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Vision Research 47 (2007) 1027–1035
Vision Research
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Apparent motion of monocular stimuli in different depth planes with lateral head movements ☆

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Received 9 May 2006; received in revised form 24 January 2007

Abstract

A stationary monocular stimulus appears to move concomitantly with lateral head movements when it is embedded in a stereogram representing two front-facing rectangular areas, one above the other at two different distances. In Experiment 1, we found that the extent of perceived motion of the monocular stimulus covaried with the amplitude of head movement and the disparity between the two rectangular areas (composed of random dots). In Experiment 2, we found that the extent of perceived motion of the monocular stimulus was reduced compared to that in Experiment 1 when the rectangular areas were defined only by an outline rather than by random dots. These results are discussed using the hypothesis that a monocular stimulus takes on features of the binocular surface area in which it is embedded and is perceived as though it were treated as a binocular stimulus with regards to its visual direction and visual depth.

Keywords: Head movement; Monocular stimuli; Apparent motion; Optical geometry; Default surface hypothesis

1. Introduction

Recent literature shows that the visual system treats monocular stimuli as binocular stimuli in direction perception (e.g., Domini & Braunstein, 2001; Erkelens & van Ee, 1997a, 1997b; Ono & Mapp, 1995; Rogers & Bradshaw, 1999; Shimono, Ono, Saida, & Mapp, 1998; Shimono, Tam, Asakura, & Ohmi, 2005; Shimono & Wade, 2002) and in depth perception (Domini & Braunstein, 2001; Rogers & Bradshaw, 1999; Shimono et al., 2005; Shimono & Wade, 2002). In direction perception, for example, Erkelens and van Ee (1997a, 1997b) have reported that when a monocular vertical line is presented in a random-dot stereogram in which the half-images oscillate in counter phase, the monocular line appears stationary—as does the surrounding binocular field of random dots (Erkelens & Collewijn, 1985). They argue that the phenomenon is due to "the capture of the visual direction of monocular objects by binocular objects" (Erkelens & van Ee, 1997b, p. 1735). In depth perception, Shimono and Wade (2002) have reported that when a vertical monocular bar is presented in each half-field of two random-dot stereo stimuli as shown in Fig. 1a, the perceived depth between the upper and lower vertical monocular lines covaries with the perceived depth between the upper and lower disparate areas. These phenomena indicate that monocular stimuli embedded in a binocular surface area are perceived as though they were treated as binocular stimuli with regards to their visual direction and visual depth.

In the present paper, we report a phenomenon in which a stationary monocular stimulus embedded in the binocular region of a stereogram appears to move concomitantly with lateral head movements, suggesting

☆ This research was supported by grant-in-aids for Scientific Research (17530526) provided by Japan Society for the Promotion of Science (JSPS). We thank S. Yasue for data collection for Experiment 2, and L. Lillakas for her editorial help. We also thank one anonymous reviewer and B. Rogers for their helpful comments on an earlier version of this article.
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doi:10.1016/j.visres.2007.01.012

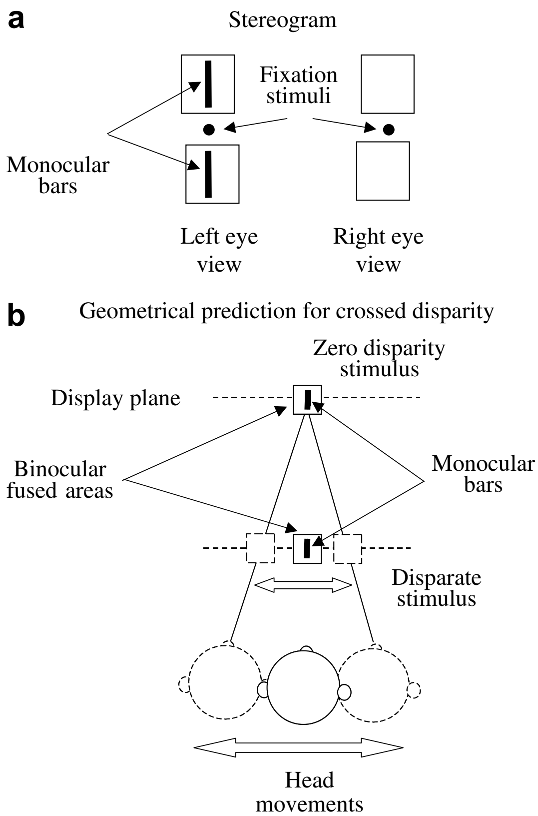

Fig. 1. Example of a stereogram used in the present study (a) and geometrical predictions based on the default surface hypothesis (b). According to the hypothesis and geometry, a monocular bar that "is defaulted to" a disparate stimulus will appear to move concomitantly with head movements. The direction of motion as well as the magnitude of the depth of the monocular bar would be the same as those of the disparate stimulus. Geometrically, the extent of motion of the disparate stimulus would covary linearly with the relative depth between the disparate stimulus and the stationary zero disparity stimulus.

that the visual system also treats monocular stimuli as binocular stimuli with regards to motion perception.[1] We have found that the extent of the apparent motion depends on the perceived depth of the surrounding binocular surface area in which the monocular stimulus is located. For example, observers may perceive a different extent of motion when two monocular stimuli are embedded in two different binocular areas with different horizontal disparities. Such a stereogram is schematically depicted in Fig. 1a. A vertical monocular bar is presented in the left half-field of each of the two random-dot stereo stimuli that are positioned one above the other. The stereo stimuli have different binocular disparities such that they appear at different depths when the two half fields of the stereogram are fused. When a viewer slowly moves his or her head laterally while viewing the stereogram, the two monocular bars appear to move by different extents.

