Perception & Psychophysics
2002, 64 (8), 1218-1226

Stereoillusory motion concomitant with lateral head movements

KOICHI SHIMONO, WA JAMES TAM, LEW STELMACH, and EVAN HILDRETH
Communications Research Centre Canada, Ottawa, Ontario, Canada

Stationary objects in a stereogram can appear to move when viewed with lateral head movements. This illusory motion can be explained by the motion–distance invariance hypothesis, which states that illusory motion covaries with perceived depth in accordance with the geometric relationship between the position of the stereo stimuli and the head. We examined two predictions based on the hypothesis. In Experiment 1, illusory motion was studied while varying the magnitude of binocular disparity and the magnitude of lateral head movement, holding viewing distance constant. In Experiment 2, illusory motion was studied while varying binocular disparity and viewing distance, holding magnitude of head movement constant. Ancillary measures of perceived depth, perceived viewing distance, and perceived magnitude of lateral head movement were also obtained. The results from the two experiments show that the extent of illusory motion varies as a function of perceived depth, supporting the motion–distance invariance hypothesis. The results also show that the extent of illusory motion is close to that predicted from the geometry in crossed disparity conditions, whereas it is greater than the predicted motion in uncrossed disparity conditions. Furthermore, predictions based on perceptual variables were no more accurate than predictions based on geometry.

When we observe a stereogram and move our heads laterally, stereo stimuli appear to move concomitantly with our heads (Frisby, 1979; Julesz, 1971; Lee, 1969; Rock, 1983; Tyler, 1974). For example, when the stereogram in Figure 1 is viewed with lateral head movements, one or both of the stimuli appear to move. This stereoillusory motion[1] can be explained by the motion–distance invariance hypothesis, which states that a physically stationary stimulus can appear to move as an observer moves, when the visual system incorrectly registers the distance to it (e.g., Gogel, 1990; Howard & Rogers, 1995).[2] In general, the hypothesis states that an object will appear to move in the same direction as the head does if the distance to the object is underestimated, and in the opposite direction if the distance is overestimated. For stereo stimuli, when the distance to the display plane is registered correctly, the distance to other stimuli depicted in depth would be registered "incorrectly," out of the frontoparallel plane in which the images are actually being displayed. Head movements produce illusory motion in the same direction as the head movement when the stereo stimulus appears in front of the plane in which the image is displayed. Head movements produce illusory motion in the opposite direction of the head movement when the stereo stimulus appears behind the display plane. The extent of illusory motion can be predicted from geometry based on head movement, viewing distance, stimulus configuration, and optics (see Figure 2).

In the present study, we examined two predictions of the motion–distance invariance hypothesis with respect to stereograms. First, according to the geometry of the stimulus configuration shown in Figure 2, the extent of illusory motion (m) would increase linearly as a function of stereo depth (d) and head movement (M), when the viewing distance (D) is kept constant. Second, the extent of illusory motion would increase linearly as a function of viewing distance (D), when binocular disparity and extents of head movement are kept constant. We measured the extent of the illusory motion while varying stereo depth and the extent of head movement in Experiment 1 and while varying stereo depth and viewing distance in Experiment 2.

EXPERIMENT 1

We tested predictions based on the motion–distance invariance hypothesis, by varying stereo depth for different extents of head movement, at a fixed viewing distance. The hypothesis predicts that the extent of illusory

---

The first author, who is from Tokyo University of Mercantile Marine, worked on this study while he was a visiting researcher in 1996 at the Communications Research Centre, Ottawa, Canada, and while he was a visiting researcher in 2000 at the University of Dundee, Dundee, Scotland. We thank A. Higashiyama, S. Nakamizo, and N. J. Wade for their useful comments on an earlier version of the manuscript. The results described in this paper were reported by Shimono, Tam, Stelmach, and Hildreth in 1997 at the Association for Research in Vision and Ophthalmology meeting in Fort Lauderdale, FL. Part of the present study was supported by a Grant-in-Aid for Scientific Research (10610069) provided by the Japanese Ministry of Education, Science, and Culture. Correspondence concerning this article should be addressed to K. Shimono, Department of Information Processing Engineering and Logistics, Tokyo University of Mercantile Marine, Ettchujima 2-1-6, Koto-ku, Tokyo, Japan 135-8533 (e-mail: shimono@ipc.tosho-u.ac.jp).

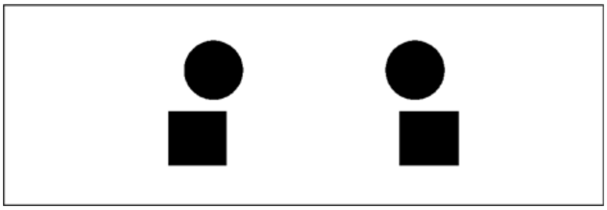

Figure 1. Example of a stereogram used in the present study.

motion will vary linearly with stereo depth, when the extent of the head movement and the viewing distance are constant. This prediction can be easily derived from the geometrical relationships among the following parameters: depth between stimuli (d), viewing distance (D), illusory motion (m), and head movement (M). According to the geometry, the ratio between d and D is equal to that between m and M (see Figure 2):

$$d/D = m/M. \qquad (1)$$

Furthermore, stereo depth can be expressed as

$$d \approx \delta D(D+d)/I \text{ for crossed disparity, and} \qquad (2A)$$

$$d \approx \delta D(D-d)/I \text{ for uncrossed disparity,} \qquad (2B)$$

where I is the interocular distance and δ is binocular disparity between stereo stimuli (for a derivation, see Ono & Comerford, 1977). If d is relatively small with respect to D, then $D \approx D + d$. Consequently, we have for both disparities,

$$d \approx \delta D^2/I. \qquad (3)$$

From Equations 1 and 3, illusory motion would be

$$m \approx \delta MD/I. \qquad (4)$$

Equation 4 shows that the motion of the depth stimulus covaries with the binocular disparity when the extent of head movement and the viewing distance are constant.

Method

Subjects. Twelve members of our laboratory, 3 females and 9 males, participated in the experiment. They ranged in age from 21 to 43 years, and they reported having normal or corrected-to-normal visual acuity and stereopsis. Six observers were assigned to a condition in which the extent of head movement was 10 cm, and the other 6 were assigned to a condition in which the extent of head movement was 20 cm.

