Jeffrey W. McCandless
jmccandless@mail.arc.nasa.gov
San Jose State University Foundation
M.S. 262-2, NASA Ames Research Center
Moffett Field, CA 94035-1000

Stephen R. Ellis
silly@eos.arc.nasa.gov
NASA Ames Research Center
M.S. 262-2, NASA Ames Research Center
Moffett Field, CA 94035-1000
Send reprint requests to this author.

Bernard D. Adelstein
bda@eos.arc.nasa.gov
NASA Ames Research Center

Presence, *Vol. 9, No. 1, February 2000,* 15–24

Localization of a Time-Delayed, Monocular Virtual Object Superimposed on a Real Environment

Abstract

Observers adjusted a pointer to match the depicted distance of a monocular virtual object viewed in a see-through, head-mounted display. Distance information was available through motion parallax produced as the observers rocked side to side. The apparent stability of the virtual object was impaired by a time delay between the observers' head motions and the corresponding change in the object position on the display. Localizations were made for four time delays (31 ms, 64 ms, 131 ms, and 197 ms) and three depicted distances (75 cm, 95 cm, and 113 cm). The errors in localizations increased systematically with time delay and depicted distance. A model of the results shows that the judgment error and lateral projected position of the virtual object are each linearly related to time delay.

1 Introduction

The cost, weight, and complexity of a head-mounted display (HMD) can be reduced by presenting the images to one eye rather than both eyes. However, one drawback of monocular display is that a user cannot employ stereopsis to gauge object distance. As an alternative to stereopsis, an observer could determine object distance by relying on motion parallax, defined as the ''relative movement of images across the retina resulting from movement of the observer or the translation of objects across his field of view'' (Rogers & Graham, 1979). Motion parallax, which is helpful in distinguishing the different distances of objects ahead of the observer, can be produced by an observer who rocks to the left and right to obtain different views of a scene.

The examination of motion parallax dates back to Helmholtz (1925), who noted that there is an inverse relationship between the distance to an object and the velocity of the object across the retina during head translation, assuming the viewer is fixated at optical infinity. Later, Gibson (1950) examined the usefulness of motion parallax and other consequences of observer movement in a study of the ability of pilots to estimate airplane heading during simulated landings. Motion parallax was also found to be effective during simulated head-movement conditions in which stationary observers viewed targets presented via a video projector (Braunstein, 1966; Dees, 1966). In virtual environments with low spatial resolution, active head-coupled camera motion (motion parallax) provides a more effective cue than passive camera motion (Smets & Overbeke, 1995). Motion parallax under translating head conditions was examined in an early head-tracking study by Vircks (1968). In this experiment, a perspective drawing of a cube was presented on a cathode-ray tube while observers translated their heads. Head position was monitored in real time with a photo-optical apparatus, and the perspective of the cube shifted with head position to simulate a real cube. Not surprisingly, observers made better distance judgments while translating their heads as opposed to remaining stationary. One possible cause for the improved performance in that study was the presence of internal perspective of the target. Motion parallax is a relatively weak cue for egocentric distance judgments if the target has no internal perspective, such as a single point of light (Gogel & Tietz, 1979; Philbeck & Loomis, 1997). The effectiveness of motion parallax with single uniform targets can be improved through training sessions in which observers are informed of the correct target distance after making each judgment (Ferris, 1972). In addition to being a cue for object distance, motion parallax is also helpful in gauging object depth (Koenderink & van Doorn, 1975; Ono et al., 1986; Rogers, 1993; Rogers & Graham, 1979, 1982). (*Depth* is defined as the length of an object along the visual axis, and *distance* as the separation between the observer and object.)

All of these studies examined motion parallax with the assumption that the objects were statonary in space. In an HMD, however, time delay between the observer's motion and the image update causes instabilities in the depicted position of the virtual object (Azuma, 1997), thereby degrading performance (Held & Durlach, 1993). The effects of this phenomenon were investigated in a recent study by Ellis et al. (1997), in which observers aligned a pointer with the apparent position of the virtual object while maintaining a fixed head position or translating from side to side. In that experiment, the position and orientation of the virtual object on the display were not precisely synchronized with head position due to a time delay. Ideally, the object on the display should shift instantaneously as the head moves to support the percept that the virtual object has a constant exocentric position (that is, stationary in the environment). However, because the processing time of the computer and sensors produced a time delay, the object position at time t corresponded to the head position at time t-τ, where τ was a mean time delay of 49 ms (with a non-normal distribution with $\sigma = 8$ ms). This time delay did not completely eliminate the ability to localize the virtual object.

The primary study presented here parametrically examines how different time delays affect the ability of observers to localize a virtual object. *Localization* refers to a physical alignment task (not a perceptual task) in which the observer aligns a pointer at the depicted distance of a virtual object. In this study, the time delay and depicted distance of a virtual object were systematically varied. The errors in localization of the virtual object increased monotonically with time delay and depicted distance.

2 Control Study

This control study was used to determine a baseline of performance at zero time delay with real, physical objects for the localization technique. It also helped determine the parameters for the primary study.