The apparent movement of the monocular stimulus can be explained by assuming that the visual system treats a monocular stimulus as a binocular stimulus that has taken on features of its surrounding binocular surface area (Domini & Braunstein, 2001; Erkelens & van Ee, 1997a, 1997b; Ono & Mapp, 1995; Shimono et al., 1998, 2005; Shimono & Wade, 2002) and that, by default, the monocular stimulus is attributed with the same depth and direction as the surrounding binocular area. Given a geometrical analysis of the stimulus configuration (Shimono, Tam, Stelmach, & Hildreth, 2002), for the binocular areas illustrated in Fig. 1a, the stimulus depicted in depth with respect to the display plane (disparate stimulus) appears to move concomitantly with lateral head movements while the other stimulus depicted in the display plane with zero disparity (zero disparity stimulus) will appear stationary (Fig. 1b). Thus, given the assumption that a monocular stimulus takes on the features of its surrounding area, the monocular stimulus presented in the binocular disparate area would appear to move in the same manner as the surrounding area.

In the present study, we measured the extent of apparent movement of stationary monocular stimuli embedded in binocular surfaces and compared the perceived movement to predictions based on the "default surface" hypothesis.[2] The default surface hypothesis and a geometrical analysis of the stimulus configuration predict that the extent of apparent motion of the monocular bar would covary with the amplitude of the head movement and the magnitude of perceived depth between the binocular fused surface areas. We examined these predictions in Experiment 1. When there is no binocularly fused area with which the monocular stimulus can be associated, the monocular stimulus will appear to be in the plane of fixation (e.g., Howard & Rogers, 2002; Shimono, Tam, & Nakamizo, 1999) and, thus the geometry predicts that no apparent movement is seen. We examined this prediction in Experiment 2 using a binocular stimulus that consisted of outlines and were therefore without "explicit" binocular surfaces areas (Shimono & Wade, 2002).

[1] As mentioned in the main body of the manuscript, Erkelens and van Ee (1997a, 1997b) demonstrated that a moving vertical bar can appear stationary when it is embedded in a moving binocular area in depth. This demonstration also suggests that a monocular stimulus can be treated as if it were a binocular stimulus with regards to motion perception.

[2] In an earlier version of this article, our hypothesis was named the "capture" hypothesis because the term, "capture" has been used to describe the phenomenon (Erkelens & van Ee, 1997a, 1997b; Shimono et al., 2005; Shimono & Wade, 2002). However, in agreement with a suggestion from one of the referees, we have changed the term to "default surface hypothesis" because the term "capture" assumes an active process, and in the case where "there is no disparity information for the depth of the monocular bar" the term "default" is more appropriate. The change is consistent with a discussion in our previous study that "the visual system does not have to develop a specific *(an active)* system or process to deal with a monocular stimulus that is surrounded by a binocular stimulus (Shimono et al., 2005, p. 2639; *italic ours*)".

2. Methods

2.1. Stimuli and apparatus

Stimuli were generated using a VSG 2/3 (Cambridge Research System) controlled by a computer (Gateway, 2000). The stimuli consisted of stereograms with an upper and a lower rectangular area, each with a monocular bar that was presented only to the left eye, as depicted schematically in Fig. 1a. The stereograms were presented on a 17" CRT screen (Mitsubishi RD17GII) with its center at eye level, at a distance of 90 cm from the observer's corneal plane. The stimuli were red in color to avoid activation of the long-persistent green phosphor, which can create undesired cross-talk between left-eye and right-eye views. They were viewed through LCD shutter glasses (Stereographics, Crystal Eyes) and remained on the screen until observers finished responding with their estimates.

The upper and lower rectangular areas (3.4×3.2 deg arc) in each half-field of the stereogram were vertically separated from each other by 4.8 deg arc from center to center. Between the upper and lower rectangular areas, a small elliptical stimulus (6.7×12.9 min arc) was provided for viewers to fixate. The rectangular areas were filled with a random-dot pattern in Experiment 1, and they were defined only by an outline at the perimeter of the rectangular area in Experiment 2. For the random-dot stereogram, each rectangle in each half-field consisted of 120×120 picture elements, with each pixel subtending 1.7×1.6 min arc. The disparity of the random-dot rectangle was selected from seven levels—zero, 6.7, 13.4, 26.7 min arc (crossed and uncrossed) in Experiment 1. For the stereogram used in Experiment 2, the width of the lines forming each rectangle was 3.4 min arc, and the disparity was selected from the following seven levels: zero, 6.7, 13.4, 19.1 min arc (crossed and uncrossed). The range of disparities for the stereogram with the outline rectangles was smaller than that for the random-dot rectangles, because observers reported difficulties in getting stable fusion when the disparity was 26.7 min arc and beyond (crossed and uncrossed). One of the two rectangular areas in the stereogram had zero disparity and is referred to as the *zero disparity random-dot patch* in Experiment 1 and *zero disparity outline patch* in Experiment 2. The other rectangular area had either crossed or uncrossed disparity and was designated the *disparate random-dot patch* in Experiment 1 and *disparate outline patch* in Experiment 2. With respect to the monocular stimuli, one bar (3.4×96.9 min arc) was presented in each of the rectangular areas within one half-field of the stereogram; the bars were objectively aligned vertically, and their horizontal position was at the center of the zero disparity stimulus.

