PERGAMON

Vision Research 42 (2002) 1127–1135

Vision Research

www.elsevier.com/locate/visres

Monocular alignment in different depth planes

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Received 31 March 2001; received in revised form 11 October 2001

Abstract

We examined (a) whether vertical lines at different physical horizontal positions in the same eye can appear to be aligned, and (b), if so, whether the difference between the horizontal positions of the aligned vertical lines can vary with the perceived depth between them. In two experiments, each of two vertical monocular lines was presented (in its respective rectangular area) in one field of a random-dot stereopair with binocular disparity. In Experiment 1, 15 observers were asked to align a line in an upper area with a line in a lower area. The results indicated that when the lines appeared aligned, their horizontal physical positions could differ and the direction of the difference coincided with the type of disparity of the rectangular areas; this is not consistent with the law of the visual direction of monocular stimuli. In Experiment 2, 11 observers were asked to report relative depth between the two lines and to align them. The results indicated that the difference of the horizontal position did not covary with their perceived relative depth, suggesting that the visual direction and perceived depth of the monocular line are mediated via different mechanisms. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Visual line; Relative visual direction; Stereo-depth; Monocular; History

1. Introduction

The history of research on binocular vision reflects a struggle between two approaches—one based on phenomenology and the other on geometry. The former is concerned with visual directions as they are observed and the latter with optical projections. The origins of both approaches can be traced to antiquity. The observational tradition was espoused by Aristotle, but its ablest early protagonist in binocular vision was Ptolemy (see Howard & Wade, 1996); the optical tradition was most clearly enunciated by Euclid, who reduced space perception to the geometry of projections from the eye (see Wade, 1998a). Euclid (≈323–283 B.C.) examined binocular vision in the context of optical projections to spheres differing in diameter with respect to the interocular separation. While Euclid's analysis of binocular vision was geometrical, it was also cursory; he examined three dimensions of spheres that could be observed by two eyes, and simply related them to the amount of the spheres in the optical projections. Ptolemy (≈100–170) carried out controlled observations of the perceived locations of vertical cylinders; from these he specified the conditions for singleness of vision, the distinction between crossed and uncrossed disparities, and the direction in which objects are seen with two eyes. Ptolemy's analysis was extended by Ibn al-Haytham or Alhazen (see Sabra, 1989; Smith, 1996, 1998).

Ptolemy appreciated that monocular and binocular visual directions were not necessarily the same. In order to confirm this empirically, he constructed a board on which he could place vertical rods at different distances in the midline between the eyes. He provided a description of one of the most commonly used examples of crossed and uncrossed visual directions: with fixation on a distant rod, a nearer one appeared double, and to the left with the right eye and to the right with the left eye; the reverse occurred with fixation on the nearer rod. Ptolemy stated that singleness of vision with two eyes occurred when the two visual directions corresponded, thus introducing the concept of correspondence into binocular vision. These observations were interpreted in terms of the visual axes and the common axis. Similar experiments were conducted by Wells (1792), who formulated principles of visual direction in binocular

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PII: S0042-6989(02)00051-2

vision, and these were rediscovered in the nineteenth century by Hering (see Ono, 1981).

The optical tradition was based upon projections from the eye until the dioptrical properties of the eye were described by Kepler in the seventeenth century (see Wade, 1998b). Thereafter, optical projections were to, rather than from, the eye and representing the characteristics of retinal images became common place. However, analyses of binocular vision remained confined to singleness with corresponding optical projections, and double vision with noncorresponding stimulation. This position was epitomized by the binocular circles of Vieth (1818) and Müller (1826). The situation was changed by Wheatstone (1838), who essentially conflated the observational and optical perspectives. By means of the stereoscope Wheatstone was able to present defined horizontal retinal disparities to yield predictable relative depth perception. That is, differing visual directions were associated with depth rather than diplopia, providing that the disparities were not too large. Wheatstone was able to demonstrate that singleness of binocular vision was not restricted to the Vieth–Müller circle.

The union between observation and optics, initiated by Wheatstone, has become enshrined in the language we use to describe the factors involved in binocular vision. For example, objects in the same optical line for one eye, so that a nearer one would occlude a farther one, are referred to as being in the same visual line (see Howard & Rogers, 1995). That is, an optical construct is described in terms of an aspect of observation. Visual alignment is one of the few observational tasks that is equated with optical projections. Others, like visual direction, reflect a clear distinction between the two domains. To all intents and purposes the term visual line is unnecessary because it is redundant; it could be replaced by the term optical line. However, since visual line is a part of the vocabulary of spatial vision it will be retained here.