Stimuli and Apparatus. The stimuli were generated by a VSG 2/3 (Cambridge Research Systems) controlled by a computer. The stimuli were stereograms consisting of a square and a disk, depicted schematically in Figure 1. The square subtended 1.8° × 1.8° of arc, and the disk subtended a diameter of 1.8° of arc. They were presented on a 21-in. CRT screen (Hitachi SuperElite) that was positioned so that its center was at eye level, at a distance of 160 cm from the observer's corneal plane. LCD shutter glasses (Stereographics, Crystal Eyes) were used to view the stimuli. The stimuli in the stereogram were red in color to avoid the activation of the long-persistent green phosphor, which can create undesired cross-talk in the shutter glasses. The stimuli were visible until the observers finished responding with their estimates. The stereograms were observed in a room illuminated by fluorescent lights. We assumed that under such a condition there would be ample egocentric distance information and, thus, that the distance to the reference stimulus depicted at zero disparity on the surface of the computer monitor would be registered correctly.

Design. Two extents of head movement were studied: 10 and 20 cm, and the extent of head movement was varied between sub-

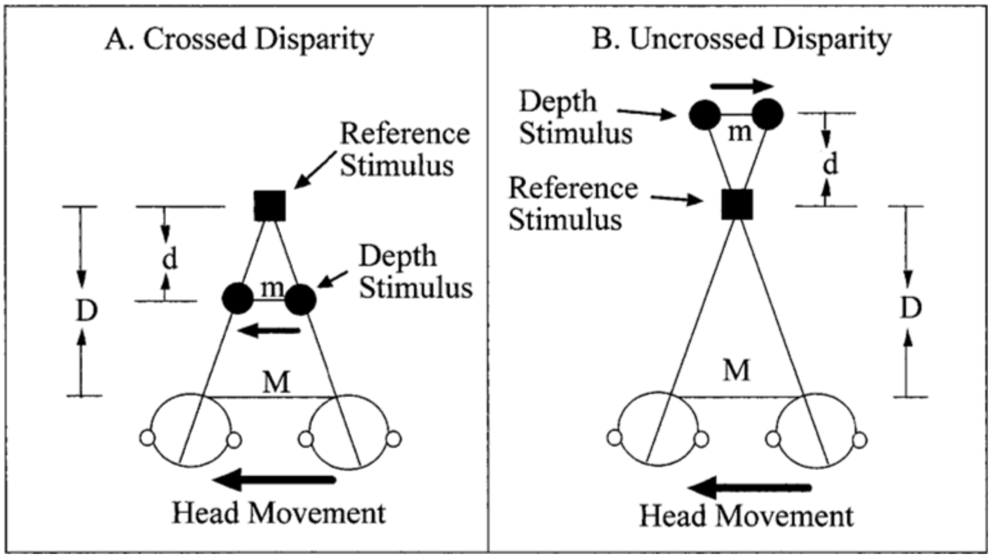

Figure 2. Predictions based on the motion–distance invariance hypothesis. According to the hypothesis, a stimulus with depth appears to move as the head moves. The direction of the perceived movement would be the same as or opposite to the direction of the head movement, when the stimulus is crossed (A) or uncrossed (B) disparity, respectively. Geometrically, the extent of motion of the depth stimulus, labeled "m" in the figure, would covary linearly with the relative depth between the depth stimulus and the stationary reference stimulus, labeled "d" in the figure.

jects. One of the stimuli (either the disk or the square) was designated as *reference* and had zero disparity. The other, designated as *test*, had a crossed or uncrossed disparity. Disparity was varied within subjects at nine levels: −20′, −15′, −10′, −5′, 0′, 5′, 10′, 15′, or 20′ of arc, where negative numbers represent uncrossed disparity, and positive numbers represent crossed disparity. Thus, there were two factors in the experiment: extent of head movement at two levels and disparity at nine levels.

Procedure. Each subject was assigned randomly to the 10- or the 20-cm head movement condition. The subjects completed 36 experimental trials, 4 at each level of disparity. The observers moved their heads laterally while viewing the stimuli and reported whether none, one, or two of the stimuli appeared to move and whether motion was in the same or in the opposite direction of the head movement. The observer's head was supported on a chinrest that could move freely in a horizontal direction along a track parallel to the surface of the monitor's screen. At the end of each trial, the subjects reproduced the extent of the illusory motion by using an adjustable caliper with an accuracy of 0.5 mm.

Ancillary measures. Three types of ancillary measures were made (1) to validate the use of the caliper, (2) to estimate the magnitude of perceived head movement, and (3) to estimate the relative depth between the two stimuli. To verify that use of the caliper was a valid method for measuring perceived extent of motion, a display was designed in which the stimuli actually moved and the subjects estimated the extent of motion. The motion of the stimulus was yoked to head movement, and the direction of stimulus motion was in the same direction as, or in the opposite direction to, that of the head. The extent of head movement was either 10 or 20 cm. In the 10-cm condition, extent of stimulus motion was 0, 1.25, 2.5, 3.75, or 5.0 cm. In the 20-cm condition, extent of stimulus motion was 0, 2.5, 5.0, 7.5, or 10.0 cm. Head movement was monitored by the computer by using an optical encoder with a spatial resolution of 0.032 mm. The stimulus was displayed at zero disparity and could be either a square or a disk. The same observers were used for method verification as for the main experiment for either the 10- or the 20-cm condition. Each observer completed 18 trials in which there were nine different stimuli with zero movement and four different movement extents, each of which had two different movement directions, and they were presented twice in a randomized order. The results show that the subjectively measured extents of stimulus motion corresponded with those of the actual motion of the stimulus on the screen, confirming the validity of the present method for measuring the extent of illusory motion. Mean coefficients of determination (r^2) were .988 and .993 for the 10- and 20-cm head movement conditions, respectively. Mean slopes were 1.025 and 1.239 for the 10- and 20-cm head movement conditions, respectively, and were not significantly different from unity [$t(11) = 1.14$, $p > .10$]. Method verification was conducted randomly either before or after the experiment.

In a second ancillary task, the subjects estimated the magnitude of perceived head movement by using the adjustable sliding caliper. These estimates were used in a later analysis that compared perceived extent of head movement with the actual extent of head movement as a predictor of perceived stimulus motion. Four estimates of head movement were obtained; two prior to each experimental session and two at the end of the session. The stimuli were motionless and at zero disparity when estimates of head movement were made. The mean reproduced head movements were 17.3 cm and 26.1 cm for the 10- and 20-cm head movement conditions, respectively.