The stereograms were viewed in a room illuminated by fluorescent lights. We assumed that under such a condition there would be ample egocentric distance information and, thus, the distance to the zero disparity stimulus depicted on the surface of the computer monitor would be "registered" correctly and the zero disparity stimulus would be perceived stationary with or without head movements (see Gogel, 1990; Gogel & Tietz, 1974; Howard & Rogers, 2002; Shimono et al., 2002) at the intersection between the two visual axes. The experiment was conducted one person at a time, with the observer's head positioned on a chin-rest that could move freely in a horizontal direction along a track parallel to the surface of the monitor's screen.

2.2. Procedure

During each trial, observers performed a "depth" task and then a "motion" task. In the depth task, observers were asked to estimate the magnitude of perceived depth between either (a) the two binocular rectangular areas or (b) the two monocular bars, while maintaining a steady head position. This was done by asking observers to fixate the elliptic stimulus between the two binocular rectangular areas and to report which of the upper and lower binocular areas appeared to be closer, and then to reproduce the perceived depth between them by adjusting a caliper inscribed with markings in gradations of 0.5 mm (Shimono et al., 2002). The same steps were repeated with respect to the perceived depth between the two monocular bars.

In the motion task, observers reported on the direction and extent of perceived motion of each binocular rectangular area individually and those of each monocular bar, while moving the head and maintaining gaze on the fixation point. The observers were asked to report whether none, one, or both of the upper and lower stimuli (binocular or monocular) appeared to move and whether motion was in the same or in the opposite direction of the head movement. Second, observers were asked to reproduce the perceived extent of motion of the rectangular area(s) and bar(s) using the same adjustable caliper as used in the depth task.

For each experiment, there were two practice trials using randomly selected stimulus conditions. For the experimental trials, stimulus disparities were selected from the seven different binocular disparities. The upper rectangle had zero disparity for half the trials and the lower rectangle had zero disparity in the other half. Thus, each observer carried out a total of 14 trials, during which s/he performed both the depth and motion tasks.

2.3. Observers

Sixteen observers participated in Experiment 1. There were two head movement conditions, 15 and 30 cm, with eight observers assigned to each group. Eight observers participated in Experiment 2 in which the amplitude of head movement was kept constant at 30 cm. In both experiments the stereogram was presented for as long as the observer required, and the order of presentation of the stimuli for the different experimental conditions was randomized. The observers were allowed to rest at any time during the sessions. All observers reported having normal or corrected-to-normal vision.

3. Results

3.1. Experiment 1: Role of binocular disparity and head movements

First, we coded the reproduced depth between the disparate random-dot patch and the zero disparity random-dot patch as well as between the monocular bars. The procedure used to code the data was similar to that used by Shimono and Wade (2002). A positive sign was assigned to the depth magnitude if the disparate patch appeared in front of the zero disparity patch; a negative sign was assigned if it appeared behind the zero disparity patch. Similarly, a positive sign was assigned to the depth magnitude of the bars if the monocular bar in the disparate patch appeared in front of the monocular bar in the zero disparity patch, and was assigned a negative sign if it appeared behind the monocular bar in the zero disparity parch.

Fig. 2 shows the mean perceived depth based on the data of 16 observers as a function of binocular disparity. Because the depth task was conducted with the observers maintaining a steady head position and there was no particular difference between the depth data for the two head movement conditions, we combined the data from the different disparity conditions. As shown in Fig. 2, the mean perceived depth difference between the two monocular bars and the two random-dot patches both covaried with the disparity of the patch. Note that the perceived depth between the monocular bars was smaller than that between the random-dot patches for all non-zero disparity conditions. While the covariation between the perceived depth of the monocular bar and the disparity has already been reported in Shimono and Wade (2002), the difference in the perceived depth between the monocular bar and the

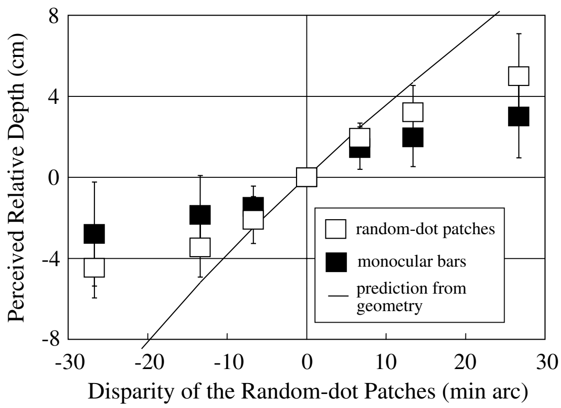

Fig. 2. Mean perceived relative depth of the random-dot patches and monocular bars as a function of the disparity of the random-dot patch, in Experiment 1. Open and solid squares indicate the mean for the random-dot patches and that for the monocular bars, respectively. The vertical lines attached to the data points indicate the standard deviations. The solid line indicates the perceived relative depth predicted from the default surface hypothesis and geometry of the stimulus configuration. See Shimono et al. (2002) for equations to compute the geometrical prediction.

random-dot patch has not been reported previously. We discuss this difference later in this section.

Second, we coded the reproduced extent of motion separately for the disparate random-dot patch and the zero disparity random-dot patch as well as for each of the monocular bars using the same procedure as described in Shimono et al. (2002). A positive sign was assigned to the extent of motion when it was reported to be in the same direction as the head movement; a negative sign was assigned when it was reported to be in the opposite direction. A value of zero was assigned when there was no perceived motion.