One reason for the general acceptance of the conflation of optics and observation is that attention has been directed to visual depth based on disparity rather than upon visual direction. The distinction between direction and distance (or depth) was clearly stated by Wells (1792). Indeed, the inadequacy of optical projection to account for visual direction is at the heart of his analysis of binocular vision, as it was for Hering (1879). Both Wells and Hering assumed that the visual direction of a binocularly fused stimulus is midway between that of each monocular stimulus. This assumption is based on the observations that had been called "allelotropia" (von Tschermak-Seysenegg, 1955 cited in Kaufman, 1974) or "displacement" (Werner, 1937) historically and recently has been reconfirmed under various stimulus conditions (e.g., Erkelens & Collewijn, 1985; Mansfield & Legge, 1996; Nakamizo, Shimono, Kondo, & Ono, 1995; Ono, Angus, & Gregor, 1977; Ono, Shimono, Saida, & Ujike, 2000; Sheedy & Fry, 1979). For the monocular stimulus, its visual direction is assumed to be the same when it is on the same visual line and to be different when it is on the different visual lines. This assumption is based on the observation in visual alignment for a monocular stimulus and the idea that the retinal local sign of a monocular stimulus is fixed when it is transformed into visual direction.

Recently, however, some studies reported the phenomena that contradict this law of visual direction for the monocular stimulus (e.g., van Ee, Banks, & Backus, 1999; Erkelens & van Ee, 1997a, 1997b; Erkelens & van de Grind, 1994; Ono, Ohtsuka, & Lillakas, 1998; Ono, Wade, & Lillakas, 2002; Popple & Findlay, 1998; Shimono, Ono, Saida, & Mapp, 1998). For example, Shimono et al. (1998) found that physically misaligned Nonius vertical lines, which were dichoptically presented, nonfusable and monocular stimuli, can appear in the same visual direction when the lines were presented in a random-dot stereogram (see Fig. A1 in Ono & Mapp, 1995, for the demonstration of the phenomenon). This finding shows that visual alignment does not necessarily reflect the optical projection. Furthermore, Erkelens and van Ee (1997a,b) found that, when a monocular vertical line was presented in a random-dot stereogram in which half-images oscillated in counterphase, the monocular line as well as the stereogram appeared stationary. Their finding shows that the visual direction of the monocular line can be the same even when it is on a different visual line.

Shimono et al. explained their findings by assuming that "the visual system treats each of the two monocular Nonius lines as a part of its respective binocular stimulus" (Shimono et al., 1998, p. 594). Erkelens and van Ee also explained their results in a similar way by stating that "a plausible explanation for seeing the vertical line as stationary is that monocular objects are assigned binocular visual directions that lie in between those of neighbouring binocular objects" (Erkelens & van Ee, 1997a, p. 1194).

If monocular lines can be treated as a part of their surrounding binocular areas, as suggested, then we can expect that the distance perception of the lines may correspond with that of the binocular areas. For the distance perception of the binocular areas, it is well known that perceived relative distance (depth) covaries with disparity between the binocular areas (see Howard & Rogers, 1995). Our primary concern was to examine whether the monocular lines presented in the binocular areas can change their perceived depth as well as their visual directions.

Two experiments are reported which presented two monocular lines to the same eye; each one was embedded on a rectangular area in each half-field of a randomdot stereogram (see Fig. 1). In Experiment 1, we examined whether the monocular lines presented to the same eye can be seen in the same visual direction when

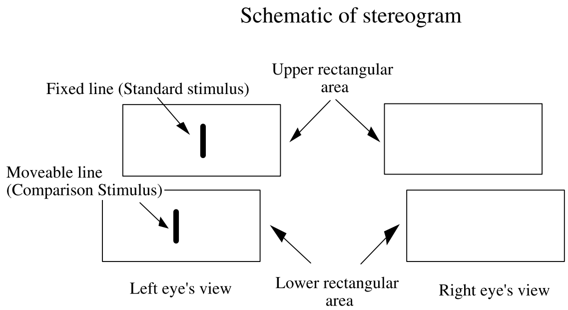

Fig. 1. Schematic of a stereogram. One of two vertical lines was presented in the upper rectangular area and the other was presented in the lower rectangular area. The line presented in the upper area was the standard stimulus and was fixed in the centre of the area. The line presented in the lower area was the comparison stimulus and its horizontal location was moveable. Although the insides of the rectangles are depicted as open for the descriptive purposes, they were filled with random dots to define a stereogram.

