ABSTRACT

THE EFFECT OF FEEDBACK TRAINING ON DISTANCE ESTIMATION IN VIRTUAL ENVIRONMENTS

by Adam R. Richardson

This paper investigates the perception of distance in virtual environments. It describes an experiment designed to determine observers' ability to make use of error corrective feedback to improve the accuracy of judgments of absolute egocentric and exocentric distances. Observers viewed objects at varying distances in a virtual environment and gave their estimates of distance through a blindfolded walking task, in which observers walked the distance to or between previously viewed targets. Feedback training was provided to observers based on experimental condition. The effect of feedback was quite specific. Receiving egocentric feedback significantly improved only observers' egocentric distance estimates, and exocentric feedback improved only people's exocentric distance estimates. This improved ability to estimate egocentric as well as exocentric distances persisted for at least one week's time.

The Effect of Feedback Training on Distance Estimation In Virtual Environments

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The efficacy of visually immersive interfaces designed for applications such as simulation, education, production, and training is largely a function of how well these interfaces can communicate a sense of the world to their users. Users' descriptions of such interfaces often reveal difficulties in representing scale appropriately (Knapp, 1999; Loomis & Knapp, 2003; Witmer & Kline, 1998; Witmer & Sadowski, 1998; Thompson et al., 2002). For example Thompson et al., (2002) have shown that even very high fidelity virtual worlds can appear much smaller than their intended size. In reviewing the experiments that have investigated this phenomenon, it is not unwarranted to conclude that absolute egocentric distance judgments to targets presented in visually immersive displays are often compressed by as much as 50% of their intended size (Thompson et al., 2002; Proffitt, 2003; Knapp, 1999; Loomis & Knapp, 2003; Witmer & Kline, 1998; Witmer & Sadowski, 1998).

There has been much speculation about the cause of this compression effect. Loomis & Knapp (2003) investigated the limited horizontal field of view (HFOV) available to users wearing head mounted displays (HMD's) as a possible cause for the foreshortening effect of egocentric distance. They compared the performance of users who made distance judgments in the real world with that of users in a virtual environment (VE), utilizing the same HFOV in each condition. Performance under real world conditions was superior to that in the VE condition, and led the researchers to conclude that the HFOV is not responsible for this compression of distance estimates. Sinai, Ooi and He (1998), on the other hand, speculated about the importance of information available in the vertical field of view (VFOV). They designed a study that investigated the influence of texture discontinuity of the ground surface and its effects on distance perception. Observers were asked to estimate distances to targets on the ground plane by means of a blindfolded walking task and a perceptual matching task. The ground surface

between the observers station point and the target was either continuous or included a gap, which effectively disrupted the texture gradient. Estimates from individuals judging distances across the gap underestimated the distances in contrast to individuals judging distances without the gap who gave accurate estimates. Overall, the results from their investigation led them to conclude that texture discontinuity on the ground plane caused errors in absolute egocentric distance estimates with both methods of response.

Thompson et al., (2002) considered errors in accommodation, and limits on the resolution and quality of images displayed in HMD's as a possible cause for the underestimation of absolute egocentric distance in VEs. These researchers manipulated the level of detail and resolution of images in the VE, ranging from wire-frame representations to photorealistic environments. Participant's performance showed the same compression effects regardless of the level of detail in the VE. This result led the researchers to conclude that the level of detail present in the environment does not effect the accuracy of distance estimates in VEs. Other theories for the cause of this compression effect include difficulty in presenting accurate binocular stereo images using HMD's, (Witmer & Sadowski, 1998) as well as the reduction in perceived effort needed to move through these VEs, (Proffitt, 2003). Most research that has investigated this phenomenon however has only been able to speculate about the causes of such misperceptions.

All of the hypothesized causes for this effect have typically involved the technological limitations of current VEs. Instead of focusing on the technological issues associated with accurate distance estimation in VEs, the present project examines a manipulation of the user. Specifically, I investigated the influence of feedback training on the perception of egocentric and exocentric distances in VEs.

Background

In this paper I distinguish between two fundamental types of distances. *Egocentric* distances are measured from an observer's location to other locations in the environment. *Exocentric* distances refer to distances between two separate locations in the environment (not including the observer's location). This distinction is important because the ability to perceive these types of distances are thought to be independent of one another. For example, Loomis et al, (1996) asked observers to make judgments of egocentric and exocentric distance. Observer's estimates of egocentric distance showed no error under full cue conditions while estimates of exocentric distance showed systematic errors resulting from foreshortening. The results of their investigation led them to conclude that the patterns of error associated with estimation of egocentric and exocentric distances are distinct. They concluded that the perception of exocentric distance is decoupled from the perception of location.

These and other findings support the concept that people use multiple frames of reference in coding object location. For instance, an *egocentric* reference system is specified with respect to the observer's location. An observer's representation of the environment given an egocentric reference frame would consist of multiple self to object relationships and is dependent on the location of the observer. This type of system facilitates perception and estimation of egocentric distances. *Allocentric* reference systems also known as *environmental* or *exocentric* reference systems are those in which location is specified with respect to objects other than the observer. From an allocentric reference frame, an observer's representation of the environment would consist of multiple object to object relationships and would therefore not be affected by the location of the observer. Such a system might naturally underlie estimations of exocentric distances.

Several theories have been posited regarding how observers are able to make both egocentric and exocentric distance estimates. One such theory of visual perception, namely direct perception, was put forth by James J. Gibson. This theory suggests that information about the visual world is perceived directly from the ambient optic array, requiring no cognitive processing, and is therefore not dependent upon the retinal image (Gibson, 1979). This theory considers variant and invariant structure found in the optic array to be the sources of information for visual perception. For example, an egocentric distance could be perceived directly by means of attending to structures in the environment such as texture gradients and the horizon ratio invariant based upon the point of observation. However, an exocentric distance remains invariant regardless of the point of observation and serves as information for making an estimate of distance.