In a third ancillary task, the subjects estimated the relative depth between the reference and test stimuli, while holding their heads still. Prior to each trial, the subjects reported whether the two stereo stimuli appeared in depth and, if they did, which stimulus appeared in front of or behind the screen plane. This estimate was obtained without head movement because the observers had difficulty in reproducing the perceived depth while moving their heads. (We assumed that the perceived depth obtained without lateral head movements would be the same as that obtained with lateral head movements [Patterson & Fox, 1984b]. Geometrically, the depth for a stationary stereo stimulus is constant with lateral head movements as long as the head moves parallel to the stereo stimulus [see, e.g., Lee, 1969].) The apparent separation in depth between the stimuli was reported by subjects using the caliper. A positive sign was as-

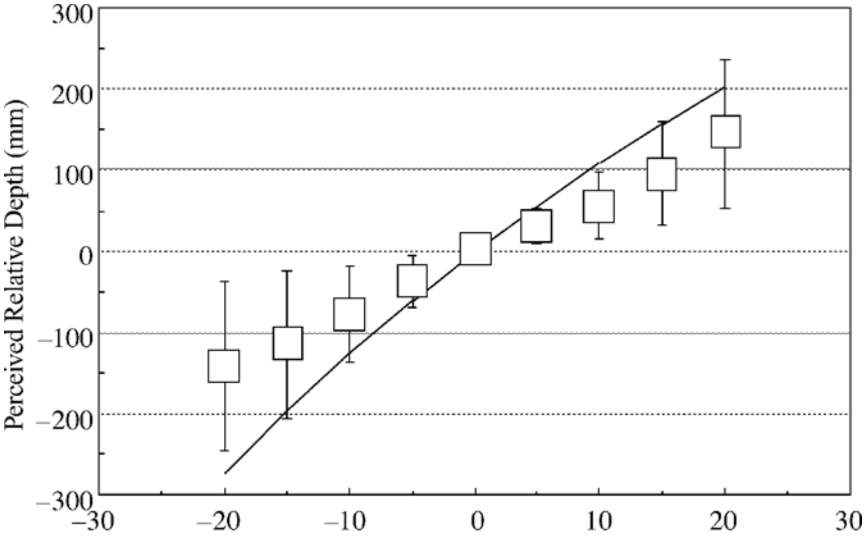

Figure 3. The mean perceived depth between the test and reference stimuli as a function of binocular disparity between them. Open squares indicate the average over 12 observers. The vertical lines attached to the data points indicate the standard deviations. The solid line indicates the perceived depth predicted from geometry based on stimulus configuration and optics.

signed to the depth magnitude if the stimulus appeared in front of the reference stimulus, and a negative sign was assigned if it appeared behind the reference stimulus. All observers reported the correct direction of depth. The mean perceived depth data are shown in Figure 3 with square symbols, averaged for all subjects. A solid line in the figure represents the geometrically predicted depth. As is shown in the figure, perceived depth was monotonically related to binocular disparity, although it was underestimated compared with the geometrically predicted depth. Note that the symbols fall closer to zero than does the solid line. The predicted depth value was calculated by using Equation 2A for crossed disparity and Equation 2B for uncrossed disparity, and the equations are essentially the same as those from Equation 8 in Cormack and Fox (1985). The depth data were submitted to a one-way, repeated measures analysis of variance (ANOVA), with disparity as the repeated factor. The main effect of disparity was statistically significant [$F(8,80) = 25.077$, $p < .001$]. The result is consistent with those reported previously (e.g., Patterson & Martin, 1992; Patterson, Moe, & Hewitt, 1992; Richards, 1971; Ritter, 1977, 1979).

Results and Discussion

The basic unit of analysis of the magnitude of illusory motion was the average measurement over four trials for each observer. A positive sign was assigned to the magnitude of illusory motion when it was reported to be in the same direction as that of the head movement and a negative sign when it was reported to be in the opposite direction.

The mean motion data are shown in Figure 4, separately for the 10- and the 20-cm head movement conditions. The solid symbols represent the results for the reference stimuli, which were displayed at zero disparity, and the open symbols represent the results for the test stimuli, which were displayed at the disparity shown on the x-axis. The results were generally consistent with expectations. As is evident from the flat pattern of the solid symbols in Figure 4, the reference stimuli were judged to be relatively motionless, although the negative sign of the symbol suggests that the stimulus appeared to move slightly in the opposite direction to that of the observer's head movement. Recall that the reference stimuli were displayed at zero disparity on the screen surface. A series of t tests showed that the extent of illusory motion of the reference stimuli was not statistically different from zero at each disparity. In contrast, the slope of the open symbols in Figure 4 indicates that the test stimuli appeared to move as the subjects moved their heads, and the extent of this motion increased with larger disparities. Furthermore, the extent of perceived stimulus motion was greater in the 20-cm than in the 10-cm head movement condition; compare the left and right panels of Figure 4. These effects were confirmed statistically in a two-way ANOVA, with disparity as the repeated measure. It was found that the main effects of head movement [$F(1,10) = 7.23$, $p < .05$] and disparity [$F(8,80) = 63.98$, $p < .001$] and their interaction [$F(8,80) = 9.83$, $p < .001$] were statistically significant. A separate ANOVA on the reference stimuli revealed no statistically significant effects.

The solid lines in Figure 4 refer to predicted extents of illusory stimulus motion, based on the motion–distance invariance hypothesis. The predicted extents were calculated by using the geometrically predicted depth value, extent of physical head movement, and physical viewing distance (see Equation 1). As is shown in Figure 4, the mean motion data agree well with the geometrically based predictions except for the uncrossed disparities for the 20-cm head movement condition.

