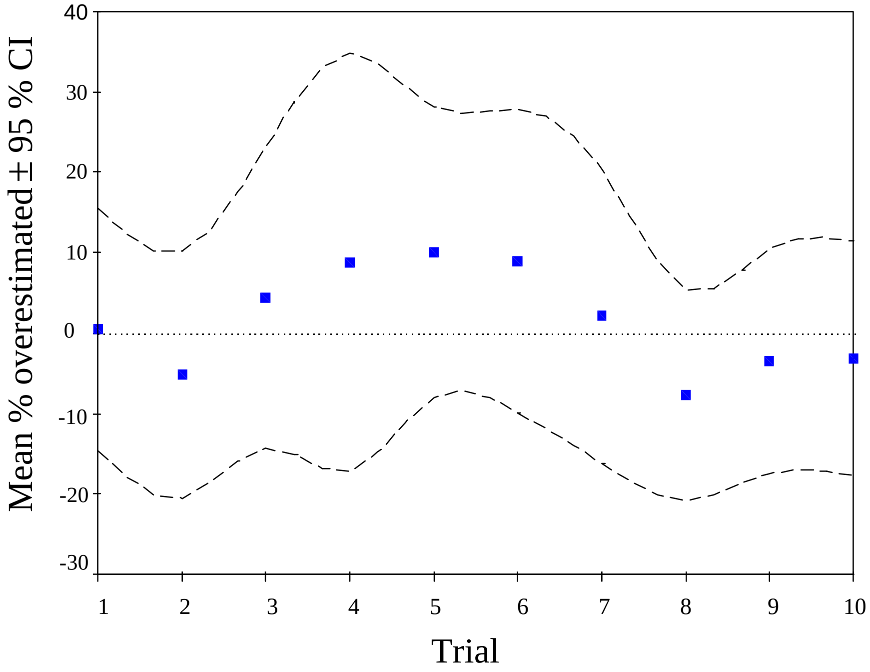

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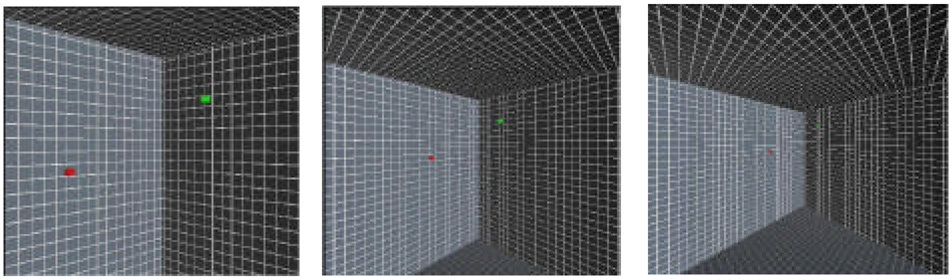

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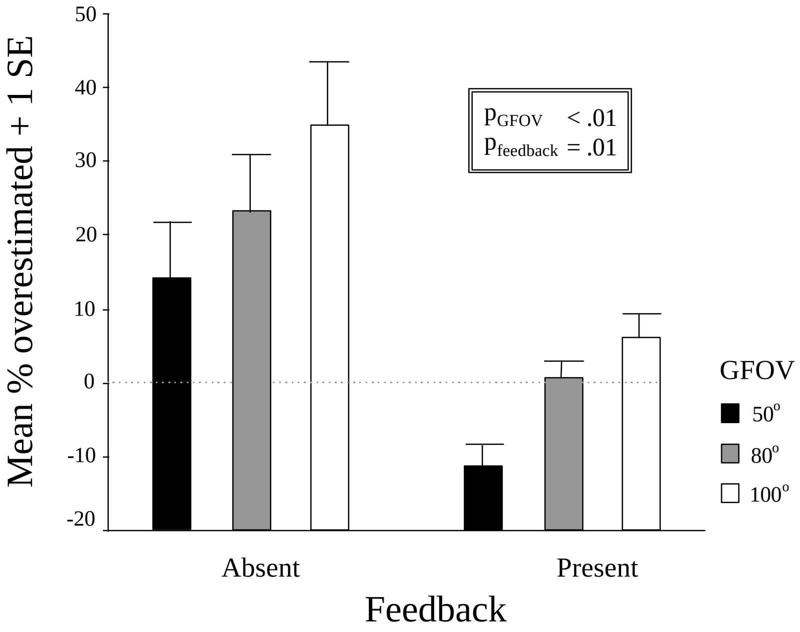
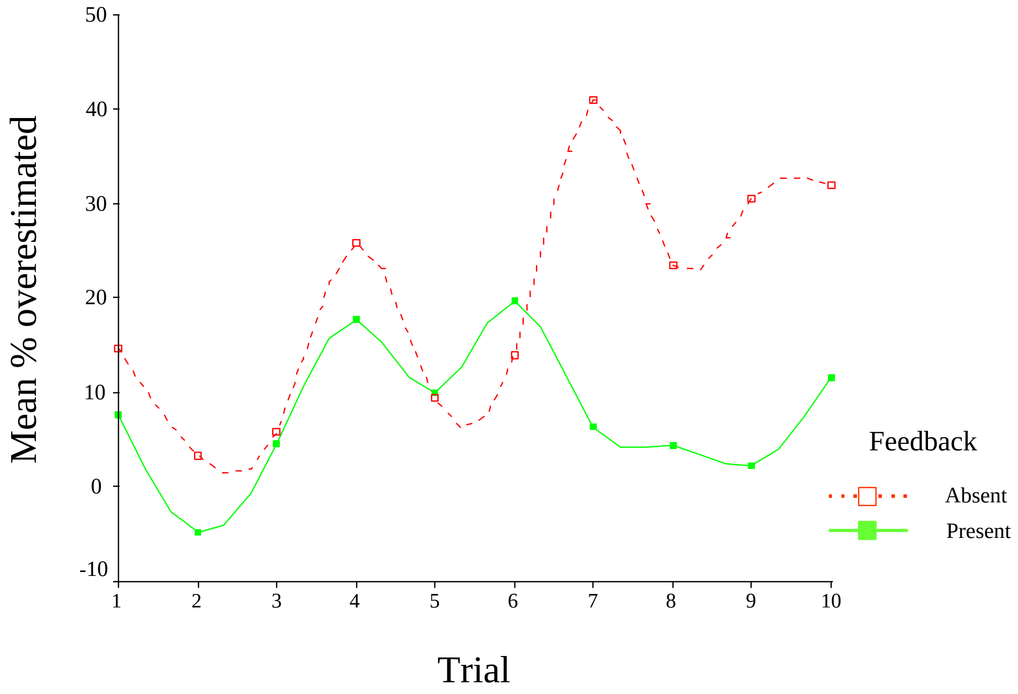


Waller, Fig. 7


50
40
30
20
10
0
-10
Mean % overestimated
1
2
3
4
5
6
7
8
9
10
Trial
Feedback
Absent
Present