Others such as Easton & Sholl (1995) and O'Keefe & Nadel (1978) suggest that mobile organisms require that egocentric and allocentric reference frames operate in unison with one another. A representation such as the one they propose would be characterized by the overlapping of egocentric self to object relationships on to a more stable set of object to object relationships. Easton & Sholl, found evidence for just such a representation of the environment from an experiment that required observers to view an array of objects and then to close their eyes and either imagine themselves in the same place but facing another direction (rotation) or to imagine themselves facing the same direction but in a different place (translation). The results suggested that participants imagined themselves mentally rotating or translating, thereby continuously updating their self to object relationships by imagining their bodies moving in space relative to a stable configuration of objects, and that access of object location occurs within updated egocentric coordinates after that process is completed (Easton & Sholl, 1995). They

came to this conclusion due to the fact that judgments that did not require imagined rotation but did require imagined translation were easier for participants than judgments that required imagined rotation but not imagined translation. In contrast to the Gibsonian framework, these findings support a theory of distance perception that requires a large amount of cognitive processing to take place before an estimate can be produced.

Methods for measuring distance perception

Much of the evidence for the underestimation of egocentric distances has been garnered from tasks in which participants make verbal estimations of distance (Lampton, Singer & McDonald, 1995; Witmer & Kline, 1998). Despite the relative ease by which these estimates can be measured, verbal responses have several disadvantages. Verbal estimates are highly variable and can be biased by external factors such as, an individual's ability to apply an external metric to their perception (Wiest & Bell, 1985). In addition they do not provide the observer directly with very accurate feedback. For example, a verbal estimate requires the participant to internalize a standard unit of measurement such as one meter or three paces, however, the concept of one meter or three paces may vary widely between individuals. Moreover, verbalizing distances is not a well-practiced task. Typically, we relate distances with motoric responses such as walking to a location, noting its distance as we approach.

A more preferred, as well as ecologically valid, method for collecting responses of visually observed distances is to use an action-based task. Action based tasks take into account that "awareness of space, is based upon action in space" (Piaget, 25, p. 4). In addition to their increased validity and reduced variability of estimates (Loomis & Knapp, 2003), action based tasks also serve to provide excellent feedback, which can in turn be a source of valuable

information (Loomis & Knapp, 2003, Gibson, 1953). These action-based tasks can take many forms: triangulated walking (Loomis et al., 1992; Fukusima, Loomis, & Da Silva, 1997; Worchel, 1952), and open-loop walking (Philbeck & Loomis, 1997; Sinai, Ooi and He, 1998; Thomson, 1983; Worchel, 1952) are examples of such tasks.

The study reported here makes use of the open-loop walking task paradigm. Open-loop walking is a method of absolute distance estimation in which the observer, after initially seeing a target, walks to the target location without visual feedback. The observer thus receives no information about positional error.

In contrast, during closed-loop walking, the observer views the target and begins to walk toward the target, while receiving information from visual input. This allows for the “looping-back” of information in the form of error, this information can then be used to modify the path or distance walked to reach the target. Without this visual feedback, the loop remains “open”. Under conditions in which the loop remains “open”, the response is more reflective of the initial visual input. Unlike verbal distance estimates, which depend upon an individual's conception of what constitutes the unit of measure, open-loop walking appears to provide an accurate, unbiased measure of perceived distance (Witmer & Sadowski, 1998). If an environment, in this case a VE, distorts perceived distance, then responses made during open-loop walking should accurately reflect those distortions.

Distance perception in the real world

The study of distance perception in the real world has shown that the relationship between the actual distance (d) and the estimated distance ($\hat{d}$) can often be adequately modeled by Steven's power law:

$$\hat{d} = k \cdot d^n$$

where the modulus (k), and the exponent (n), depend on the nature of the judgment (Stevens, 1975).

Although traditionally, most research has focused upon the exponent estimate, which is most often used to measure the degree of underestimation or overestimation, absolute accuracy in distance estimation must account for both modulus and exponent estimates (Montello, 1991). For example, Waller, (1999) illustrated overall distance overestimation despite exponent estimates less than one. In 1985, Wiest & Bell, compiled the results from over 70 experiments that yielded Steven's exponents for distance in an attempt to uncover the main sources of variation in the relationship between perceived and actual distance. Their findings showed that the type of distance judgment, whether it be perceived, remembered or inferred distance accounts for over 40% of the variation of exponent values. Wiest & Bell concluded that this variation may represent the level of complexity and amount of cognitive processing necessary to produce an estimate of distance. Producing an estimate of perceived distance may take some minimal level of processing, but an estimate of remembered distance would be more complex and require more processing, lastly producing an estimate of an inferred distance would be even more complex and require still more processing. According to Wiest & Bell, this would theoretically produce a pattern of mean estimates of the exponent in which perceived distance exponents are

larger than remembered distance exponents, which are also larger than inferred distance exponents.

In addition, Wiest & Bell (1985) concluded that well practiced observers, (those that received feedback while producing estimates of distance) should generate exponent values closer to unity as opposed to non-practiced observers due to the reduction in the level of processing necessary to make the judgment. In other words, the practiced observers will make more accurate estimations than non-practiced observers due to the lower amount of cognitive processing needed to generate the estimate. In real world settings, judgments of egocentric distance have been shown to be accurate when participants are first asked to view an object and then walk to it without further visual information (Elliot, 1987, Thomson, 1983). The results of experiments conducted with similar methods (i.e., open-loop walking tasks) report real world estimates of distance to be 87% to 91% of the true distances (Witmer & Sadowski, 1998).