2.1 Task

Observers translated their heads from side to side to induce motion parallax while monocularly viewing a target and making distance judgments. Head oscillations were paced with a metronome set to a 3 sec. period. For comparison, observers also made judgments while attempting to hold their heads stationary. Observers spent approximately 10 to 20 sec. for each judgment. To make the judgment, each observer rotated a knob to move a physical pointer along a rail until the pointer was directly below the apparent position of the target, as shown in Figure 1 and described by Ellis and Menges (1997). The pointer position was measured with an encoder attached to its base. The target distances were 75 cm, 95 cm, and 113 cm for three reasons: to correspond with previous studies in the laboratory, to stay within the physical range of the equipment, and to stay within the range of tabletop displays.

Prior studies have found that, within limits, the speed and extent of head movements do not affect the ability

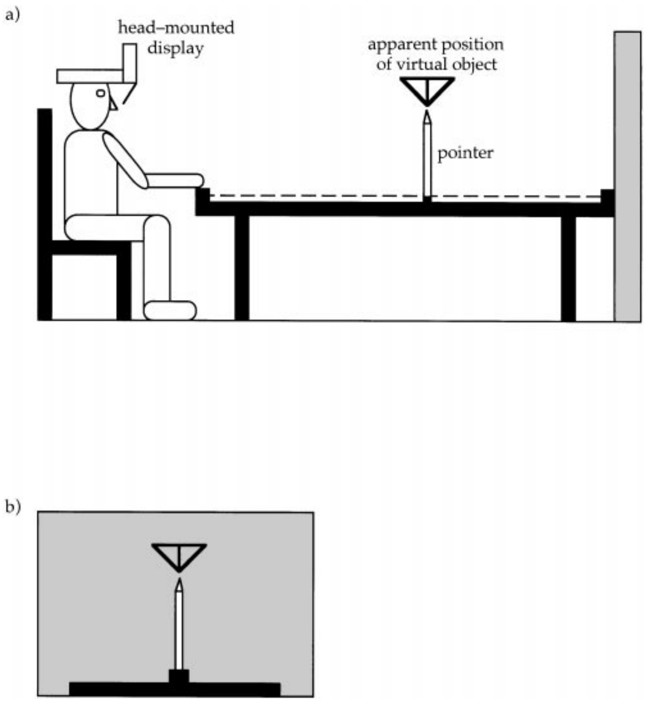

Figure 1. *Experimental apparatus. Observers viewed a virtual object presented in an HMD and moving a vertical pointer under the apparent position of the target. a) Side view of the apparatus. b) Frontal view.*

to perceive depth (Rogers & Graham, 1982; Ono et al., 1986). As a result, head translation amplitude was not precisely constrained to a particular value during the primary study. (The approximate amplitude was 25 cm.) Observers were instructed not to hesitate at each reversal of head direction. As a comparison to the moving-head condition, judgments were also made with the user remaining nearly stationary. To replicate the conditions typical in an application environment, the head was not fixed with a clamp or bitebar.

2.2 Equipment

The object viewed by the observers was an inverted wireframe pyramid with approximate luminance of 40 cd / m^2. It was viewed monocularly by each observer's dominant eye against an orthogonal wall with a luminance of 2.9 cd / m^2. The wall was 2.4 m from the observer and perpendicular to the line of sight. The dominant eye was determined with a sighting test. Each observer's nondominant eye was patched during the control experiments. Observers were allowed to wear their prescription lenses during the experiment. The wall and table were visible during the experiment. The visible features in the background, such as the tracking mechanism on the table and texturing on the wall, provided distance cues.

In the control study, the pyramid was a real object made of balsa wood and covered with cotton to simulate the approximate appearance of the virtual object. Two pyramids of different sizes were used. One had dimensions of 5 × 5 × 5 cm, and the other had dimensions of 10 × 5 × 5 cm (where 10 cm refers to the base length along the visual axis). To deter observers from using size cues, the pyramids were randomly switched among various trials while the observers closed their eyes.

2.3 Results

In the control study, five observers (four experienced, including two authors, and one naive) with an age range of 21 to 51 years estimated the distance to a real object with and without motion parallax. Localizations were made for three object distances with and without head translation, for a total of six different conditions. Each condition was repeated five times per observer.

As expected with a real object, performance improved with a translating head compared with a nearly stationary head. Figure 2 illustrates the mean judgments (with standard errors) over all five observers. As shown in this figure, the results with a moving-head condition are nearly veridical. The mean error between the judged and actual distances was 1.8% for the head-moving condition and 3.2% for the head-stationary condition. Here, the error E is defined as

$$E = \frac{d_a - dj}{d_a} * 100\%, \qquad (1)$$

where d_a is the actual distance from the observer to the target, and d_j is the pointer position (judged distance from observer to target).