Furthermore, we examined whether or not the motion data obtained could be accurately predicted by the per-

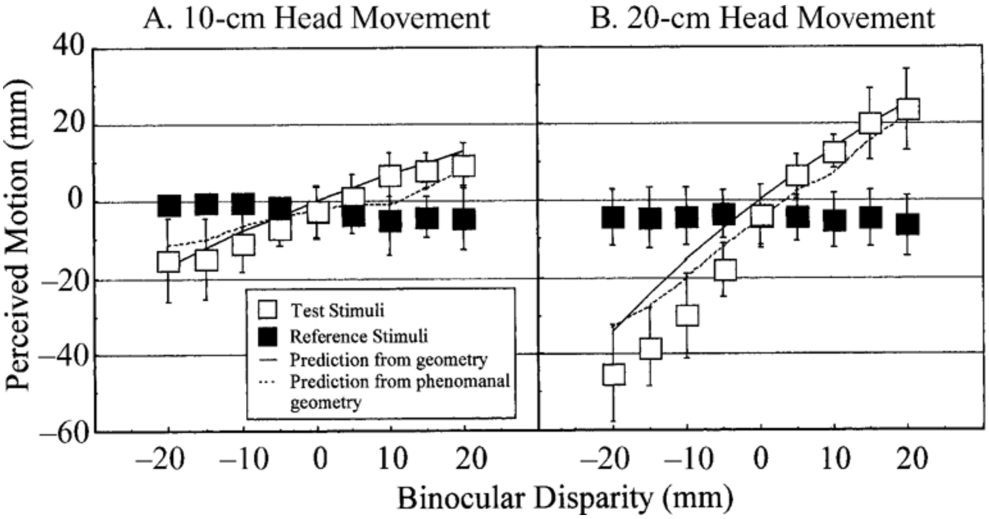

Figure 4. Mean perceived motion as a function of binocular disparity between the test and reference stimuli for the 10-cm head movement condition (A) and that for the 20-cm head movement condition (B). The open and solid squares indicate the averages over 6 observers for the test and reference stimuli, respectively. The vertical lines attached to the data points indicate standard deviations. The solid and dotted lines indicate the magnitude of perceived motion predicted from geometry (see text) and from phenomenal geometry (see text), respectively.

ceived variables rather than by stimulus geometry. In the past, some researchers have suggested that perceptually derived predictions are more accurate than geometrically derived predictions (Gogel, 1990; Swanston, Wade, & Day, 1987). In this vein, Gogel suggested that the perceived space is described geometrically in terms of perceptual variables, and he referred to it as *phenomenal* geometry. On the basis of this geometry, the concomitant perceived movement of a stationary target with lateral head movement is determined by the difference between two distances: the apparent and the physical distance of the target from the observer (Gogel, 1990).

According to the phenomenal geometry, the result that the reference stimulus appeared to move slightly in the opposite direction to that of the observer's head movement (see the solid squares in Figure 4) is regarded as indicating that its apparent distance was larger than its physical distance. If this were the case, we could predict the extent of motion of the test stimulus. To predict the extent, the mean perceived head movement, mean perceived depth between the test and reference stimuli, mean perceived motion of the reference stimulus, and the physical distance are needed. (Recall that the perceived head movement and the perceived depth between the test and reference stimuli were obtained as described in the section on ancillary measures.)

We now address the details of how we predicted the extent. In Figure 5, the situation is illustrated in which the reference stimulus appears to move in the opposite direction to head movement, as was observed in the present study. Figure 5A shows the situation in which the test stimulus has crossed disparity and appears in front of the reference stimulus. The following two equations can be derived geometrically:

$$\mathrm{PD}/M' = (d' - x)/m', \tag{5}$$

$$\mathrm{PD}/M' = x/m_{\mathrm{pr}}. \tag{6}$$

PD is the physical distance to the reference stimulus, M' is the perceived extent of the head movements, d' is the perceived depth between the reference and test stimuli, and x is the relative distance between the test stimulus and the plane where the reference stimulus is physically placed. From Equations 5 and 6, we can derive the equation

$$m_{\mathrm{pr}} = M'd'/\mathrm{PD} - m'. \tag{7}$$

In a similar manner, for the situation in which the test stimulus has uncrossed disparity and as is shown in Figure 5B, the predicted motion can be expressed by the following equation:

$$m_{\mathrm{pr}} = M'd'/\mathrm{PD} + m'. \tag{8}$$

From Equations 7 and 8, we estimated the extent of perceived motion for the test stimulus. These estimates are based on phenomenal geometry and are indicated by the dotted lines in Figure 4. As is shown in the figure, the data obtained from the observers are greater than the perceptual prediction in most disparity conditions. The

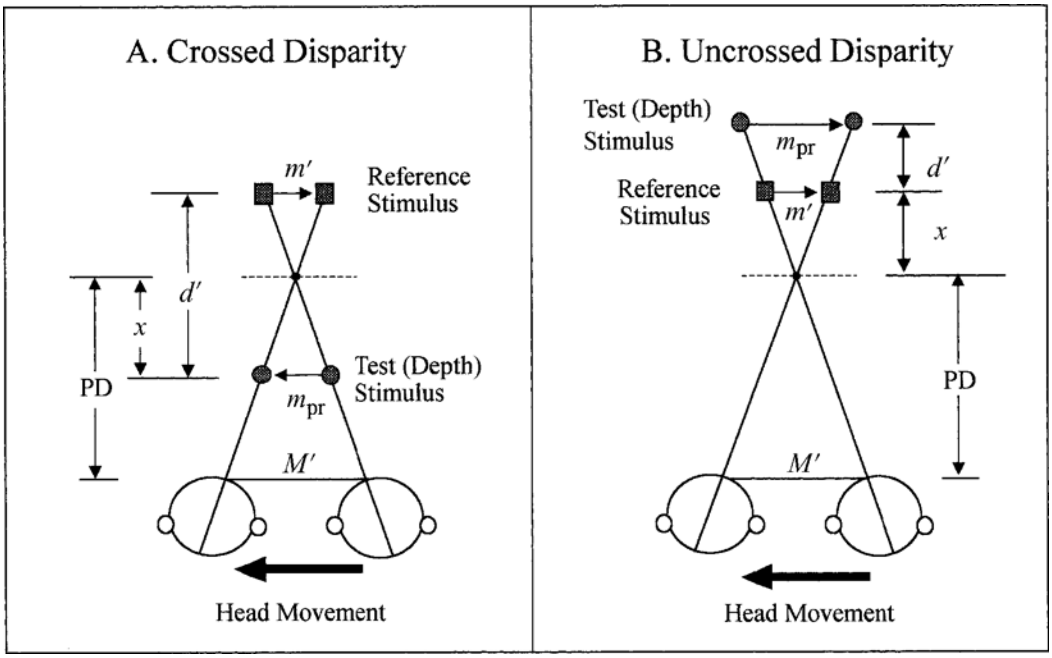

Figure 5. Predictions based on phenomenal geometry (see text) for crossed disparity (A) and uncrossed disparity (B) conditions, when the reference stimulus appears to move in the opposite direction to the head movement. On the basis of phenomenal geometry, the perceived motion of the test (depth) stimulus is determined by the perceived motion of the head, perceived depth between the test and reference stimuli, perceived motion of the reference stimulus, and the physical distance, which are labeled "M'," "d'," "m'," and "PD," respectively, in the figure. Please refer to the main text for a more detailed explanation.

main reason for this is that the viewer's estimate of depth was lower than the physical depth value. The present analysis suggests that perceptually derived predictions are not necessarily more accurate than geometrically derived predictions.