Although there are comparatively few studies pertaining to exocentric distance perception, those that have been conducted, find that exocentric distances are less likely to be underestimated (Gogel, 1977), than egocentric distances. In a study of intercity distance estimation by means of magnitude estimation, Da Silva et al., (1987) found the same ordinal pattern of results for mean estimates as Wiest & Bell (1985). Perceived intercity distance (from a map) yielded exponent estimates larger than those of remembered intercity distance, which were also larger than exponent estimates from inferred intercity distance. In addition Da Silva et al., also found that the magnitude estimates for each of the perceived, remembered and inferred exponent estimates remained stable after a one month intersession interval.

Another, perhaps more commonly used measure of accuracy of distance estimates is the percentage of under (or over) estimation, defined as:

$$\text{Underestimation / Overestimation} = [e / d]$$

Where (e) represents the estimated distance and (d) represents the actual distance. This measure of accuracy is preferred over exponent estimates because of its intuitive nature and will be employed in the analyses of the study that is to follow.

Distance perception in virtual environments

There is strong evidence to support the notion that an observer's tendency to underestimate egocentric distances is even more pronounced in VEs (Witmer & Kline, 1998; Witmer & Sadowski, 1998; Loomis & Knapp, 2003; Thompson et al, 2002). These studies have found that in some cases egocentric distances in a VE may be perceived as being less than half their modeled distance. Witmer & Kline, (1998), conducted a study of distance perception in a VE in which participants made verbal reports of estimated distance and found that estimates represented only 50% to 60% of the true distance. Other research that has employed motoric responses, such as walking to a previously viewed target have shown similar results. Witmer & Sadowski, (1998); Loomis & Knapp, (2003); Thompson et al, (2002), found that using motoric system responses as estimates of distance increased the reliability of observer's estimates but that the same compression effects persisted. Study's conducted concerning exocentric distance perception have shown the same compression effect but to a much lesser extent than that of egocentric distance perception (Waller, 1999).

Typically, investigators have looked for the cause of this underestimation in the aspects of the display. The findings from experiments such as those by Knapp, (1999) regarding HFOV of HMD's and Thompson et al., (2002) regarding limits on the resolution and detail of images in VEs and Witmer & Sadowski (1998) regarding the accuracy of binocular stereo images available

from HMD's have not yielded any answers to the question of why this compression effect occurs. Virtually none of these studies have dealt with the issue of compensating for these known errors in judgment and bringing observers estimates of distance closer to veridical.

Feedback training

As opposed to focusing on features of the VE that can be refined in order to eliminate this compression effect, the study reported here attempts to investigate the ability of the users themselves to overcome the limitations of the current systems that create such errors in judgment. It is likely that in time, the increased fidelity and realism of VEs will provide a more realistic experience and may ultimately lead to veridical distance perception. It so happens that, humans are currently capable of retrieving spatial information from environments with reduced cues (Thompson et al., 2002; Waller, Knapp & Hunt, 1998). Although gathering information about people's initial abilities is informative, it is possible that if given appropriate feedback early on in the use of a VE application, users could learn to mediate their estimates of distance. What is of interest here is to assess the influence of error corrective feedback on the accuracy of distance perception in VEs. Feedback may provide an immediate and cost-effective alternative to the improvement of VE applications if increased accuracy of perceptual judgments is necessary.

Feedback may work to increase the accuracy of people's performance in one of several ways. The theory of perceptual learning states that feedback can provide the observer with information about the visual scene that would otherwise go unnoticed. Once this information is revealed to the observer it can be attended to in order to provide them with more accurate information regarding perceptual judgments. An alternative theory as to how feedback can

improve the accuracy of perceptual judgments involves the concept of recalibration. This theory states that an individual will inherently make perceptual judgments based upon their own internal scale of measurement, and then feedback will provide the individual with the true scale of the world. The individual is then able by means of the feedback to recalibrate their perceptual scale to match the veridical world scale, resulting in the increased accuracy of perceptual judgments.

Past research in real world situations regarding the effect of feedback on egocentric distance estimation from a stationary viewpoint has shown that overall accuracy is improved and that the variance of people's estimations is reduced when they are provided with feedback (Gibson, 1953; Gibson & Bergman, 1954; Gibson, Bergman & Purdy, 1955). For example, Gibson & Bergman asked participants to make judgments of absolute egocentric distance to targets in an open field from several station points and provided them with feedback after each judgment. Participants then made judgments of identical distances from several station points without feedback in order to investigate the effect that feedback had on their level of accuracy. The results of this experiment showed an immediate and significant improvement in the accuracy of individuals' distance estimation skill as a result of feedback training (Gibson & Bergman, 1954).

It was the opinion of Gibson and her colleagues that feedback training did not involve perceptual learning but rather involved recalibration. They came to this conclusion because feedback did not lead to an increased ability to pick up on information in the optic array such as an invariant structure like texture gradients that would provide the individual with accurate distance information. Instead the increased accuracy of estimates of distance was thought to be the result of cognitive processes leading to a calibration of the individuals perceptual scale and the veridical world's scale. According to perceptual learning theory, once training occurs

estimates should immediately improve and remain at accurate levels, in contrast according to recalibration, estimates would improve gradually as the variability of estimates decreases and accuracy increases, yet the effects of training would not be permanent. Based on these reports, one would theorize that feedback could be equally effective in VEs. Feedback should allow people to recalibrate their internal perceptual scale with that of the VE.