For the two closest distances, the mean judgments were nearly veridical (even in the nearly stationary condi-

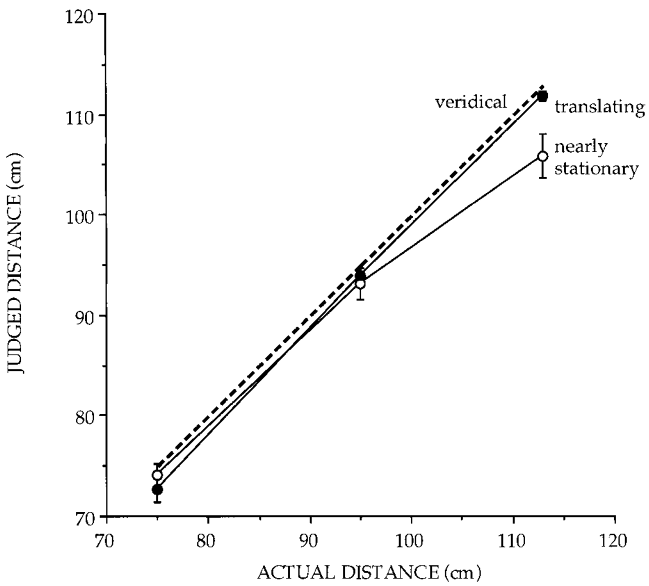

Figure 2. *Results of the control study. Each point is the mean judgment (with standard errors) over all five observers. Observers viewed a real object while either translating their heads or remaining nearly stationary. The target was presented at three distances (75, 95, and 113 cm).*

tion), presumably because of the saliency of several physical distance cues such as accommodative demand.

These results indicate an upper limit on the distance judgment accuracy that can be achieved with virtual objects in this setup, assuming that accommodative demand is veridical and the time delay is zero. Presumably, more-accurate judgments could be obtained with targets that have high texture gradients with well-defined edges, as discussed by Fisher and Ciuffreda (1988).

3 Primary Study

The purpose of the primary study was to examine the effects of time delay on localizations of a virtual target. The time delays were 31 ms, 64 ms, 131 ms, and 197 ms. (Each time delay was from a non-normal distribution with $\sigma = 5$ ms.) Time delays were computed using the techniques described in Jacoby et al. (1996). The task was identical to that of the control study in that observers adjusted a pointer to indicate the position of the object.

3.1 Equipment

In the primary study, the pyramid was a computer-generated virtual object (with luminance of 65 cd / m^2) visible in a see-through HMD, as described by Ellis and Menges (1997). The pyramid was projected on the partially silvered (15%), polycarbonate mirror of the HMD. With this arrangement, the observers could simultaneously view the monocular virtual object as well as the binocular real environment. As in the control study, the natural features on the wall and table provided relative distance cues to the pyramid target. The pyramid had a nominal base size of 10 $\times$ 10 cm and a height of 5 cm. Because size is a strong distance cue in monocular tasks (for example, Beall et al., 1995), the pyramid was randomly scaled such that its projected size in 3-D space varied by a factor between 0.5 and 1.0 on each trial. Analysis of pilot data indicated that judgments were independent of relative target size when the target was scaled. The accommodative demand of the virtual object was fixed at 1.5 D (about 65 cm). The HMD weighed 1.5 kg and contained a Citizen 1.5 in. 1,000-line miniature CRT. The monochrome display was presented in NTSC mode (60 Hz interlaced fields). It was driven by a Silicon Graphics Onyx computer (four MIPS R4400 CPUs) with a Reality Engine 2 graphics board. Head position was tracked at 120 Hz with a Polhemus FasTrak sensor. The measurements of head position were used to update the image such that zero time delay would correspond to the target being depicted as perfectly stationary.

3.2 Results

In the primary study, eleven observers (four experienced, including three authors, and seven naive) with an age range of 17 to 51 years judged the depicted position of a virtual object with and without motion parallax. This study required five separate, one-hour sessions for each observer. Localizations were made for three object distances (75 cm, 95 cm, and 113 cm) and four time delays (31 ms, 64 ms, 131 ms, and 197 ms) to produce twelve conditions. In addition, localizations were made at the three object distances without head motion at a

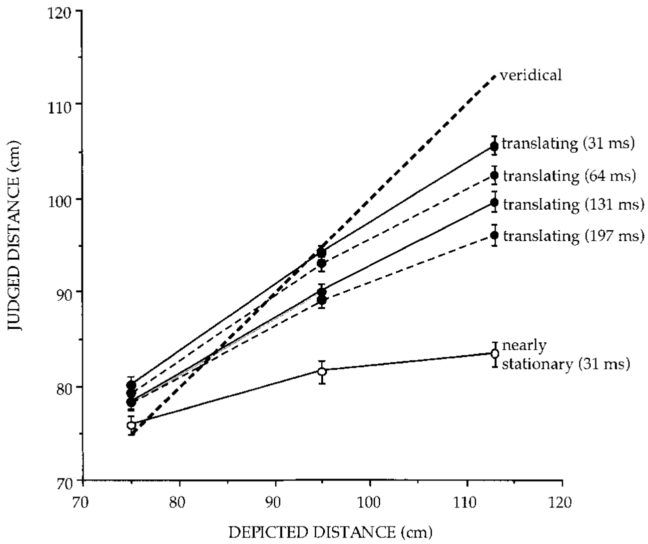

Figure 3. *Results of the primary study. Each point is the mean judgment (with standard errors) over all eleven observers. Observers viewed a virtual object while either translating their heads or remaining nearly stationary. The target was presented at three distances (75, 95, and 113 cm) with four time delays (31, 64, 131, and 197 ms).*

31 ms time delay (for a total of fifteen conditions in the primary study). Each condition was repeated twenty times (in random order without blocking) per observer. Observers were told that the target could be positioned anywhere along the span of the table. Consequently, an additional number of judgments (7%) were made to targets randomly depicted at other distances besides the three primary distances. The results for these sham conditions were discarded.