EXPERIMENT 2

In this experiment, the motion–distance invariance hypothesis was studied by varying disparity and viewing distance, while holding extent of head movement constant at 20 cm. The motion–distance invariance hypothesis predicts that the extent of illusory motion should be larger at farther viewing distances and at greater stimulus disparities. These predictions were derived from Equation 4, which was presented in the introduction to Experiment 1.

Methods

Subjects. Two female and 4 male members of our laboratory served as subjects. They ranged in age from 21 to 43 years and had normal stereopsis and normal or corrected-to-normal visual acuity.

Design and Procedure. The stimuli and apparatus were the same as those in Experiment 1. As before, extent of illusory motion was estimated by the subject at the end of each trial by using an adjustable caliper. Disparity was 10′ or 20′ of arc, crossed and uncrossed. The viewing distance to the screen was 60, 90, or 120 cm. Both disparity and viewing distance were varied within subjects. Lateral head movement was fixed at 20 cm. Each observer completed 48 trials, with four repetitions for each of the 12 experimental conditions, defined by combinations of disparity and viewing distance. Viewing distance was constant for a given session and randomized across sessions. Disparity was varied randomly within a session.

Ancillary measures. Two types of ancillary measures were made. In one, the subjects were required to estimate the relative depth between the two stimuli presented on the screen. This measure was performed on each trial and was identical to that in Experiment 1. Perceived depth judgments are summarized in Figure 6A for the 60-, 90-, and 120-cm viewing distance conditions of the experiment. For comparison, mean depth judgments from Experiment 1 are also shown for the 160-cm viewing distance. As can be seen in Figure 6A, mean perceived depth matched the predicted depth (depicted as a solid line) at smaller viewing distances but tended to be underestimated at larger viewing distances. The predicted depth was calculated by using Equation 2A for crossed disparity and Equation 2B for uncrossed disparity, as in Experiment 1. As expected, perceived depth was greater in the 20′ of arc than in the 10′ of arc disparity condition, and, furthermore, perceived depth for each disparity condition increased as a function of viewing distance. The latter result is consistent with those previously reported in the literature relevant to stereoscopic depth constancy (e.g., Glennerster, Rogers, & Bradshaw, 1996; Ono & Comerford; 1977; Patterson et al., 1995; Patterson & Martin, 1992; Ritter, 1977, 1979; Shimono, Nakamizo, & Tsuchida, 1990). The depth data were submitted to a two-way repeated measures (4 disparity × 3 viewing distance) ANOVA. The analysis showed that the main effect of disparity [$F(3,15) = 46.89$, $p < .001$] and the interaction between disparity and viewing distance [$F(6,30) = 32.24$, $p < .001$] were statistically significant.

In a second ancillary measure, the subjects were required to estimate the perceived distance to the screen by using a tape measure. The tape was unwound in a direction orthogonal to the viewing direction. Perceived distance was taken as the average of four estimates, two performed at the beginning of a session and two performed at the end of a session. The mean distance estimates, shown in Table 1, were close to the physical viewing distances and were not statistically different from the physical viewing distances.

Results and Discussion

By convention, a positive sign was assigned to the magnitude of illusory motion when it was reported to be in the same direction as that of the head movement and a negative sign when it was reported to be in the oppo-

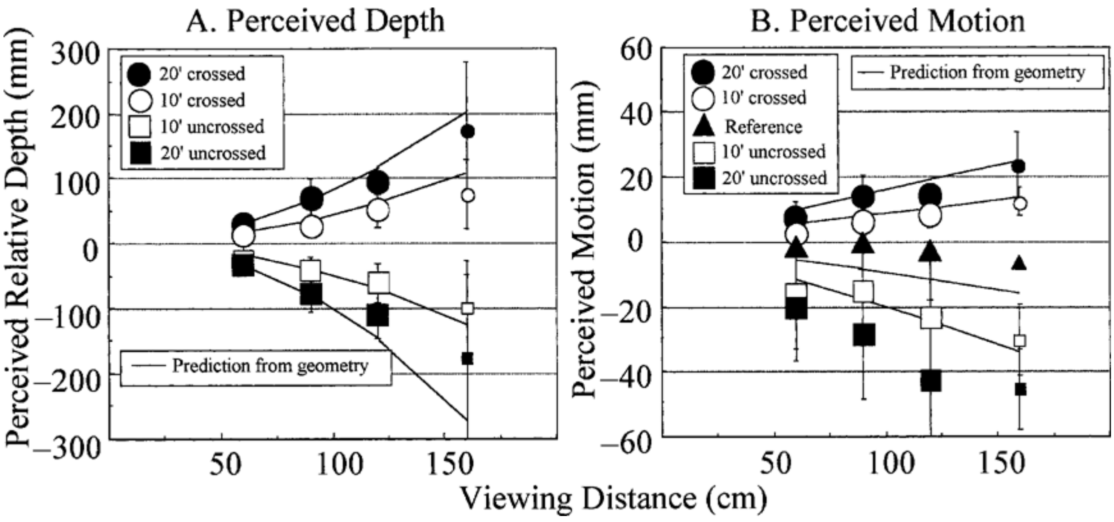

Figure 6. The mean perceived depth as a function of viewing distance (A) and the mean perceived motion as a function of viewing distance (B), for four different binocular disparities. The solid lines in (A) and (B) indicate the geometrically predicted depth and the geometrically predicted motion, respectively, for each viewing distance. The filled triangles in Panel B indicate means of perceived motion for the reference stimulus, with zero disparity. The smaller symbols in Panel B indicate the data that were obtained from Experiment 1 at a viewing distance of 160 cm.