An interesting aspect of feedback training deals with the distribution of practice. How long will improvement in performance last and how often will people need to be retrained in order to remain at an accurate level of performance? Horowitz and Kappauf (1945), trained observers in the absolute estimation of distance. They found an increase in error after 60 days had elapsed from the initial training, yet after a brief training period, accurate performance was again achieved.

The present study investigated the ability of feedback to affect the accuracy of individuals' performance on tasks requiring absolute egocentric as well as exocentric distance estimation in *personal space* (defined by Cutting & Vishton as the area at an arm's reach away from an observer and *action space* which extends from personal space out to 30m (Cutting & Vishton, 1995)). The effect of feedback on the perception of distance was assessed by providing immediate feedback to participants regarding their estimates of distance. Participants were assigned to three separate groups, which were given different types of feedback. One group received feedback regarding only their egocentric distances estimates (Figure 1). A second group received feedback regarding only their exocentric distance estimates (Figure 2) and finally the third group received no feedback about either their egocentric or exocentric distance estimates. This manipulation was intended to assess the degree to which feedback improved estimates in two ways. First, not only would it allow me to determine if egocentric feedback

could improve egocentric distance estimates, it also allowed me to determine if egocentric feedback could improve observers exocentric distance estimates. Conversely, it also allowed me to determine if exocentric feedback could improve observers exocentric distance estimates as well as their egocentric distance estimates. The analysis of this manipulation could have important ramifications in terms of the dissociation between egocentric and exocentric distances. If in fact the two types of distance judgments rely on different mental systems, then egocentric feedback should not influence exocentric distance estimates and vice versa.

Finally, I was interested in how long the effect of feedback lasts by means of testing observers one week after initial training had occurred. This is an important factor in training, because one must understand the ability of individuals to retain what has been learned and is also informative about how often supplemental training must occur in order to sustain an accurate level of performance.

In summary, this experiment was designed to address the following questions.

- 1) Can the estimation of distance in VEs be improved by providing feedback?
- 2) If so, can this level of improvement persist for at least a week?
- 3) Does feedback on one type of distance judgment (e.g. egocentric) influence accuracy in judgments of another type, (e.g. exocentric) and vice versa?

Method

Observers

24 (12 male, 12 female) individuals participated in this study. Their average age was 21.67 years ($SD = 3.05$). Three gender-balanced groups, each with 8 participants, composed the

three main conditions of the experiment. All participants had normal or corrected to normal vision. Individuals participated in the experiment in return for \$15 or credit toward a requirement in their introductory psychology course.

Design

We employed a 3 phase: (pretest vs. immediate posttest vs. retention posttest) X 3 feedback type: (egocentric feedback vs. exocentric feedback vs. no feedback) X 2 judgment type: (egocentric judgment, exocentric judgment) X 5 distances: (.75 m, 1.25 m, 2.25 m, 3.5 m, 4.25 m) X 3 (replication) mixed design. All factors except feedback type were manipulated within subjects.

Stimuli and apparatus

The virtual environment consisted of a textured ground plane upon which, at the beginning of every trial, a set of 3 posts, each modeled to be 100 cm tall and of differing color (red, green, blue) were randomly placed (Figure 3). The three targets were placed at depths away from the observer ranging from 75 cm to 425 cm. The targets were placed in the environment in such a way that ensured each egocentric distance had an equivalent exocentric distance (Appendix A).

The environment was presented using a Virtual Research V8 headset with interlaced 640 x 480 resolution and 50° HFOV. The display allowed for a binocular stereo image of the scene to be displayed (i.e., separate images were projected to each eye). The overlap of the images displayed to each eye in the HMD was set to the participant's own inter-pupillary distance. Height above the simulated ground plane was also set to the participant's actual standing

eye-height. Mounted on the HMD was an Intersense Intertiacube² tracker. This inertial tracker allowed for updating of the orientation of the visual image as the participant moved his or her head with an accuracy of 1° RMS and a latency of 2 ms.

The participants viewed the environment from a point of observation that allowed them limited freedom of movement. Observers stood with their feet against the edge of a walkway and were instructed not to move their feet. No other restrictions were placed on their movements. This limited freedom of movement allowed for additional visual information such as motion parallax, while eliminating strategies such as walking to a target location to gauge its depth or distance from another target location.

The computer-generated environment was rendered using an Intel Pentium 4 chipset and an Nvidia Gforce2 MX graphics card, allowing for updating of the graphics and display at 72 Hz. Assignment to each condition, randomization and presentation of the stimuli as well as collection of distance estimates and delivery of proper feedback when necessary, was controlled through a scripting facility in the Python programming language, supplemented with a utility module designed specifically for virtual environment applications. Estimates of distance were determined by means of a passive video tracking system that triangulated the position of an LED worn on the observer's head accurately down to 1 mm (Beall, 1997). The information from the position tracker was then incorporated into the Python routine, and estimates of distance were recorded to an external file.

Participants gave their response of distance by open-loop walking along a narrow foam pathway on the lab floor. Because blindfolded observers could easily determine whether or not they stood on the foam, the pathway effectively kept participants walking in one direction without veering.

Procedure

Instruction and training phase. Participants were met outside of the lab where they consented to participate in the experiment. Standing eye-height and inter-pupillary distance of each observer was obtained in the lab prior to the delivery of task instructions.

Instructions for the open-loop walking of egocentric distances directed the participant to walk confidently and without hesitation straight ahead from their point of observation along a pathway the distance that they had observed and to stop when they thought they were standing on the target's location. Instructions for the open-loop walking trials of exocentric distances directed the participant to imagine themselves at one of the target locations rather than their point of observation and to walk confidently and without hesitation from that location the distance to another target location (e.g. standing at the green post walk the distance to the blue post) and to stop when they thought they were standing on the target's location.