they were on different visual lines. We examined this question before examining the distance perception of the monocular stimuli. As discussed above, the monocular lines on the different visual lines can be seen in different visual direction when the monocular lines are dichoptically presented in a random-dot stereogram (Shimono et al., 1998). However, Erkelens and van de Grind (1994) showed that when the vertically separated monocular lines, one of which was presented on the random-dot stereogram, were presented to the same eye and appeared aligned, they had been on the same or nearly the same visual line (see the left upper and middle lower panels in their Fig. 4). In Experiment 2, we examined whether the difference between the horizontal positions of the two monocular lines, which appeared aligned, covaried with perceived relative depth between them.

For the sake of the clarity, we wish to emphasize that we measured the relative visual direction of monocular lines but not their absolute visual directions to determine whether or not monocular lines can be treated as binocular stimuli. To examine the relative direction, we used the visual alignment task and did not control or measure eye positions of observers. Even without monitoring eye positions, we can infer whether the monocular lines are treated binocularly or monocularly (see preamble in Experiment 1 for more detailed discussion). [Note that to examine the absolute visual direction, it is critical to measure or monitor the eye position (see, e.g., van Ee et al., 1999; Mansfield & Legge, 1996; Ono & Mapp, 1995; Shimono et al., 1998).]

2. Experiment 1: monocular lines on different visual lines can appear aligned

In Experiment 1, observers were asked to align a vertical line in a lower binocular area to a fixed line in an upper binocular area, both of which were in the same half-field of a stereogram (see Fig. 1). In each half-field, the lower area was placed on the left or right side of the upper area with the same separation horizontally so that, according to the law of visual direction for the binocular stimulus, they would fuse to be seen in the same visual direction. Thus, if the monocular lines behave like their surrounding binocular areas, they may appear aligned even when their horizontal positions differ as in their surrounding areas. For example, when the stereogram has a crossed disparity as in Fig. 1 and the lower and upper areas fuse, the lower line may be to the left side of the upper line when they appear aligned and furthermore, the difference in the physical horizontal position between the lower and upper lines would equal half of the disparity between the lower and upper areas. On the other hand, if the monocular lines behave as predicted from the law of the visual direction for the monocular stimulus, they would be seen in the same visual direction when they are horizontally on the same visual line or have no difference in their horizontal positions.

For comparison, we also presented the monocular lines on a rectangular stereogram, which had no surrounding binocular random-dot area in its half-fields. We expected that the monocular lines may appear aligned when they are on the same visual line, because there is no explicit binocular areas as a part of which the monocular lines can be interpreted or by which they can be "captured" (Erkelens & van Ee, 1997a,b).

2.1. Method

2.1.1. Apparatus

Stimuli were generated by NEC PC9801 computer and were displayed on NEC colour monitor (PC KD853). One of them is shown schematically in Fig. 1. The centre of the monitor was set at eye level, 100 cm away from the corneal plane. Polarized filters made the left half of the screen visible to the right eye and the right half of the screen visible to the left eye. The convergence distance was about 40 cm and a -1.5 dp lens was placed in front of each eye to match the required accommodation to the convergence distance.

There were two sets of stereograms: random-dot and rectangular. Each of the two sets had upper and lower rectangles (1.0×2.1 deg arc), which were separated 10.6 min arc from each other, in its half-field. The lower rectangular areas had a crossed disparity of 10.4 min-arc, zero, or an uncrossed disparity of 10. 4 min arc, with respect to the upper rectangular areas. Thus, three random-dot stereogram and three rectangular stereograms were presented. For the random-dot stereogram, each of the upper and lower areas consisted of 23×48 picture elements, each subtending 2.6×2.6 min arc, in each half-field. For the rectangular stereogram, the widths of the lines that made a rectangle were 2.6 min-arc and the inside of the rectangle was open. One pair of red lines (5.2×19.8 min of arc) was presented in the right half-field of the stereogram on the screen, that is, to the left eye; one line was a fixed standard stimulus and the other line was a moveable comparison stimulus. The standard stimulus was presented in the centre of the upper area and the comparison was presented 6.5 min-arc to the right or left of the horizontal position of the standard in the lower area. The vertical distance between the two stimuli was 29.0 min arc. The observer controlled the horizontal position of the comparison via two keys on a keyboard.

2.1.2. Procedure

Each observer was asked on each trial (a) to report whether or not the two perceived rectangular planes appeared in the same plane, and if they were not, which rectangular appeared closer and (b) to adjust the lower red line until it appeared to be aligned with the upper reference line.