Fig. 3 shows the mean coded extent of motion as a function of binocular disparity for the 15-cm head movement condition (a) and for the 30-cm head movement condition (b). In Fig. 3, the mean motion of the disparate random-dot patch, that of the monocular bar embedded in it, and that of the zero disparity random-dot patch are depicted. For both head movement conditions, the perceived motion of both the disparate random-dot patch and the monocular bar embedded in it, covaried with the disparity of the random-dot patch. As might be expected, the reported extent of perceived motion in the 30-cm head movement was larger than that in the 15-cm head movement for the larger disparity conditions. The results for the disparate patch are similar to those reported in Shimono et al. (2002), and those for the monocular bar are consistent with the idea that the monocular stimulus is treated as if it were part of its surrounding binocular area. However, the extent of the perceived motion for the monocular bar in the disparate patch was smaller than that for the patch, particularly in the 30-cm head movement condition, suggesting an effect of stimulus ocularity (binocular disparate patch versus monocular bar) on the extent of the perceived motion. Fig. 3 also shows that the mean extent of motion of the zero disparity patch was small and relatively constant in both the 15 and 30-cm head movement conditions. Furthermore, the mean extent of motion of the monocular bar in the zero disparity patch was also small and constant, although it is not depicted in Fig. 3.

To further examine the effects of both stimulus ocularity and head movement on the extent of perceived motion, we calculated the slope of the regression lines for each observer's data. It was found that the mean slopes of the monocular bars embedded in the disparate random-dot patch (0.03 and 0.05 for the 15 and 30-cm head movements, respectively) were smaller than those of the disparate random-dot patch (0.05 and 0.09 for the 15 and 30-cm head movements, respectively). A two-way ANOVA (2 head movements × 2 stimulus ocularities) on the slope indicated that the main effects of head movements and stimulus ocularity and their interaction were statistically significant,

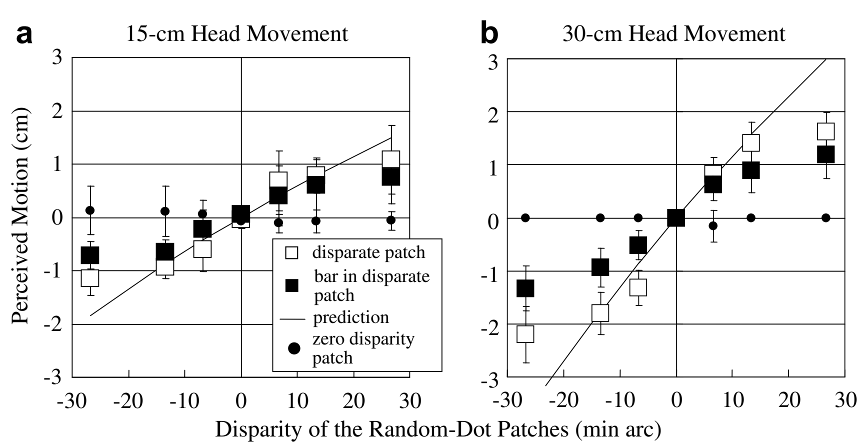

Fig. 3. Mean perceived motion of the disparate random-dot patch, the monocular bar presented in it and the zero disparity random-dot patch, as a function of disparity of the random-dot patches for the 15-cm head movement condition (a) and that for the 30-cm head movement condition (b). Open and solid squares indicate the mean for the disparate random-dot patch and the monocular bar in it, respectively. Solid circle indicates the mean for the zero disparity random-dot patch. The vertical lines attached to the data points indicate standard deviations. The solid lines indicate the extent of perceived motion predicted from the default surface hypothesis and geometry. See Shimono et al. (2002) for equations to compute the geometrical prediction.

$F(1,14) = 14.15$, $p < 0.01$, $F(1,14) = 53.28$, $p < 0.001$, and $F(1,14) = 5.45$, $p < 0.05$, respectively. The simple main effect of head movements was statistically significant for the binocular area, $F(1,28) = 19.22$, $p < 0.01$, and for the monocular bar, $F(1,28) = 6.23$, $p < 0.05$. The simple main effect of stimulus ocularity was statistically significant for the 15 and 30-cm head movement conditions, $F(1,14) = 12.33$, $p < 0.01$, and $F(1,14) = 53.27$, $p < 0.001$, respectively. These results indicate that both the stimulus ocularity and the amplitude of the head movement have an effect on the extent of perceived motion of the disparate random-dot patch and of the monocular bar in it.

The effect of stimulus ocularity on the extent of perceived motion can be explained using the default surface hypothesis, together with the fact that (a) the extent of perceived motion of the zero disparity random-dot patch is nearly zero (see Fig. 3), (b) the extent of perceived motion of the monocular bar in the zero disparity patch is zero and (c) the magnitude of perceived depth between the monocular bars is less than that between the binocular areas (see Fig. 2). According to a geometrical analysis of the stimulus configuration, if the monocular bar in the zero disparity patch is localized in the same plane as the patch and serves as the pivot point, the extent of perceived motion of the monocular bar would be zero (as that of the zero disparity patch). As well, if the monocular bar in the disparate random-dot patch is localized in a plane slightly farther (closer) than the plane of the disparate patch from observers in the crossed (uncrossed) disparity condition and if the monocular stimulus in it appears to move in a front-parallel plane, the extent of perceived motion of the monocular bar in the disparate patch would be smaller than that of the disparate patch (Fig. 1b). This geometrical analysis further predicts that when the monocular bar in the zero disparity patch is localized in the same plane as the patch, the extent of the perceived motion of the monocular bar in the disparate patch would covary with the magnitude of the perceived relative depth of the monocular bars (Fig. 1b). The covariation can be seen in Fig. 4 in which the mean extent of perceived motion is plotted as a function of the perceived relative depth for the two amplitudes of head movement.