The results of the primary study are shown in Figure 3, in which each point represents the mean (with standard error) over all eleven observers. For the motion parallax condition, significant effects were related to the depicted target distance (ANOVA: $F_{2,438} = 916.5$, $p < 0.001$), time delay (ANOVA: $F_{3,657} = 81.7$, $p < 0.001$), and their interaction (ANOVA: $F_{6,1314} = 14.2$, $p < 0.001$). For the nearly stationary head condition, significant effects were caused by target distance (ANOVA: $F_{2,438} = 40.0$, $p < 0.001$).

The standard deviations of the distance judgments were analyzed with nonparametric statistics because the standard deviations exhibited a possible lack of homogeneity of variance. For the motion-parallax condition, the standard deviations of the distance judgments over all eleven observers increased over the depicted distance range of 75 cm to 113 cm (Friedman two-way ANOVA by ranks: $\chi^2_{2,20} = 10.4$, $p < 0.01$). The standard deviations decreased over the latency range of 31 ms to 197 ms (Friedman two-way ANOVA by ranks: $\chi^2_{3,30} = 11.4$, $p < 0.01$).

The results were also examined separately for each observer. For the motion-parallax condition, the judged target distance was dependent on the depicted target distance for each observer (ANOVAs: $F_{2,38} > 63.4$, $p < 0.001$), and it was dependent on time delay for ten of the eleven observers (ANOVAs: $F_{3,57} > 3.7$, $p < 0.05$). (For simplicity, the smallest F value of the observers is listed in this analysis.) The target distance interacted with the time delay for two experienced and two naive observers (ANOVAs: $F_{6,114} > 2.8$, $p < 0.05$). For the nearly stationary head condition, the judged distance increased a small amount with the depicted distance for three experienced and five naive observers (ANOVAs: $F_{2,38} > 3.2$, $p < 0.05$). This phenomenon was most likely due to slight shifts in head position during each trial.

4 Model of the Results

Because of the time delay in the primary study, the displayed target position did not correspond to that of a stationary object. An initial simplified analysis of the effect of time delay is shown in Figure 4. For this initial analysis, the observer is assumed to translate with constant velocity v to the right (Figure 4a) and left (Figure 4b) through eight different head positions. The open triangles represent the ideal (zero time delay) target position and the filled triangles illustrate the actual (nonzero time delay) target position. Because the head-translation speed is constant, the projected target positions intersect at the same point for a given direction of motion (except for the time delay period about the direction-reversal points of observer motion). For example, as the observer translates to the right, the projected positions of the delayed target intersect at target position A. The projected displacement from the ideal projected

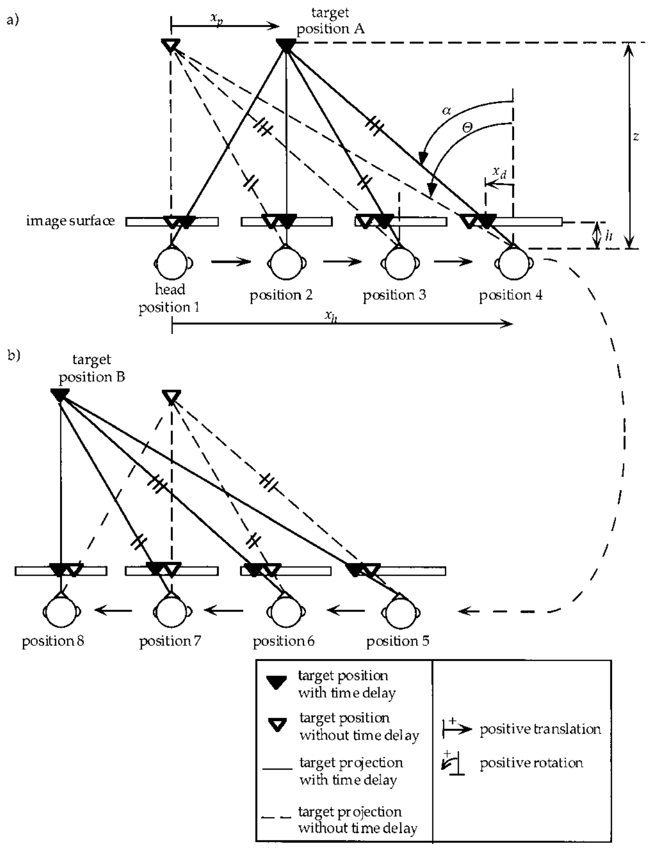

Figure 4. *Illustration of the observer's head position (x_h), target display position (x_d), and target projected position (x_p) under constant translational head motion. The angle α is the actual displayed target angle, and the angle Θ is the ideal displayed target angle. The solid lines represent actual target projections and the dashed lines represent ideal target projections. a) Geometry during rightward head motion with constant speed (where the observer is already in motion at head position 1). b) Geometry during leftward head motion with constant speed. In both cases, the target appears to be located on the same side as the direction of the head translation. The matching hatchmarks within each figure illustrate the parallel lines (for example, lines with two parallel hatchmarks are parallel to one another).*