After reading the instructions, participants were shown a full-scale model of one of the target posts to allow them to familiarize themselves with the target. Participants were then given training in how to walk without vision. This was done to reduce variance in walking estimates that might be associated with unfamiliarity with the task, as well as to develop a level of trust between the experimenter and the participant during these blindfolded portions of the trials. Participants walked back and forth in the lab four times along pathway and were kept blindfolded for the duration of the training. Once this training was completed, participants were given two practice trials for each type of distance estimate in order to familiarize themselves with the procedure. No feedback about errors in the participant's distance estimates was provided at this point.

Pre-test. A pre-test assessed the accuracy of the observers' distance estimates in the absence of formal training. The data collected from this portion of the experiment served as a baseline for assessing the impact of the feedback training. On any given trial there were three posts placed in the environment. For egocentric trials, the red post was considered to be the target and observers estimated the distance that separated their point of observation from the target. For exocentric trials, the green and blue posts were the targets and observers judged the distance between the green and blue post. Observers were not given a specific time limit in which to give their response, but they were instructed that the experimenter was interested in their initial percepts and not to take too much time with any one estimate. This pretest resulted in 15 (three replications of each of the five distances) estimates of egocentric distance and 15 estimates of exocentric intervals for each participant. The order of trials, egocentric vs. exocentric was counterbalanced across all participants in each phase of the experiment.

Feedback Training. After the pretest, observers were given training based on their experimental condition. Observers were given another set of 15 trials, each with novel arrangements of the target locations. One third of the observers were given feedback on egocentric distance estimates, one third were given feedback about exocentric distance estimates and one third were given no feedback about their estimates at all. Observers who received feedback about their estimates of distance received this information in the form of a visual depiction of the scene in the headset (see Figures 1 & 2). This feedback showed an image of the scene with the participants starting location and target location marked accordingly. A bar extended from the starting location toward the target location representing the observers estimated distance to the target location (i.e., the distance they had walked). In addition to this, a numerical value of the difference in distance was provided in text on the display (e.g. the actual

distance was 4.25m, you estimated 3.65m). All other observers received no feedback about their estimates.

Immediate post-test and retention post-test. After the feedback training, an immediate post-test was administered to assess the effect of training. Again a new set of 30 trials with novel target locations was presented to the observers.

Observers returned after a week and were given another set of 30 trials for which the target locations matched the locations from the pretest. This set of trials was considered the retention post-test condition, and served to determine if the effect of training persisted for at least a week's time. The procedure for the immediate post-test and retention post-test phases of the experiment were the same as those used for the pre-test.

Results

Five observations from four individuals indicated distance estimates that were beyond the boundaries of the lab and were likely a result of computer error. These trials were removed from all analyses and represent only 0.2% of the total number of trials. The main dependent variable used in the following analyses was observers' error in judgment, defined as the (judged distance / actual distance). This measure allows for a straightforward interpretation of the results (e.g., a result of .5 indicates that the estimated distance was half of the modeled distance, and a result of 1 represents no error in judgment). For all of the following analyses we have collapsed over the five judged distances and the three replications. This was done in order to determine the overall effect of feedback, as opposed to determining if the effect of feedback was more pronounced at certain distances. All significance tests use $\alpha = .05$ two-tailed.

The Effect Of Feedback On The Accuracy Of Distance Judgments

The results of this portion of the experiment can be stated simply: feedback training improved the accuracy of both absolute egocentric and exocentric distance judgments in VEs. For ease of interpretation the following analyses have been broken down based upon the type of distance judgment that was made (egocentric / exocentric).

Egocentric Judgments:

The following analyses focus only on egocentric judgments made in the pre-test and immediate post-test by participants in the egocentric feedback and no feedback groups. In general, egocentric feedback raised accuracy from .58 to 1.02 representing a large and significant improvement of 43%, ($t(7) = 6.80, p < .001$). Not only was this improvement significant, it represents improvement to the correct value, as it is not significantly different from a value of one. This pattern contrasted with the no feedback group, for whom accuracy improved only 4% from .76 to .80 this level of improvement was not significant. To further confirm these results, a 2x2 repeated measures ANOVA was conducted on the factors of phase and feedback type. The important result from this analysis was a significant interaction between phase and feedback. Egocentric judgments from participants in the egocentric feedback group improved 39% more after training than judgments from participants in the no feedback group, $F(1,14) = 8.64, p = .011$. Figure 4 shows a summary of these results.

Exocentric Judgments:

The data collected from each participant took the form of the error score described previously. The following analyses focus only upon exocentric judgments made in the pre-test

and immediate post-test by the exocentric feedback and no feedback groups. Exocentric feedback raised the accuracy of estimates from .90 to .98, although this improvement was not significant ($t(7) = 1.238, p > .05$). However, participant's pre-test judgments of .90 were already not significantly different from the correct value of 1. Surprisingly, estimates from participants in the no feedback group rose significantly from .96 to 1.15, ($t(7) = 2.73, p = .029$), representing a tendency for these participants to overestimate exocentric distances. While these individuals display a tendency to overestimate exocentric distances on the immediate post-test their estimates were not shown to deviate significantly from the correct value of 1. To further investigate these results, a 2x2 repeated measures ANOVA was conducted on the factors of phase and feedback type. The only significant effect was that of phase, indicating that on average, participants differed between pre-test and immediate post-test with respect to the accuracy of exocentric judgments, $F(1,14) = 8.13, p = .013$. Figure 5 shows a summary of these results. In order to discover whether the judgments of participants who received exocentric feedback differed from those who received no feedback on the both the pre-test and immediate post-test two independent samples t-tests were performed on estimates from each group in each phase. The results were not significant, participant's judgments of exocentric distance did not differ significantly from each other on either pre-test or immediate post-test based on feedback condition.