Fig. 4 also shows the effect of head movement on the extent of perceived motion: the extent of perceived motion increased more rapidly with increasing disparity in the 30-cm head movement condition than in the 15-cm head movement condition. This result suggests that the visual system utilizes information about the amplitude of head movement as well as the perceived depth of the monocular bars in arriving at the perception of motion of the monocular bars. However, the mean slope (0.46) of the regression line for the motion data shown in Fig. 4, computed for each observer for the 30-cm head movement is not as large as that predicted from geometry. Geometry predicts that as long as the visual system utilizes the information of the physical extent of the head movement "veridically", the mean slope for the 30-cm head movement should be two

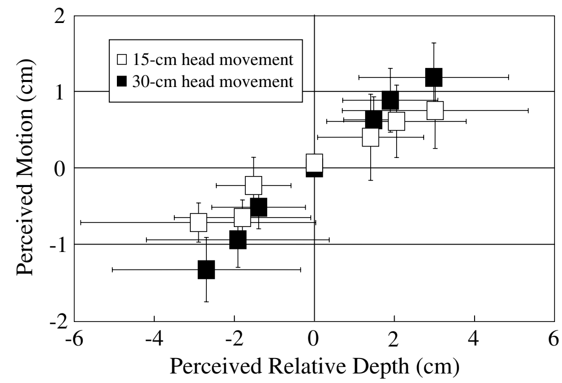

Fig. 4. Mean perceived motion of the monocular bar in the disparate random-dot patch as a function of perceived depth between the monocular bars. Open and solid squares indicate the means obtained with 15-cm and 30-cm head movements, respectively. The vertical and horizontal lines attached to the data points indicate standard deviations of the perceived motion and those of the perceived depth, respectively.

times larger than that for the 15-cm head movement (0.36). The fact that the difference in the mean slope between the two head movement conditions is not as large as predicted can be explained by assuming that the visual system uses the perceived extent of the head movement, rather than its physical extent (e.g., Gogel, 1990). Empirical evidence, consistent with this assumption has been reported by Shimono et al. (2002), who measured the perceived amplitude of head movement and found that the ratio of the 20-cm head movement to that of the 10-cm head movement was 1.5. This value is close to the ratio found in the present study of the mean slope of the 30-cm head movement condition to that of the 15-cm head movement condition of 1.3.

The default surface hypothesis together with the geometry also predicts that the perceived motion of the monocular bar in the disparate random-dot patch would covary with its perceived depth as the perceived motion of the disparate random-dot patch covaries with its perceived depth. To examine this prediction, we compared the slope of the regression line for the motion data of the monocular bar depicted in Fig. 4 and those of the disparate random-dot patch for each observer. A t test showed that the mean slope (0.36) for the monocular bar was not significantly different from that (0.33) for the disparate patch for the 15-cm head movement condition, $t(7) = 0.78$, $p > 0.05$, and the mean slope (0.46) for the monocular bar was also not significantly different from that (0.51) for the disparate patch for the 30-cm head movement conditions, $t(7) = 1.42$, $p > 0.05$. Furthermore, for the 15-cm head movement condition, the mean slope for the monocular bar and that for the disparate patch were significantly different from zero, $t(7) = 2.89$, $p < 0.05$ and $t(7) = 4.41$, $p < 0.01$, respectively. The mean slope for the monocular bar and that for the disparate patch were also significantly different from zero for the 30-cm head movement condition, $t(7) = 6.60$, $p < 0.001$ and $t(7) = 10.15$, $p < 0.001$, respectively. These results are consistent with the hypothesis that predicts that the extent of perceived motion would covary with perceived depth and that the covariation for the monocular bar and the disparate patch would be similar.

If the perceived motion of the monocular bar in the disparate random-dot patch is due to its "defaulting" to the surrounding binocular surface area as previously discussed, it would be interesting to see how perceived depth and motion are affected by changing the features of the binocular area that the monocular stimulus is embedded in. To examine the effect of changing the features, in Experiment 2 we removed the random dots that defined the disparate patch in Experiment 1 and instead delineated the disparate patch with an outline such that the monocular bar was surrounded basically by empty space bounded by an outline as shown in Fig. 1a.

3.2. Experiment 2: Role of binocular areas

The depth and motion data were coded as in Experiment 1. Fig. 5 shows the mean values for the depth data (a) and those for the motion data (b) as a function of binocular disparity. Data for the monocular bar in the disparate outline patch and those for the disparate outline patch itself are shown separately. As shown in Fig. 5a, the mean perceived depths of both the disparate outline patch and the monocular bar in the disparate outline patch covaried with its disparity and the perceived depths of the monocular bars were much smaller than those of the disparate outline patches. As shown in Fig. 5b, the perceived extent of motion of the outline patch increased more rapidly than that of the monocular bar in it, as a function of disparity. A *t* test indicated that the mean slopes of the regression line for each observer's depth and motion data of the monocular bar depicted in Fig. 5 were significantly different from zero, $t(7) = 3.62$, $p < 0.01$, and $t(7) = 4.31$, $p < 0.01$, respectively. Whether this result is consistent with the default surface hypothesis will be discussed later in this section. The coded motion of the monocular bar embedded in the zero disparity outline patch and that of the zero disparity outline patch itself were both zero and are not depicted in Fig. 5b.