Table 1
Mean Perceived Viewing Distances (*M*) in Centimeters and Their Standard Deviations (*SD*) for Experiment 2

Physical Viewing Distance	Perceived Viewing Distance *M*	*SD*
60	50.30	10.58
90	85.56	12.48
120	112.03	8.80

site direction. As before, the basic unit of analysis was the average extent of illusory motion reported by each observer in each condition. Figure 6B shows the results, summarized for all 6 observers. For comparison, the figure also shows the results (smaller symbols) obtained at a viewing distance of 160 cm in Experiment 1. Mean estimates of extents of illusory motion for the four disparity conditions, ranging from 20′ of arc crossed to 20′ of arc uncrossed, and the reference condition are shown with different symbols. The results formed orderly patterns, as is predicted by the motion–distance invariance hypothesis. The perceived extent of illusory motion increased as a function of viewing distance and as a function of disparity. As expected, the extent of illusory motion for the zero-disparity reference stimulus was close to zero in all conditions (shown as triangles in Figure 6B). This result is consistent with measurements that indicated that the perceived viewing distance to the reference matched the physical viewing distance to the screen (see Table 1). As in Experiment 1, the predicted responses based on geometry were also derived, and they are represented by solid lines in Figure 6.[3] The match between predicted and observed data was not perfect in that extents of illusory motion were close to those geometrically predicted for crossed disparity conditions but were smaller than those for uncrossed disparity conditions. This pattern of results was also observed in Experiment 1.

The results were submitted to a two-way repeated measures ANOVA (4 disparities × 3 viewing distances), separately for the test and reference stimuli. The analysis for the test stimulus showed that the main effect of disparity [$F(3,15) = 24.90$, $p < .001$] and the interaction between disparity and viewing distance [$F(6,30) = 8.38$, $p < .001$] were statistically significant. The analysis for the reference stimulus revealed no statistically significant effects.

Furthermore, using Equation 1, we analyzed the relationship between the perceived depth and the perceived motion to verify our conclusion in Experiment 1 that predictions based on perceived variables are not necessarily more accurate than those based on physical variables. According to Equation 1, the extent of the illusory motion would covary linearly with stereo depth for constant viewing distance and head movement. We calculated the predicted extents of illusory motion by using physical as well as perceptual variables and compared them with the motion data obtained in this experiment. In calculating the perceptually predicted extent of motion, we used the mean perceived head motion measured

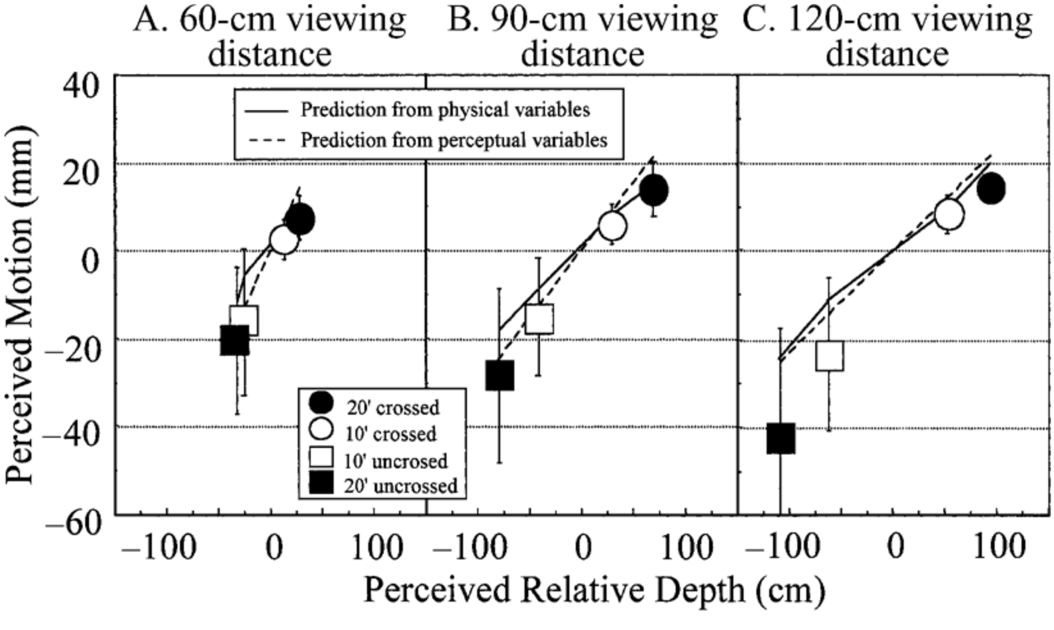

Figure 7. Mean perceived motion as a function of mean perceived depth at viewing distances of 60 cm (A), 90 cm (B), and 120 cm (C). The open and solid circles indicate the averages over 6 observers for 10 and 20 min of arc crossed disparities, respectively. The open and solid squares indicate the averages over 6 observers for 10 and 20 min of arc uncrossed disparities, respectively. The vertical lines attached to the datapoints indicate standard deviations. The solid and dotted lines in each panel indicate the extent of motion predicted from physical variables and that predicted from perceptual variables, respectively (see text).

main reason for this is that the viewer's estimate of depth was lower than the physical depth value. The present analysis suggests that perceptually derived predictions are not necessarily more accurate than geometrically derived predictions.

EXPERIMENT 2

In this experiment, the motion–distance invariance hypothesis was studied by varying disparity and viewing distance, while holding extent of head movement constant at 20 cm. The motion–distance invariance hypothesis predicts that the extent of illusory motion should be larger at farther viewing distances and at greater stimulus disparities. These predictions were derived from Equation 4, which was presented in the introduction to Experiment 1.

Methods

Subjects. Two female and 4 male members of our laboratory served as subjects. They ranged in age from 21 to 43 years and had normal stereopsis and normal or corrected-to-normal visual acuity.