The Persistence Of Improved Distance Estimation

The results of this portion of the experiment can be stated simply as well: Improved accuracy of absolute distance judgments in VEs after feedback training persisted for at least one

week. For ease of interpretation the following analyses have been broken down based upon the type of distance judgment that was made (egocentric / exocentric).

Egocentric Judgments:

The following analyses consider only estimates in the pre-test and retention post-test made by participants from the egocentric and no feedback groups. Estimates from the egocentric feedback group showed a significant increase of 38% in accuracy of their estimates from .58 in the pre-test to .97 in the retention post-test, ($t(7) = 5.25, p = .001$). In general the no feedback group's estimates remained relatively steady, showing a non-significant improvement from .75 in the pre-test to .80 in the retention post-test. The level of improvement achieved by the egocentric feedback group, remained intact after a one week intersession interval and was not significantly different from the correct value of one. To further investigate these results, a 2x2 repeated measures ANOVA was conducted on the factors of phase and feedback type. Of primary interest was a significant interaction between phase and feedback type. The level of improvement in the accuracy of egocentric judgments was significantly larger for the egocentric feedback group than the no feedback group, $F(1,14) = 5.90, p = .029$. In addition, a significant main effect of phase was found, estimates were found to be significantly different between the pre-test and retention post-test, $F(1,14) = 10.37, p = .006$. Figure 6 shows a summary of these results.

Exocentric Judgments:

The following analyses consider only estimates in the pre-test and retention post-test made by participants from the exocentric and no feedback groups. Estimates from the exocentric

feedback group increased in accuracy from .90 in the pre-test to 1.05 in the retention post-test. Although the improvement was not significant, this level of accuracy was also not found to be different from an accurate level of performance at either the pre-test or retention post-test. Surprisingly, however the no feedback group showed a significant change in their level of performance from a pre-test level of .96 (within our accurate level of 1) to 1.22 (significantly different from 1 at ($t(7) = 2.59, p = .036$)) in the retention post-test. Participants in the no feedback group continued to overestimate exocentric distances one week after training, ($t(7) = 3.67, p = .008$). To further investigate these results, a 2x2 repeated measures ANOVA was performed on the factors of phase and feedback type. The only significant effect was that of phase, indicating a trend for estimates of exocentric distance to increase over time, $F(1,14) = 14.91, p = .002$. Figure 7 shows a summary of these results.

The Specificity Of Feedback's Effects

The results of this section show that the effects of feedback training appear to be restricted to the type of feedback being presented (e.g. egocentric feedback will not improve exocentric distance judgments and vice versa).

When determining the level of improvement in judgment accuracy one can take two approaches. The first approach, which may be more relevant from an applied perspective, measures the absolute improvement in distance judgments. In other words, how close to veridical does feedback make an individuals distance estimates? The second approach involves measuring participant's improvement while taking into account how much room there is for improvement. For example, consider the case of one observer who improves his or her estimates from 50% to 75% of the actual distance after feedback training, while another improves his or

her estimates from 90% to 95% of the actual distance. The first observer has made an improvement of 25% while the other only improved by 5%, however a measure of relative improvement would say that they both improved at equivalent levels, because each observer was able to improve their estimates by 50% of the room that was left for improvement based on their original estimates. We consider each of these measures in turn.

Resultant Error:

Data collected for these analyses took the form of an absolute score defined as the unsigned deviation from accuracy immediately after feedback training.

$$\text{Resultant Error} = | (1 - \text{Immediate post-test error score}) |$$

As a result, lower scores represent more accurate estimations and a score of 0 would be ideal. The following analyses consider both egocentric and exocentric estimates provided from participants during the immediate post-test, who were assigned to the egocentric and exocentric feedback conditions. In general, egocentric feedback was effective only for egocentric judgments as evidenced by an absolute error of .18 for egocentric judgments and .41 for exocentric judgments. The case is analogous for exocentric feedback; it is effective mainly for exocentric judgments as evidenced by an absolute error of .08 for exocentric judgments as opposed to .29 for egocentric judgments. Stated simply, egocentric feedback results only in more accurate egocentric distance estimation, while exocentric feedback results primarily in accurate exocentric distance estimation. This relationship was verified by a significant

interaction between the above factors, $F(1,14) = 19.96$, $p = .001$. The first four bars of Figure 8 illustrate these results.

In order to further determine if egocentric feedback was able to improve exocentric distance judgments in an absolute sense, the exocentric resultant error scores from participants in the egocentric feedback group were compared with those from participants who received no feedback. The difference between these groups was not significant, $(t(14) = -.76, p > .05)$. The level of absolute improvement in exocentric distance judgments was no different for the egocentric and no feedback groups (See figure 8).

In order to further determine if exocentric feedback was able to improve egocentric distance judgments the resultant error of estimates of egocentric distances from participants in the exocentric feedback group were compared to those from participants who received no feedback. The difference between these two groups was not significant, $(t(14) = -.30, p > .05)$. The resultant error in egocentric distance judgments was no different for the exocentric and no feedback groups¹ (See figure 8).