Similar to the discussion in Section 3.1, the result of Experiment 2—that the extent of perceived motion of the monocular bar in the disparate outline patch is less than that of the patch itself—can also be explained by the default surface hypothesis and geometry. As can be seen in the crossed disparity condition of Fig. 1b, for example, if the monocular bar in the zero disparity outline patch is localized in the plane of the zero disparity patch (Howard & Rogers, 2002; Shimono et al., 1999) and if the monocular bar in the disparate outline patch is localized in a plane that is farther from observers than the plane of the disparate patch, then the depth between the monocular bars would be less than that between the disparate and zero disparity patches. Further, the extent of perceived motion of the monocular bar in the disparate patch would be less than that of the disparate patch itself and the extent of perceived motion of the monocular bar in the zero disparity patch would be zero (as that of the zero disparity patch). The results of the present experiment are consistent with these geometrical analyses, because (a) the perceived depth of the monocular stimulus was found to be smaller than that of the binocular stimulus, (b) the monocular bar in the zero disparity patch appeared stationary, and (c) the extent of perceived motion of the monocular bar is less than that of the disparate patch (Fig. 5b).

The default surface hypothesis together with geometry predicts that the perceived motion of the monocular bar would covary with its perceived depth. This covariation can be seen in Fig. 6; the disparate outline patch and the monocular bar covaried in a similar manner. The slopes of the regression line calculated for the perceived motion as a function of the perceived depth were significantly

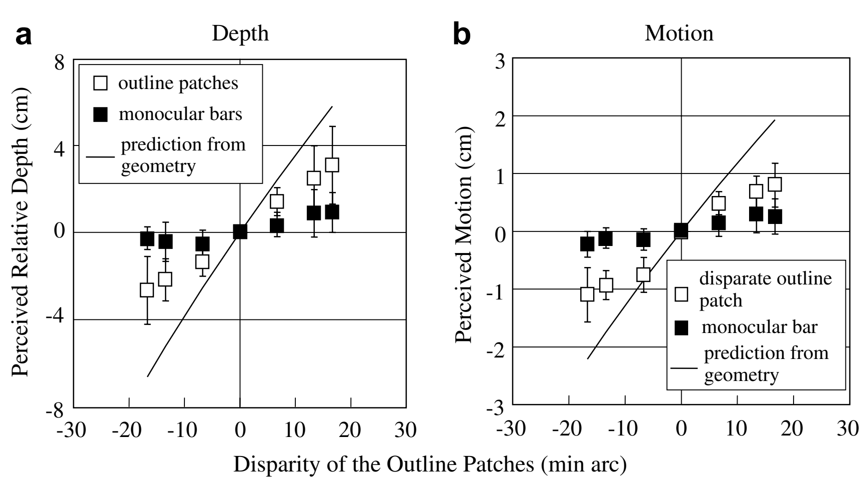

Fig. 5. Mean perceived relative depth of the outline patches and monocular bars (a) and mean perceived motion of the disparate outline patch and the monocular bar presented in it (b), as a function of disparity of the outline patch. In (a), the open and solid squares indicate the mean for the outline patches and that for the monocular bars, respectively. In (b), open and solid squares indicate the means for the disparate outline patch and the monocular bar, respectively. The vertical lines attached to the data points indicate the standard deviations. The solid lines in (a) and (b) indicate the perceived depth and motion, respectively, predicted from the default surface hypothesis and geometry. See Shimono et al. (2002) for equations to compute the geometrical prediction.

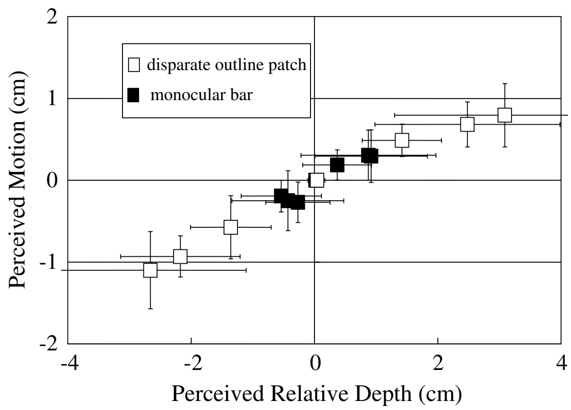

Fig. 6. Mean perceived motion as a function of perceived depth in Experiment 2. Open and solid squares indicate the means of the disparate outline patch and the monocular bar, respectively. The vertical and horizontal lines attached to the data points indicate standard deviations of the perceived motion and those of the perceived depth, respectively.

different from zero, $t(6) = 4.23$, $p < 0.01$[3] and $t(7) = 6.57$, $p < 0.001$, for the monocular bar and disparate patch, respectively. In addition, the mean slope of the monocular bar (0.38) was not significantly different from that of the disparate patch (0.37), $t(6) = 0.14$, $p > 0.05$. These results are consistent with the prediction and an analysis of the geometrical configuration of the stimuli (see Fig. 1b).