Design and Procedure. The stimuli and apparatus were the same as those in Experiment 1. As before, extent of illusory motion was estimated by the subject at the end of each trial by using an adjustable caliper. Disparity was 10′ or 20′ of arc, crossed and uncrossed. The viewing distance to the screen was 60, 90, or 120 cm. Both disparity and viewing distance were varied within subjects. Lateral head movement was fixed at 20 cm. Each observer completed 48 trials, with four repetitions for each of the 12 experimental conditions, defined by combinations of disparity and viewing distance. Viewing distance was constant for a given session and randomized across sessions. Disparity was varied randomly within a session.

Ancillary measures. Two types of ancillary measures were made. In one, the subjects were required to estimate the relative depth between the two stimuli presented on the screen. This measure was performed on each trial and was identical to that in Experiment 1. Perceived depth judgments are summarized in Figure 6A for the 60-, 90-, and 120-cm viewing distance conditions of the experiment. For comparison, mean depth judgments from Experiment 1 are also shown for the 160-cm viewing distance. As can be seen in Figure 6A, mean perceived depth matched the predicted depth (depicted as a solid line) at smaller viewing distances but tended to be underestimated at larger viewing distances. The predicted depth was calculated by using Equation 2A for crossed disparity and Equation 2B for uncrossed disparity, as in Experiment 1. As expected, perceived depth was greater in the 20′ of arc than in the 10′ of arc disparity condition, and, furthermore, perceived depth for each disparity condition increased as a function of viewing distance. The latter result is consistent with those previously reported in the literature relevant to stereoscopic depth constancy (e.g., Glennerster, Rogers, & Bradshaw, 1996; Ono & Comerford; 1977; Patterson et al., 1995; Patterson & Martin, 1992; Ritter, 1977, 1979; Shimono, Nakamizo, & Tsuchida, 1990). The depth data were submitted to a two-way repeated measures (4 disparity × 3 viewing distance) ANOVA. The analysis showed that the main effect of disparity [$F(3,15) = 46.89$, $p < .001$] and the interaction between disparity and viewing distance [$F(6,30) = 32.24$, $p < .001$] were statistically significant.

In a second ancillary measure, the subjects were required to estimate the perceived distance to the screen by using a tape measure. The tape was unwound in a direction orthogonal to the viewing direction. Perceived distance was taken as the average of four estimates, two performed at the beginning of a session and two performed at the end of a session. The mean distance estimates, shown in Table 1, were close to the physical viewing distances and were not statistically different from the physical viewing distances.

Results and Discussion

By convention, a positive sign was assigned to the magnitude of illusory motion when it was reported to be in the same direction as that of the head movement and a negative sign when it was reported to be in the oppo-

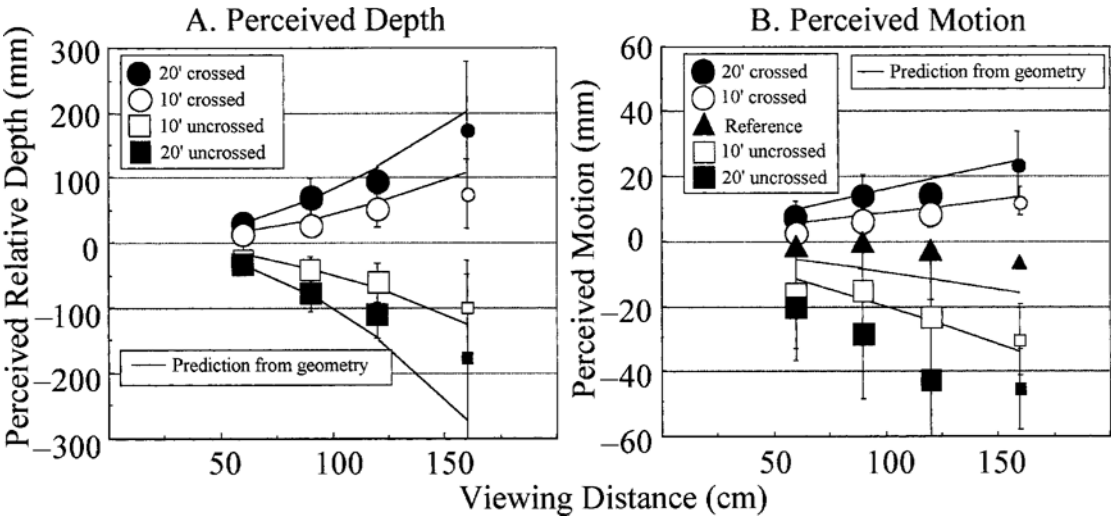

Figure 6. The mean perceived depth as a function of viewing distance (A) and the mean perceived motion as a function of viewing distance (B), for four different binocular disparities. The solid lines in (A) and (B) indicate the geometrically predicted depth and the geometrically predicted motion, respectively, for each viewing distance. The filled triangles in Panel B indicate means of perceived motion for the reference stimulus, with zero disparity. The smaller symbols in Panel B indicate the data that were obtained from Experiment 1 at a viewing distance of 160 cm.

sponded well with the obtained illusory motion for crossed disparities and was underestimated for uncrossed disparity. Furthermore, we found that the predicted extent based on phenomenal geometry (Gogel, 1990) and perceptual variables (Equation 1) did not completely agree with the measured extent of illusory motion. Thus, it is not possible to conclude from the present findings whether physical or perceptual variables are used by the visual system to determine stereoillusory motion.

REFERENCES

Anstis, S. M. (1986). Motion perception in the frontal plane: Sensory aspects. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I: Sensory process and perception* (pp. 16.1-16.17). New York: Wiley.

Becker, S., Bowd, C., Shorter, S., King, K., & Patterson, R. (1999). Occlusion contributes to temporal processing differences between crossed and uncrossed stereopsis in random-dot displays. *Vision Research*, **39**, 331-339.

Cormack, R., & Fox, R. (1985). The computation of disparity and depth in stereograms. *Perception & Psychophysics*, **38**, 375-380.

Frisby, J. P. (1979). *Seeing*. London: Houghton Mifflin.

Glennerster, A., Rogers, E. J., & Bradshaw, M. F. (1996). Stereoscopic depth constancy depends on the subject's task. *Vision Research*, **36**, 3441-3456.

Gogel, W. C. (1990). A theory of phenomenal geometry and its applications. *Perception & Psychophysics*, **48**, 105-123.

Howard, I. P., & Rogers, B. J. (1995). *Binocular vision and stereopsis*. New York: Oxford University Press.