There were two or three practice trials and 12 main experimental trials. The practice trials were randomly selected from the main experimental trials. The experimental trials were the combination of the two stereograms (random-dot and rectangular) and three binocular disparities (uncrossed, zero and crossed) with the left or right initial position of the comparison stimulus. The stereogram was presented for as long as the observer required and the order of presentation was randomized. The observers were allowed to take a rest at any time in the sessions, if they wished.

2.1.3. Observers

Fourteen students (2 females and 12 males) and one professor (male) participated in the experiment. They ranged in age from 18 to 40 and they reported having normal or corrected-to-normal acuity and binocular stereopsis.

2.2. Results and discussion

First, we examined whether the observers reported the perceived depth of the stereogram correctly. It is a prerequisite for the present experiment that the binocular areas with disparities appeared fused and at different depth planes; we assumed that the perceived depth would provide an index that the visual system treated the rectangular area as "binocular". All the observers reported the depth correctly and thus, we proceeded with further analysis.

Next, the different horizontal position between the adjusted comparison and fixed standard was coded for each trial. A value of zero was assigned when there was no difference in the horizontal position between the two stimuli. When the comparison was on the left side of the standard stimulus, a negative value was given; conversely, a positive sign was given when the comparison was the right side of the standard stimulus. Thus, if the presented red lines are treated as a part of the binocular rectangular area, the difference for the crossed disparity condition and that for the uncrossed disparity condition would have negative and positive values, respectively. For coding, the initial position of the comparison was not treated as the major variable; for each experimental condition, the differences of the horizontal position between the standard and comparison for the left and right initial positions were averaged as a score.

We performed separate one way repeated-measures ANOVAs (3 disparities) on the averaged scores separately for the random-dot and rectangular stereograms. The main effect was statistically significant, $F(2,28) = 21.33$, $p < 0.001$, and $F(2,28) = 10.08$, $p < 0.001$, for the random-dot and rectangular stereograms, respectively. Post hoc analyses (Tukey test) for the random-dot stereograms showed that the mean (-4.31 min arc) for crossed disparity was significantly different from that (2.24 min arc) for uncrossed disparity and that (-0.79 min arc) for the zero disparity; the mean for the uncrossed disparity was also significantly different from that for the zero disparity. Post hoc analyses (Tukey test) for the rectangular stereograms showed that the mean (-2.02 min arc) for crossed disparity was significantly different from that (-0.97 min arc) for the uncrossed disparity and that (-1.14 min arc) for the zero disparity; the mean for the crossed disparity was not significantly different from that for the zero disparity.

The statistical significance can be seen in Fig. 2 in which the averages over 15 observers were depicted separately for the stereograms with three different disparity types. The right panel shows the data for the random-dot stereograms and the left panel shows the data for the rectangular stereograms. For the random-dot stereograms, the horizontal position of the comparison with respect to the standard differed depending on the three disparity conditions. Furthermore, the difference for the crossed disparity condition and that for the uncrossed disparity condition had negative and positive values, respectively, as expected. However, the difference was not as large as that (5.2 min of arc) predicted from the law of the visual direction for the binocularly fused stimulus. This result is consistent with that of Shimono et al. (1998), Experiment 1. We will discuss this aspect of the result in Experiment 2. For the rectangular stereograms, in contrast, the comparison was always on the left side of the standard in the three disparity conditions, although the extent of the displacement for the crossed disparity condition was larger than that for the uncrossed or zero disparity condition.

The results for the random-dot stereogram clearly show that the monocular lines on the different visual lines can be seen in the same visual direction and con-