In addition, the hypothesis together with an analysis of the geometry lead to the prediction that the extent of perceived motion of the monocular bar embedded in the disparate patch would covary with that of the disparate patch just as the magnitude of perceived depth of the monocular bar covaries with that of the disparate patch. Because the perceived extent of motion is determined by the perceived magnitude of depth for both the monocular bar and the disparate patch, the ratio of the extent of motion of the monocular bar to that of the disparate patch would be equal to the ratio of the magnitude of depth of the monocular bar to that of the disparate patch for the same stereo-pair. To examine this prediction, we plotted the perceived motion and the depth of the monocular bar, separately, against those of the disparate patch. Fig. 7 shows the mean depth and motion data for the 15-cm head movement of Experiment 1 in (a), those for the 30-cm head movement of Experiment 1 in (b), and those from Experiment 2 in (c); the perceived motion and the perceived depth covary in a similar manner except in the largest uncrossed disparity condition of Experiment 2 (see Fig. 7c). The observed covariation is supported by the results of t tests performed on the mean slopes of the regression line computed for each observer's motion and depth data depicted in Fig. 7a–c [individual data are not depicted in Fig. 7]. The mean slopes for the motion data, 0.65, 0.61, and 0.26, were not significantly different from those for the depth data, 0.64, 0.58, and 0.29, with $t(7) = 0.91$, $p > 0.05$, $t(7) = 0.78$, $p > 0.05$, and $t(7) = 0.91$, $p > 0.05$, respectively, for the data in (a–c) of Fig. 7. Furthermore, the mean slopes for the motion and depth data in Experiment 2 were significantly different from zero, $t(7) = 4.85$, $p < 0.01$ and $t(7) = 4.22$, $p < 0.01$, respectively.

Fig. 7 also shows that the mean perceived depth and motion increased more rapidly when the monocular bar was presented in the random-dot patch (a and b) than when it was presented in the outline patch (c). This result indicates the effect of stimulus property (random-dot patch or outline patch) on the covariation of depth and motion, suggesting that the surrounding binocular area is an important factor in the perception of apparent depth and motion of the monocular bar (Erkelens & van Ee, 1997a, 1997b; Shimono et al., 2005; Shimono & Wade, 2002). The result can be explained by the default surface hypothesis in conjunction with the geometry and the assumption that the monocular bar embedded in the outline patch produces less depth than that embedded in the random-dot patch.

Furthermore, Fig. 7 shows that the mean perceived depth and motion for the 15-cm head movement condition in Experiment 1 (a) and those for the 30-cm head movement condition in Experiment 1 (b) increase linearly in a similar manner. This result is also consistent with a geometrical analysis; the ratio of the extent of the motion of the monocular bar to that of the disparate patch is the same as the ratio of the magnitude of the depth of the monocular bar to that of the disparate patch, irrespective of the amplitude of head movement. As suggested by the linearity of the covariation of the depth and motion, the ratio is relatively constant, at least within the disparity range used in Experiment 1, and thus, the ratio may correspond with the mean slope of the regression line computed for the data depicted in Fig. 7a and b. A two-way ANOVA [2 head movements $\times$ 2 sets of data (depth and motion)] on the slope indicated that the main effects of head movements and sets of data and their interaction were not statistically significant, $F(1,14) = 0.36$, $p > 0.05$, $F(1,14) = 0.08$, $p > 0.05$, and $F(1,14) = 0.01$, $p > 0.05$, respectively. These results indicate that the amplitude of the head movement has little effect on the mean slope, or the ratio, in agreement with the geometrical analysis.

It is interesting that the monocular bar embedded in the disparate patch appeared to move and that the extent of its movement covaried with its depth even when the disparate patch consisted of only an outline and not random-dot patterns. Apparently, the visual system still considered the monocular stimulus as linked to the disparate outline patch in which it was "embedded". However, the extent of motion of the outline was less than that observed when the disparate patch consisted of a random-dot pattern (Experiment 1). The fact that the lines constituting the disparate patch in this experiment was farther way (in the half-image) from the monocular bar, than the corresponding (horizontal) distance between the monocular bar and

[3] Of the eight observers who participated in this study, one observer reported no depth with respect to the monocular bars and, thus, we obtained only seven slopes for the t test.

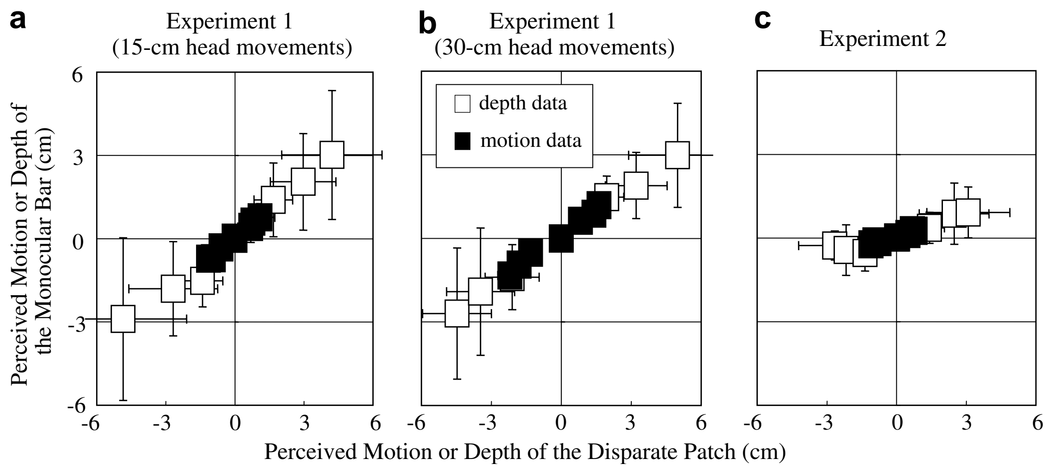

Fig. 7. Mean perceived depth and mean perceived motion of the monocular bar as a function of the corresponding data of the disparate patch (random-dot patch in Experiment 1 or outline patch in Experiment 2). Open and solid bars indicate the mean depth and the mean motion, respectively. The vertical lines attached to the data points indicate standard deviations.