Relative Improvement:

Data collected for these analyses took the form of a relative improvement score defined as follows.

$$\text{Relative Improvement} = \ln \left(\left| \frac{(1 - \text{Pre-test error score})}{(1 - \text{Immediate post-test error score})} \right| \right)$$

For this measure a positive score represents improvement, while a score of 0 indicates no improvement and negative scores indicate worse performance. Generally speaking, the effect of

¹ Although the power to detect such an effect was minimal, it is interesting to note that the direction of the differences between the group means is opposite to that which might be expected (i.e., egocentric feedback was worse than no feedback in enabling accurate exocentric distance estimates).

feedback showed the same trend as before: egocentric feedback improved only egocentric judgments and exocentric feedback improved only exocentric judgments. Stated simply, egocentric feedback results in more accurate egocentric distance estimation, while exocentric feedback results primarily in accurate exocentric distance estimation. This relationship was verified by a significant interaction between the above factors, $F(1,14) = 16.39$, $p = .001$. The first four bars of Figure 9 illustrate these results. The results from comparisons of relative exocentric improvement scores from participants in the egocentric feedback group and participants who received no feedback revealed a significant difference, $(t(14) = 2.433, p = .03)$. Egocentric feedback seems to impair individuals' ability to make accurate exocentric distance judgments. Figure 9 represents a summary of these results.

In order to further determine if exocentric feedback was able to improve egocentric distance judgments, egocentric improvement scores from participants in the exocentric feedback group were compared with egocentric improvement scores from participants who received no feedback. The results of this test were also significant, $(t(14) = 2.946, p > .01)$. Exocentric feedback seems to improve egocentric distance judgments slightly (See figure 9).

Discussion

This experiment posed three questions. The first concerned the ability of feedback training to improve observers' ability to estimate distances in a VE accurately. The results of this experiment replicate previous findings that absolute egocentric distance estimates in VEs are significantly compressed and in this case generally represented only 58% of the actual distance. However, unlike previous studies, we corrected those absolute egocentric distance estimates by as much as 43% to become nearly veridical judgments, with a brief period of feedback training.

In terms of exocentric distance estimation, again this experiment has replicated previous findings that show exocentric distance estimates in VEs are fairly accurate to begin with, representing 90% of the actual distance. Feedback training however still had an effect on observers' ability to estimate exocentric distances, improving estimates by 8% bringing estimates to within 98% of the distances viewed. A relatively limited amount of feedback training was sufficient to allow observers to calibrate their perceptual scale of the environment to match the veridical world scale, which in turn made for more accurate estimations of distance. This finding has important implications for the use of VEs for simulation, training, production, tele-operation and tele-presence in which accurate distance judgments are a necessity. Feedback training has been shown to be an effective tool in aiding the recovery of accurate perceptual judgments in VEs. Eventually VE technology will improve to such a degree that accurate perceptual judgments can be made but until then feedback training seems to be a cost effective and worthwhile alternative.

The second question posed by this experiment concerned the ability of this improved accuracy to persist for at least a week after training had occurred. The findings from this portion of the experiment suggest that the level of improvement made immediately after feedback training was maintained over the one week intersession interval. This finding also has important implications for the use of VEs and suggests that once the true scale of the environment is known to the observer and they are able to calibrate their judgments to match, this scale is now internalized and not lost after leaving the environment. This finding may play an important role in determining how often individuals may need to retrain in order to maintain accurate estimates of distance in VEs. The distribution of practice is an important component when considering how to maintain an accurate level of performance. We know so far that individuals are able to remain

at accurate levels of performance for seven days after their initial training. The question remains however, how long will individuals remain at an accurate level of performance and when their level of accuracy begins to drop off how much training will be necessary to bring performance back to accurate levels?

This study has also shown that, in contrast to the apparent longevity of feedback training, its effects are quite specific. Egocentric feedback improves only egocentric estimates of distance while exocentric feedback primarily improves exocentric estimates of distance. This finding adds further evidence to the idea that egocentric and exocentric distance perception involve separable mental systems that are perhaps related to separate reference frames.

Egocentric reference systems specify location and orientation with respect to the individual. For example egocentric judgments can be made with reference to the retina, head or body. McNamara among others, have suggested that spatial memory is organized primarily by egocentric experience. Although the present study involved spatial perception, these ideas may still be relevant. For example, Shelton & McNamara, (2001), describe the results of seven experiments that manipulated the number of views from which observers were able to learn an object array, the presence or absence of local and global reference systems during learning (e.g. the surface upon which the objects were placed and the shape of the room in which learning took place, respectively), and the congruence of local and global reference systems. In general, the results of their experiments led them to conclude that in all experiments individuals were better able to remember the spatial structure of the environment from an experienced perspective. These results suggest that participants formed multiple egocentric representations of the object array, one from each viewpoint.

This result contrasted with that suggested by Presson, Delange & Hazelrigg, (1987). Presson et al. (1987) had people learn spatial layouts by walking to spatial locations along a path blindfolded. This allowed for multiple orientations of the layout to be learned kinesthetically, while body orientation to the layout remained constant by means of forward walking, side-stepping and backward walking. The results of this study indicate that individuals who experienced multiple orientations during learning were able to perform judgments of relative direction equally well from all positions, aligned and misaligned with the original orientation of the viewpoint. Individuals who maintained a single orientation during learning were slower and showed more error in judgments of relative direction on misaligned trials than on aligned trials. This evidence led Presson et al. to conclude that experiencing multiple views allowed participants to form orientation-independent representations. Presson et al., (1987) would argue that observers had formed an allocentric representation of the array also known as an exocentric representation. These representations are associated with environmental reference frames and are specified with respect to objects rather than with the individual.