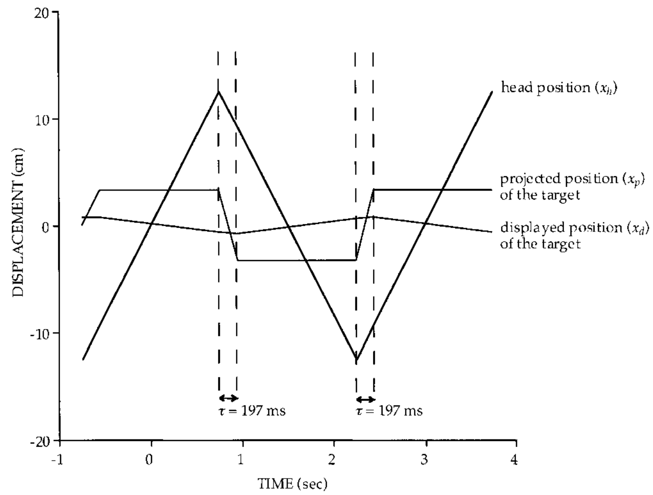

Figure 5. *Displacements of the observer's head (x_h), target display position (x_d), and target projected position (x_p) with constant head speed.*

position is denoted by x_p (where $x_p = v\tau$). Geometrically, this projection is shown in Figure 4a by angles α and θ, where α is the actual target angle and θ is the ideal target angle. Because of the time delay, the actual target angle α at time t equals the ideal target angle Θ at time t-τ. For example, the target at head position 4 is positioned on the display with the assumption that the observer is actually located at head position 3.

The displacements shown in Figure 4 can be computed using similar triangles associated with angle α and Θ:

$$\tan \alpha(t) = \frac{x_h(t) - x_p(t)}{z}, \text{ and} \tag{2}$$

$$\tan \Theta(t - \tau) = \frac{x_h(t - \tau)}{z}. \tag{3}$$

Because $\alpha(t)$ equals $\Theta(t\text{-}\tau)$, the projected target position $x_p(t)$ is simply the difference between $x_h(t)$ and $x_h(t\text{-}\tau)$, as implied in Equation (2) and (3). The displayed target position $x_d(t)$ can be computed if the distance h between the ocular nodal point and the image surface is known, as shown by

$$x_d(t) = h \tan \alpha(t). \tag{4}$$

The displacements associated with the projected target position, the displayed target position, and the head position each vary as the observer translates, as shown in Figure 5. In this figure, the displacements were computed using selected parameters from the primary study (that is, $\tau = 197$ ms, $z = 95$ cm, $T = 3$ sec., and head speed = 16.7 cm / sec. based on a head-translation amplitude of 25 cm). As shown in Figure 5, this triangular motion results in a projected target (x_p) that oscillates back and forth between two positions. If the time delay were zero, the values for x_p also would be zero.

For a more realistic analysis, the observer motion can be described with a sinusoidal profile:

$$x_h(t) = A \cos(2\pi t / T) \tag{5}$$

where A is a linear head velocity of 26.2 cm / sec (chosen so that a 25 cm head amplitude is produced with a 3 sec. period). Similarly, observer rotation can be modeled as

$$\psi(t) = B \cos(2\pi t / T), \tag{6}$$

where B is the rotational head velocity of 7.9 deg / sec. (chosen so that the head rotational velocity compensates for 50% of the head translation). If the rotational velocity compensated for 0% of the observer's translation, the observer's head would be directed straight ahead at all times. If it compensated for 100% of the observer's translation, the observer's head would be directed at the initial target position at all times. In that case, the target would always be positioned on the center of the display. Consequently, the target would appear fixed in space, regardless of the time delay. A schematic of the motion with 50% head rotation is shown in Figure 6. With 50% head rotation, angle ψ equals angle Θ. If the head rotation was 0%, ψ would be 0 deg. If the head rotation was 100%, Θ would be 0 deg.

The parameter x_p can be calculated from

$$\tan(\psi(t) + \alpha(t)) = \frac{x_h(t) - x_p(t)}{z}. \tag{7}$$

The angle θ can be calculated from

$$\tan(\psi(t) + \Theta(t)) = \frac{x_h(t)}{z}. \tag{8}$$

The displacements associated with head position and projected position are shown in Figure 7. Once again, the displacements were computed using selected parameters from the primary study (i.e., $\tau = 197$ ms, $z = 95$ cm, $T = 3$ sec.).