the random-dot surface of Experiment 1, might have contributed to the weakened response. If the horizontal distance (1.7 deg arc) of the lines of the disparate patch from the monocular bar used in the present study were increased, the extent of perceived motion of the monocular bar might have been reduced more. This expectation is consistent with the findings of previous studies (Erkelens & van Ee, 1997b; Shimono et al., 1998), which show that the horizontal distance between monocular and binocular stimuli is important for a monocular stimulus to be treated as a binocular stimulus, and that as the distance is increased the monocular stimulus is less likely to be treated so.

4. General discussion

The results of the present study show that a stationary monocular stimulus appears to move concomitantly with head movements when two objectively aligned monocular bars are embedded separately in two binocular areas that are in different depth planes and are viewed while the head moves laterally. The monocular bar in the area with non-zero disparity appears to move while the other bar, in the area with zero disparity, appears stationary. Experiments 1 and 2 indicate that both the extent of the perceived motion of the monocular bar in the disparate area and the magnitude of perceived depth between the two bars covaries with the disparity of the two binocular areas. The present results are consistent with the idea provided previously with respect to depth perception of monocular stimuli (Domini & Braunstein, 2001; Rogers & Bradshaw, 1999; Shimono et al., 2005; Shimono & Wade, 2002) and their direction perception (Domini & Braunstein, 2001; Erkelens & van Ee, 1997a, 1997b; Ono & Mapp, 1995; Rogers & Bradshaw, 1999; Shimono et al., 1998, 2005; Shimono & Wade, 2002)—that the visual system treats a monocular stimulus as if it were part of its binocular surround and that it takes on the specific characteristics of the binocular stimulus. Furthermore, the results extend this idea with respect to motion perception.

The apparent depth of the monocular stimulus in this study might reflect a rule for the localization of a monocular stimulus. Howard and Rogers (2002) proposed a "similar-surface default rule" to explain the perceived depth with a stereogram consisting of a monocular stimulus and a binocular stimulus. They argued that the monocular stimulus is defaulted to the depth of a surface that is occluded or camouflaged by the binocular stimulus. Furthermore, Howard and Rogers (2002) made reference to another rule that they call the "horopter default rule" to suggest that "monocular images are defaulted to the horopter" (or the fixation plane). They contend that "this rule does not apply when the monocular images are seen as belonging to a texture surface" (Howard & Rogers, 2002, p. 129). The present as well as previous studies (Domini & Braunstein, 2001; Rogers & Bradshaw, 1999; Shimono et al., 2005; Shimono & Wade, 2002) suggest another localization rule. For a monocular stimulus that is embedded inside a binocular surface the monocular stimulus "defaults" to the surrounding binocular surface area. This "binocular-surface default rule" can account for the current results in which the magnitude of apparent depth of the monocular bars in the binocular stimuli covaried with the disparity of the binocular stimuli in Experiments 1 and 2. The fact that the magnitude of apparent depth of the monocular bars in Experiment 2 is less than that in Experiment 1 can also be understood as a compromise between the "binocular-surface default rule" and the "horopter default rule". The binocular areas surrounding the monocular stimuli were textureless in Experiment 2 but consisted of a textured surface of random-dots in Experiment 1. Thus, it is easy to understand how the "horopter default rule" might have a stronger hold in Experiment 2 than in Experiment 1 because without the random-dots to create a textured surface in Experiment 2 the monocular bars were probably not as strongly associated with their binocular surrounding areas as they were in Experiment 1.

The apparent movement of the monocular stimulus in this study is not an isolated perceptual phenomenon with respect to explanations based on an analysis of the geometry of the stimulus configuration. Gogel's (1990) phenomenal geometry assumes that the perceived motion is determined by visual direction, the perceived depth, and the observers' perceived head position. The apparent movement of a stereoscopically presented stimulus observed during a head movement (Julesz, 1971; Rock, 1983; Shimono et al., 2002), referred to as "stereo-illusory motion" by Shimono et al. (2002), is an instance of such perceptual phenomena. Stereo-illusory motion is caused by the apparent movement of fused images in depth pivoting at the stimulus plane (Fig. 1b). Rogers and Collett (1989) also reported a phenomenon, in which a corrugated surface specified by motion parallax with zero disparity appears to rotate concomitantly with a head movement and the direction of the rotation depends on the perceived depth of the surface. Moreover, the cyclopean illusion is another instance. The cyclopean illusion refers to an apparent lateral motion of a stationary stimulus in the visual axis of one eye and occurs when the other eye moves to a different vergence position (Enright, 1988; Helmholtz, 1910/2000; Hering, 1879/1942; Ono, Mapp, & Mizushina, 2005; Wells, 1972). The explanation for the apparent movement is based on the idea that visual direction is judged from the cyclopean eye and the extent of the movement depends on the change in the visual direction of the stimulus from the cyclopean eye and on its visual distance (Khokhotva, Ono, & Mapp, 2005; Mapp, Ono, & Howard, 2002; Ono, Mapp, & Howard, 2002). At the very least, the phenomenon involving the apparent movement of monocular stimuli described in the present study adds to the list of many that are described by phenomenal geometry (See Gogel, 1990).

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