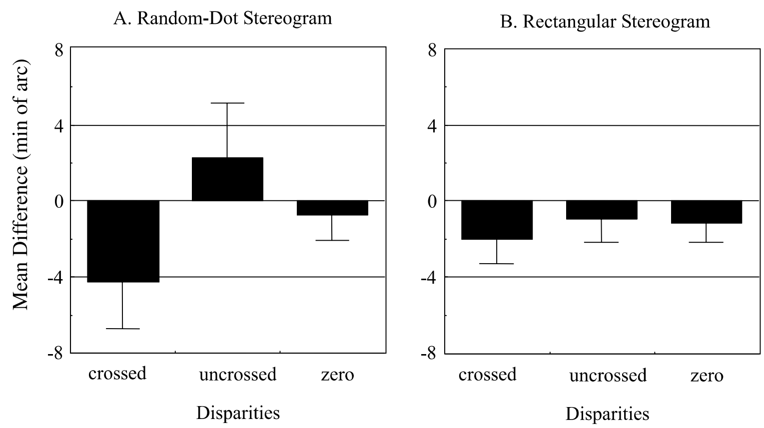

Fig. 2. Mean difference of the horizontal position between the comparison and standard. Separate panels show the results for the random-dot stereogram (A) and those for the rectangular stereogram (B). Each bar represents the mean of 15 observers. The vertical lines attached to the bar indicate the SDs. If the monocular lines are treated as binocular stimuli, the mean difference would have a negative or positive value for the crossed or uncrossed disparity condition, respectively. If the monocular lines follow the law of the visual direction for the monocular stimulus, the mean difference would be zero.

tradicts the idea that the retinal local sign of a monocular stimulus is fixed when it is transformed into visual direction. Are the present results inconsistent with those reported in Erkelens and van de Grind (1994)? They found that when the two monocular lines appeared aligned, the difference of the horizontal physical position between them are nearly zero. In their study, one solid monocular line was presented on a random dot stereogram and its visual direction was measured by adjusting the location of monocular dotted lines placed above and below the stereogram. Their results can be explained, if the dotted lines were perceived in the same depth plane as the stereogram was. If it were the case, the present results do not contradict with the results of Erkelens and van de Grind (1994).

The results for the rectangular stereogram were unexpected in two aspects. First, we expected that for the zero disparity condition the standard and comparison would appear aligned when they are physically in the same horizontal position. However, the lines appeared aligned when the comparison was positioned slightly to the left side of the standard. This result may be interpreted as an example of "monocular spatial distortion" (van Ee et al., 1999) for the monocular alignment task. Similar distortion was observed in the results for the random-dot stereogram with zero disparity. Next, we expected that when the two lines appeared aligned, their horizontal positions would be the same for the three disparity conditions. However, they differed between the crossed and the other two disparity conditions. This result may be due to the fact that the horizontal distance between the monocular and binocular line is relatively close (about 1 deg arc) in the present experiment; when the distance is closer, the monocular line is more likely to be treated as a binocular stimulus (see Erkelens & van Ee, 1997a,b; Shimono et al., 1998). However, it is still an open question as to why the monocular line can be treated so when it is embedded in a stereogram with a crossed disparity but not when it is embedded in a stereogram with an uncrossed disparity.

Although the results for the rectangular stereogram are not as expected, the difference between the results of the random-dot stereogram and those of the rectangular stereograms is consistent with the idea that the monocular stimulus can be treated binocularly. The difference between the horizontal physical positions of the two monocular aligned lines was larger in the random-dot stereogram than in the rectangular stereogram when the stereogram had disparity. The difference in the random-dot stereogram was significantly different from that in the rectangular stereogram, $t(14) = -3.62$, $p < 0.01$ and $t(14) = -3.117$, $p < 0.01$, in the crossed and uncrossed disparity conditions, respectively, but not, $t(14) = 1.00$, $p > 0.1$, in the zero disparity condition. The monocular lines seem to be treated like their surrounding when they were presented on a clearly defined binocular area as in the random-dot stereogram, than when they were presented in an "open" area surrounded by the binocular stimulus as in the rectangular stereogram. This may suggest that visual directions of the monocular stimuli can be determined after the perceived depth planes are determined (see Shimono, Tam, & Nakamizo, 1999, for a similar discussion on the "depth capture" of a monocular occluding area in a random-dot stereogram).

3. Experiment 2: perceived relative directions of monocular lines do not covary with their relative depths

In Experiment 2, we examined whether the monocular lines surrounded by the binocular area can be treated as the binocular stimulus with respect to distance