The lateral displacement of the projected target position is indicated by the difference between the peaks of the sinusoidal curve for x_p. In this example (corresponding to 50% head rotation and a 197 ms time delay), the target lateral displacement was approximately 5 cm. The lateral displacements over a range of head rotations and time delays is plotted in Figure 8. As illustrated in this

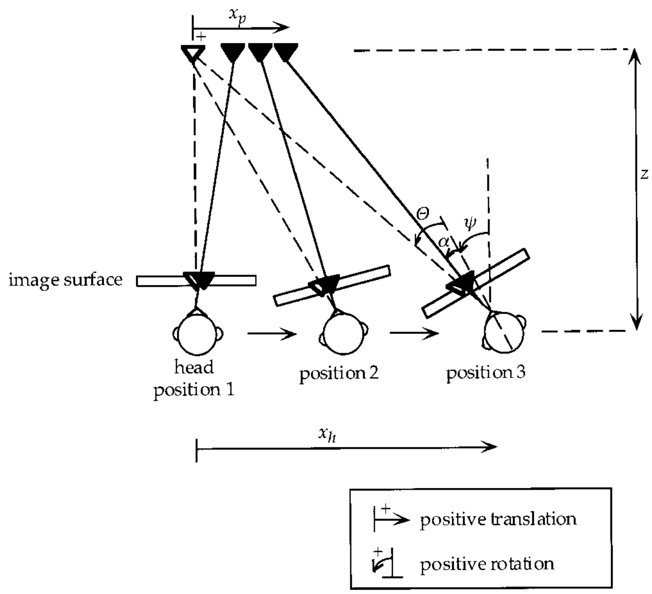

Figure 6. *Illustration of the observer's head position (x_h), target display position (x_d), and target projected position (x_p) under sinusoidal translational and rotational head motion. The angle ψ is the head angle, α is the actual displayed target angle, and Θ is the ideal displayed target angle.*

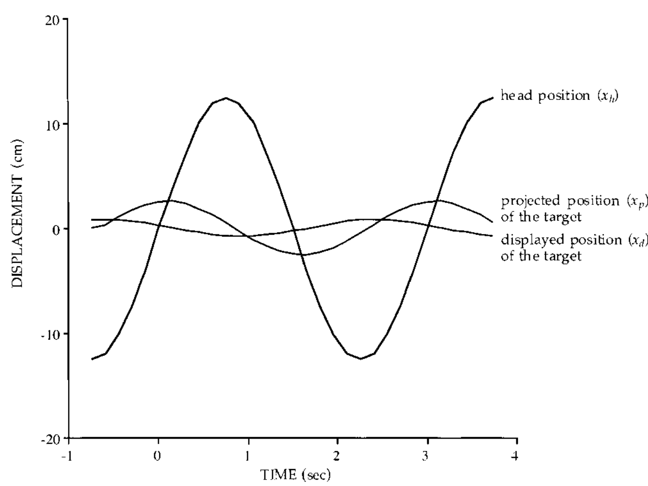

Figure 7. *Displacements of the observer's head (x_h), target display position (x_d), and target projected position (x_p) with sinusoidal head speed and rotation.*

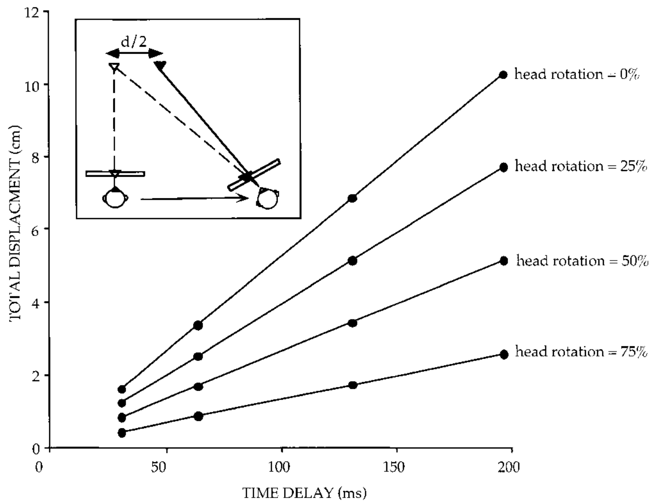

Figure 8. *Plot of the lateral projected target displacement for different head rotations as function of time delay.*

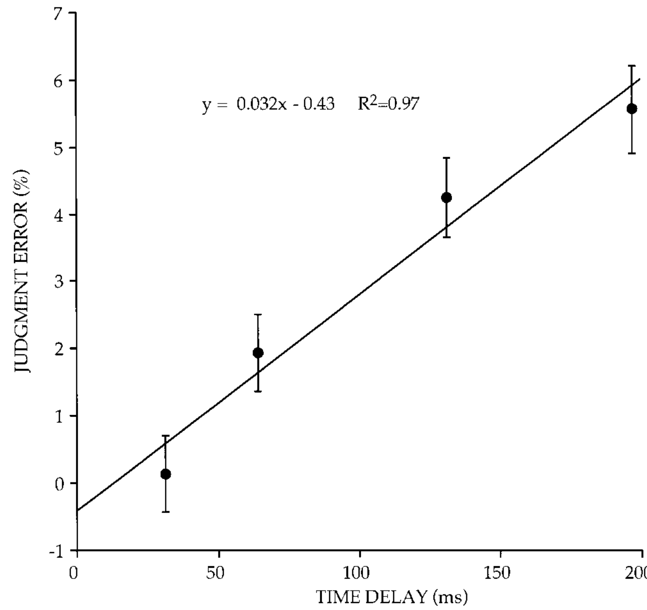

Figure 9. *Model fit to the distance-judgment errors for motion parallax in the primary study. A simple linear regression provides a reasonable fit to the projected target displacement (of Figure 8) and the distance judgment errors (shown here).*

figure, the lateral displacement of the virtual object increases linearly with time delay. In addition, the lateral displacement decreases as the observer's head rotates more to compensate for head translation. Figure 8 illustrates that, for a given time delay, the lateral displacement is a maximum when the observer only translates and does not rotate at all (head rotation = 0%). Because the lateral displacement is defined by the difference between the peaks of the curve for x_p, the type of head motion is not critical. As a result, other types of head motion (besides sinusoidal) could produce the same lateral displacement.