Julesz, B. (1971). *Foundations of cyclopean perception*. Chicago: University of Chicago Press.

Lee, D. (1969). Theory of the stereoscopic shadow-caster: An instrument for the study of binocular kinetic space perception. *Vision Research*, **9**, 145-156.

Moulden, B., Patterson, R., & Swanston, M. (1998). The retinal image, ocularity, and cyclopean vision. In G. Mather, F. F. Verstraten, & S. [M.] Anstis (Eds.), *The motion aftereffect* (pp. 57-84). Cambridge, MA: MIT Press.

Mustillo, P. (1985). Binocular mechanisms mediating crossed and uncrossed stereopsis. *Psychological Bulletin*, **97**, 187-201.

Nakayama, K., & Tyler, C. W. (1981). Psychophysical isolation of movement sensitivity by removal of familiar position cues. *Vision Research*, **21**, 427-433.

Ono, H., & Comerford, J. (1977). Stereoscopic depth constancy. In W. Epstein (Ed.), *Stability and constancy in visual perception: Mechanisms and processes* (pp. 91-128). New York: Wiley.

Patterson, R. (1999). Stereoscopic (cyclopean) motion sensing. *Vision Research*, **39**, 3329-3345.

Patterson, R., Bowd, C., Phinney, R., Fox, R., & Lehmkuhle, S. (1996). Disparity tuning of the stereoscopic (cyclopean) motion aftereffect. *Vision Research*, **36**, 975-983.

Patterson, R., Cayko, R., Short, G. L., Flanagan, R., Moe, L., Taylor, E., & Day, P. (1995). Temporal integration differences between crossed and uncrossed stereoscopic mechanisms. *Perception & Psychophysics*, **57**, 891-897.

Patterson, R., & Fox, R. (1984a). The effect of testing method on stereoanomaly. *Vision Research*, **24**, 403-408.

Patterson, R., & Fox, R. (1984b). Stereopsis during continuous head motion. *Vision Research*, **24**, 2001-2003.

Patterson, R., & Martin, W. (1992). Human stereopsis. *Human Factors*, **34**, 669-692.

Patterson, R., Moe, L., & Hewitt, T. (1992). Factors that affect depth perception in stereoscopic displays. *Human Factors*, **34**, 655-667.

Richards, W. (1971). Anomalous stereoscopic depth perception. *Journal of the Optical Society of America*, **61**, 410-414.

Ritter, M. (1977). Effect of disparity and viewing distance on perceived depth. *Perception & Psychophysics*, **22**, 400-407.

Ritter, M. (1979). Perception of depth: Processing of simple positional disparity as a function of viewing distance. *Perception & Psychophysics*, **25**, 209-214.

Rock, I. (1983). *The logic of perception*. London: MIT Press.

Shimono, K. (1984). Evidence for the subsystems in stereopsis: Fine and coarse stereopsis. *Japanese Psychological Research*, **28**, 168-172.

Shimono, K., Nakamizo, S., & Tsuchida, S. (1990). Ryougan moumaku zousa ni motuzuku okuyukiryou to zettai kyori [Role of egocentric distance on stereoscopic depth perception]. *Bulletin of Fukuoka University of Education*, **39**, 265-271.

Swanston, M. T., Wade, N. J., & Day, H. R. (1987). The representation of uniform motion in vision. *Perception*, **16**, 143-159.

Tyler, C. W. (1974). Induced stereomovement. *Vision Research*, **14**, 609-613.

NOTES

1. One anonymous reviewer claimed that this phenomenon should not be called an "illusion" because it is "quite explicable on the basis of the way perception normally works" as in stereopsis—namely, on the basis of binocular geometry. Although it is not yet clear whether the phenomenon is explained only by the geometry or not, it may be worth discussing what terms researchers use to describe the phenomenon. Some researchers have used the term *motion parallax* or *movement parallax*; Julesz (1971) called the phenomenon an *inverse movement parallax*, Rock (1983), a *motion parallax illusion*, and Howard and Rogers (1995), an *illusory motion parallax*. One researcher has called it *induced stereomovement* (Tyler, 1974). We have not used the term motion parallax because there is no "retinal motion parallax" (Tyler, 1974, p. 610) with a stereo stimulus. We have also not used the term *induced movement* because it is usually used to describe "an illusion in which real movement is attributed to the wrong part of the stimulus array" (Anstis, 1986, p. 16.2), and there is no movement with a stereo stimulus. Instead, we use the term *illusory* on the basis of our observation that a stationary stereo stimulus appears to be "moving." As described above, the terms *illusion* and *illusory* can also be found in Rock and in Howard and Rogers.

2. More generally, stereoillusory motion can occur when perceived depth, distance to the object, or magnitude of head movement is perceived nonveridically (Gogel, 1990; in Howard & Rogers, 1995).

3. As in Experiment 1, we also calculated the predicted extents of motion based on phenomenal geometry. We used the value obtained in the 20-cm head movement condition of Experiment 1 for the perceived head movement, and for other perceptual variables, we used the measurements from Experiment 2. The calculated values showed that predicted extents of motion based on perceptual variables were smaller than the measured extents of perceived motion obtained in Experiment 2.

4. Note that the suggestion is still valid even if the perceived head movement in Experiment 2 is different from that in Experiment 1. This can be understood by referring to Figure 7. If the perceived head movement were larger than that in Experiment 1, the slope of the dotted lines in Figure 7 would become steeper. If the perceived head motion in Experiment 2 were smaller than that in Experiment 1, the slope would become shallower. In either case, the predictions based on perceptual variables are not as accurate as those based on physical variables.

5. The argument for separable processing of crossed and uncrossed disparities for stereoillusory motion has a counterpart in studies of depth perception. In the depth domain, it has been suggested that there are separate mechanisms in the processing of crossed and uncrossed disparities (see, e.g., Becker, Bowd, Shorter, King, & Patterson, 1999; Mustillo, 1985; Patterson et al., 1995; Patterson & Fox, 1984a; Patterson & Martin, 1992; Patterson et al., 1992; Richards, 1971; Shimono, 1984).

6. We fitted a least squares regression line because if the visual system calculates the extent of illusory motion as if it "knows" Equation 4, the extent would covary linearly as a function of head movement, for a specific disparity and a fixed viewing distance.

(Manuscript received May 3, 2001;
revision accepted for publication February 5, 2002.)