In the present experiment it would appear that feedback is able to only operate effectively within a given frame of reference. For example, feedback associated with an egocentric frame of reference would not be of use to an individual engaged in a task that requires an allocentric representation of the environment. Similar findings and support for such theories have been found in the area of cognitive psychology and neurobiology by Easton & Sholl (1995) and Milner & Goodale (1995). Milner & Goodale, consider the concept of two separate visual pathways the ventral and dorsal stream. According to Milner & Goodale, the major difference between the two streams is not in the visual information they process, but in the transformations they perform on the available visual information. In other words, the ventral stream may

transform visual information into an allocentric framework allowing for the perception of the object as it relates to the visual world.□The dorsal stream, on the other hand, may transform visual information into an egocentric framework allowing the individual to grasp or otherwise bodily manipulate an object. The concept of two separate visual pathways would also lend support for the specific nature of feedback's impact on distance estimates. If indeed there are two distinct perceptual modules for distance perception each based on a separate frame of reference feedback directed at improving egocentric distances estimation should not permit an increased ability to estimate exocentric distances.

An unexpected finding from this experiment was the trend that developed in the exocentric estimates of observers who received no feedback. Estimates from these observers steadily increased; initially judgments were accurate but over time observers began to overestimate distances. Interestingly, this same trend does not appear in their egocentric judgments, perhaps lending more support to the separability of these systems. If it were simply the case that individuals became more comfortable with the walking task, increases should be found with both types of judgments, but they are not. It may be worthwhile to investigate the cause for this continual increase in exocentric estimation and to determine if it is indeed a genuine effect.

Further studies might consider requiring observers to make only egocentric or exocentric judgments as the task requiring both types of judgments to be made may have influenced judgments. Additional studies will also be required to determine exactly how much feedback is necessary to improve participants' estimates. This experiment provided participants with 15 trials of feedback (3 repetitions of 5 distances). It may be important to determine if fewer feedback trials could have improved estimates to the same degree.

The quality of the feedback is also of interest in future studies. In this experiment, the feedback was very rich in information, containing two forms of feedback: *perspective feedback* and *metric feedback*. Metric feedback is delivered to an observer in the form of a verbal or text based report of the amount of error (e.g. you underestimated by two feet). This assumes that the observer can be trained to become more accurate when they are provided with information about their amount of error. Feedback can also take the form of perspective feedback. This involves the observer being able to see the amount of error that was present in their estimate (i.e. visual depiction of perceptual error). In the present study a combination of the two approaches was employed as it was deemed to be most informative to the observer. An example of this combined approach can be seen in Figures 1 and 2, which were utilized during the training phase of this experiment. Future studies could look at what type of feedback is most helpful and also determine how rich feedback must be to obtain accurate estimates of distance.

Along these lines it would be of interest to see if individuals would be able to provide accurate estimates of distance given only prior knowledge of people's tendency to underestimate egocentric distances. For example, would an observer be able to recalibrate if they were given only the information that people typically underestimate egocentric distances in VEs by 58%?

In conclusion, the results of this investigation have shown support for previous findings depicting observers' tendency to underestimate absolute egocentric as well as exocentric distances in VEs. More importantly, the results of this study provide evidence that with a short period of feedback training, observers' estimates of absolute egocentric as well as exocentric distance can become accurate. Lastly, this level of improvement was shown to last for at least one week's time. Taken together these findings show support for feedback training as an

alternative to the costly improvement of current VE technology for applications in which the accurate perception of distance is necessary.

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Figure 1:

Feedback presented to participants in the egocentric feedback condition during the training phase of the experiment.

Figure 2:

Feedback presented to participants in the exocentric feedback condition during the training phase of the experiment.

Figure 3:

(Not actual stimuli used in experiment)

A simulated view of the virtual environment from an observers' point of view.

Figure 4:

Mean overestimation in judgments of egocentric distance ($\pm$) SEM from observers in the pre-test and immediate post-test phases of the experiment who received either egocentric feedback or no feedback during training.

Figure 5:

Mean overestimation in judgments of exocentric distance ($\pm$) SEM from observers in the pre-test and immediate post-test phases of the experiment who received either exocentric feedback or no feedback during training.

Figure 6:

Mean overestimation in judgments of egocentric distance ($\pm$) SEM from observers in the pre-test and retention post-test phases of the experiment who received either egocentric feedback or no feedback during training.

Figure 7:

Mean overestimation in judgments of exocentric distance ($\pm$) SEM from observers in the pre-test and retention post-test phases of the experiment who received either exocentric feedback or no feedback during training.

Figure 8:

Resultant Error in judgments of egocentric and exocentric distance ($\pm$) SEM from observers who received either egocentric feedback, exocentric feedback or no feedback during training.

Figure 9:

Relative Improvement in judgments of egocentric and exocentric distance ($\pm$) SEM from observers who received either egocentric feedback, exocentric feedback or no feedback during training.

Appendix A:

The stimuli developed for this experiment were set up in such a way that each egocentric distance would have an equivalent exocentric interval. The target for each trial differed based upon the type of trial. For example, the target post for an egocentric trial was the red post, which could be located at any of the five distances from the observer's station point on any of three vectors emanating from that point in space. For egocentric trials observers judged the distance separating themselves from the red post. Conversely, for an exocentric trial the green and blue posts were considered the target posts. The centroid of the exocentric interval between the green and blue post was then placed orthogonal to one of the vectors emanating from the station point and locations were chosen that allowed both posts to be visible in the frontal plane of the observers body. This controlled for the level of difficulty of each exocentric interval as intervals placed on the observers' sagittal plane would be inherently more ambiguous than those on the frontoparallel plane. The observer's task for the exocentric trial was to walk the distance that separated the green and blue post.