The positional disturbances shown in Figure 8 are a possible cause of the performance degradation that occurs with increased time delay. This implies that the errors in judgment should increase linearly with time delay for a given head velocity. As evidence for this hypothesis, the data are plotted in terms of the judgment error, as shown in Figure 9. The regression fit to these data provides an accurate means of modeling these results, indicating that, like the projected displacement, the localization errors are linearly related to time delay.

5 Discussion

The present results show that time delay interferes with the ability to localize a virtual object. In the current study, the systematic degradation in performance with a virtual object was due to increased time delay because that was the only parameter that was varied in the motion-parallax experiments. However, additional factors could have produced a bias in the judgments. For example, two other contributing factors could be the nonveridical accommodative demand (fixed at 1.5 D, corresponding to about 67 cm) and the specific distance tendency (Gogel & Tietz, 1973). The specific distance tendency (SDT) is defined as the tendency for observers to perceive an object at a relatively near distance (about 2 m) if it is presented in the absence of any distance cues (Gogel, 1969). In the primary study, the close proximity of the wall (as well as the accommodative demand) may have contributed to a distance bias that was closer than the 2 m described by Gogel. Because these two factors (accommodative demand and the SDT) were constant throughout the study, they could not have produced the performance deterioration associated with time delay. Rather, they most likely produced a bias in the localizations that resulted in an overestimate of target distance at the near condition and an underestimate at the far condition. As time delay increased, observers tended to move the pointer position closer to them, presumably closer to their distance bias. An additional bias could be caused by the presence of a real object (the pointer) in the vicinity of the virtual object (the inverted pyramid). Virtual objects are seen farther away than real objects when both are presented at the same depth plane (Rolland et al., 1995). However, in that study, the virtual object was collimated (presented at optical infinity), which could play a significant role in the measured errors of depth veridicality.

The standard deviation of the distance judgments increased strongly (by 56%) with depicted distance and decreased slightly (by 12%) with time delay. The standard deviation increase with depicted distance is not surprising because distance judgments are measured in absolute units (cm). The standard deviation decrease with time delay was most likely due to an increased reliance on a fairly robust distance bias caused by the constant accommodative demand and the specific distance tendency. The interaction between time delay and depicted distance was most likely caused by the small relative motion of the distant target versus the near target. In an extreme case (optical infinity), motion parallax would not provide any information about the target distance.

These results indicate the substantial improvement of localizations that occurs in an HMD with a translating observer as opposed to a nearly stationary observer. Similar results were found by Ellis et al. (1997). In that study, the judgment variance was reduced, and the frequency distribution was more symmetric with translating observers versus stationary observers. Even with the large time delay (for example, 197 ms) present in the current study, performance was markedly improved for translating versus stationary observers. Similarly, Lane and Akin (1997) found that even moderately accurate head tracking (for example, 50%) dramatically improves depth judgments in an HMD.

As discussed in the introduction, a key purpose of this study is to examine the detrimental effects that occur with a monocular display. If a binocular stereoscopic display is provided, the user presumably will not have to rely on motion parallax for distance and depth information. However, in a natural setting, the user will most likely shift head position, thereby producing motion parallax anyway. An appropriate issue to examine next is the change in performance (during observer motion) that occurs with a binocular display as opposed to a monocular display. In a related study, Rogers and Graham (1982) found that disparity thresholds for stereopsis (binocular viewing) were approximately twice as low as those for motion parallax (monocular viewing). In that study, the time delay was zero. Presumably, motion parallax under binocular viewing will provide more-accurate judgments than motion parallax under monocular viewing.

This study was conducted in an augmented environment, that is, an environment in which the user can see the real world as well as virtual objects (Azuma, 1997). Other studies have examined the effects of time delay in fully immersive virtual environments. For example, Watson et al. (1998) examined how user performance is affected by the mean system response (MSR), defined as ''the elapsed time until a system responds to user control.'' They found that an increase in MSR in a fully immersive environment increased the time necessary to grasp a virtual object and decreased the accuracy with which it could be transported to a virtual pedestal.

The present results show that, in a monocular see-through HMD, localizations using motion parallax are an improvement over the case in which the user remains nearly stationary. However, these judgments are nonveridical even if the time delay is relatively short (for example, 31 ms). Although motion parallax does not eradicate the effect of factors such as the SDT, it does aid in distance judgments (Ferris, 1972). The results presented here show that observers can partially overcome these biasing factors for time delays up to 197 ms.

Acknowledgments

The authors thank Brent R. Beutter and Robert B. Welch for their helpful comments. The authors also thank Eric H. Barrett and Brian M. Menges for their help in writing the software and running the experiments. Funding was provided by NASA (Code UL) RTOP 199-06-1238 to S.R.E.

References

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments, 6,* 355–385.

Beall, A. C., Loomis, J. M., Philbeck, J. W., & Fikes, T. G. (1995). Absolute motion parallax weakly determines visual scale in real and virtual environments. In *Proc. SPIE, 2411* (pp. 288–297).

Braunstein, M. L. (1966). Sensitivity of the observer to transformations of the visual field. *J Exp Psych, 72,* 683–689.

Dees, J. W. (1966). Accuracy of absolute visual distance and size estimation in space as a function of stereopsis and motion parallax. *J Exp Psych, 72,* 466–476.

Ellis, S. R., & Menges, B. M. (1997). Judgments of the distance to nearby virtual objects: interaction of viewing conditions and accommodative demand. *Presence: Teleoperators and Virtual Environments, 6,* 452–460.

Ellis, S. R., Menges, B. M., Adelstein, B., Jacoby, R. H., & McCandless, J. M. (1997). Influence of head motion on the judged distance of monocularly presented virtual objects. *Proc Human Factors and Ergonomics Soc, 2,* 1234–1238.

Ferris, S. H. (1972). Motion parallax and absolute distance. *J Exp Psych, 95,* 258–263.

Fisher, S. K., & Ciuffreda, K. J. (1988). Accommodation and apparent distance. *Perception, 17,* 609–621.

Gibson, J. J. (1950). *The perception of the visual world.* Boston: The Riverside Press.

Gogel, W. C. (1969). The sensing of retinal size. *Vision Research, 9,* 1079–1094.

Gogel, W. C., & Sturm, R. D. (1972). A comparison of accommodative and fusional convergence as cues to distance. *Perception and Psychophysics, 11,* 166–168.

Gogel, W. C., & Tietz, J. D. (1973). Absolute motion parallax and the specific distance tendency. *Perception and Psychophysics, 13,* 284–292.

———. (1979). A comparison of oculomotor and motion parallax cues of egocentric distance. *Vision Research, 19,* 1161–1170.

Held, R., & Durlach, N. (1993). Telepresence, time delay, and adaptation. In S. Ellis, M. Kaiser, & A. Grunwald (Eds.), *Pictorial Communication in Real and Virtual Environments* (pp. 232–246). London: Taylor and Francis.

Helmholtz, H. von. (1925). In J. P. C. Southall (Ed.), *Helmholtz's Treatise on Physiological Optics, Vol. III.* New York: Optical Soc. America.

Jacoby, R. H., Adelstein, B. D., & Ellis, S. R. (1996). Improved temporal response in virtual environments through system hardware and software reorganization. *Proc. SPIE 2653, Stereoscopic Displays and Virtual Reality Systems, III,* 271–284.

Koenderink, J. J., & van Doorn, A. J. (1975). Invariant properties of the motion parallax field due to the movement of rigid bodies relative to an observer. *Optica Acta, 22,* 773–391.

Lane, J. C., & Akin, D. L. (1997). Stereopsis and motion parallax cues in virtual reality control applications. In M. J. Smith, G. Salvendy, & R. J. Koubek (Eds.), Design of computing systems: Social and ergonomic considerations. In *Proc. Seventh Int. Conf. on HCI* (pp. 917–920). Amsterdam: Elsevier.

Ono, M. E., Rivest, J. R., & Ono, H. (1986). Depth perception as a function of motion parallax and absolute-distance information. *J Exp Psych, 12,* 331–337.

Philbeck, J. W., & Loomis, J. M. (1997). Comparison of two indicators of perceived egocentric distance under full-cue and reduced-cue conditions. *J Exp Psych: Human Perception and Performance, 23,* 72–85.

Rogers, B. J. (1993). Motion parallax and other dynamic cues for depth in humans. In F. A. Miles & J. Wallman (Eds.), *Visual Motion and its Role in the Stabilization of Gaze* (pp. 119–137). Amsterdam: Elsevier Sciences Publishers.

Rogers, B., & Graham, M. (1979). Motion parallax as an independent cue for depth perception. *Perception, 8,* 125–134.

———. (1982). Similarities between motion parallax and stereopsis in human depth perception. *Vision Research, 22,* 261–270.

Rolland, J. P., Gibson, W., & Ariely, D. (1995). Towards quantifying depth and size perception in virtual environments. *Presence: Teleoperators and Virtual Environment, 4,* 24–49.

Smets, G. J. F., & Overbeeke, K. J. (1995). Trade-off between resolution and interactivity in spatial task performance. *IEEE Computer Graphics and Applications, 15*(5), 46–51.

Vircks, R. M. (1968). Investigation of head movement and intensity as depth cues in a perspective contact analog display. S. M. Thesis MVT-68-3, Massachusetts Institute of Technology.

Watson, B., Walker, R., Ribarsky, W., & Spaulding, V. (1998). Effects of variation in system responsiveness on user performance in virtual environments. *Human Factors, 40,* 403–414.