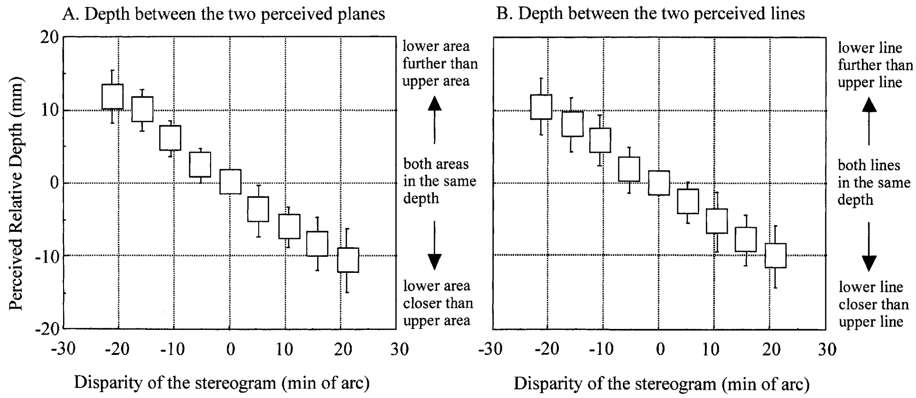

Fig. 3. Perceived depth as a function of the binocular disparity between the upper and lower areas. Separate panels show the perceived depth for the two perceived planes (A) and that for the two perceived lines (B). Each open square represents the means of 11 observers. The means were transformed back from the geometrical means of verbally reported values over 11 observers. The vertical lines attached to the data points indicate the SDs whose values were also transformed back from the SDs calculated from the verbally reported values.

perception [1] as well as visual direction. Observers were asked to report the relative distances (depths) between the two monocular lines and between the upper and lower binocular areas and also to align the two lines as in Experiment 1. If the monocular stimuli were treated as binocular stimuli, the depth between the two lines would correspond to that between the binocular areas.

3.1. Method

3.1.1. Apparatus

Stimuli were generated using the same apparatus as used in Experiment 1. The stimuli were the random-dot stereograms used in Experiment 1.

3.1.2. Procedure

Each observer was asked on each trial (a) to report whether the two perceived rectangular planes appeared in the same plane, and if they were not, which rectangular area appeared closer, (b) to report the perceived depth between the two rectangular planes in mm or cm, (c) to report the perceived depth between the two red lines in mm or cm, and (d) to adjust the lower red line (the comparison) to appear aligned with the upper reference line (the standard).

There were two or three practice trials and 36 main experimental trials. The disparity conditions for practice trials were randomly selected from the nine disparity conditions. In the main experimental trials, the stereogram having one of the nine binocular disparities (5.2, 10.4, 15.6 and 21.1 min arc uncrossed, zero and 5.2, 10.4, 15.6 and 21.1 min arc crossed) with the left or right initial position of the comparison stimulus presented two times. The stereogram was presented for as long as the observer required and the order of its presentation was randomized. The observers were allowed to take a rest at any time in the sessions.

3.1.3. Observer

Eleven male students participated in the experiment. They ranged in age from 18 to 20 and they reported having normal or corrected-to-normal acuity and binocular stereopsis.

3.2. Results and discussion

As in Experiment 1, we initially examined whether the direction of the perceived depth between the two planes corresponded to the disparity type. The observers reported correct depth directions so that further analysis could be undertaken. For the analysis, we transformed the reported depth value logarithmically for every trial, because some observers assigned relatively large number to the depth value. By transforming, we attempted to make the distribution of the depth values normal. We, then, average the transformed values for the left and right initial positions of the comparison at each disparity condition for each observer. The average was used as a score. Fig. 3A shows the means, which were transformed back from the means of the score over 11 observers, as a function of binocular disparity; negative values were given to the mean values that were transformed back, when the lower plane appeared in front of the upper plane and positive values were given when the lower plane appeared behind the upper plane.

Next, we examined the reported depth between the two monocular lines. It was found that the direction of the reported depth between the lines coincided with that between the depth planes. As for the depth data of the planes, we transformed the reported depth values be-

[1] Rogers and Bradshaw (1999) demonstrated that Nonius stimuli can be tilted in depth as if they were treated as surround binocular stimuli when they are superimposed on a pair of stereoscopic images related by a horizontal shear (see Fig. 4 in Rogers & Bradshaw, 1999).

tween the lines logarithmically and averaged the transformed values for each disparity condition for each observer. Fig. 3B shows the means (which were transformed back from the means of the score over 11 observers) as a function of binocular disparity; negative values were given to the mean values that were transformed back when the lower plane appeared in front of the upper plane, and a positive value was given when the lower plane appeared behind the upper plane.

As shown in Fig. 3, the perceived depths for the two monocular lines changed linearly as a function of the binocular disparity of the two depth planes and the slope of the perceived depth was almost identical to that for the perceived depth between the two depth planes. To examine how the depth data of the line corresponded to those of the plane, we fitted the least square regression to the line data against the depth data for each observer. The mean slope and intercept across 11 observers were 0.923 and 0.433, respectively, with 0.947 mean coefficient of the determination (r^2). The fact that the mean slopes and intercepts are not significantly different from one, $t(11) = 1.87$, $0.05 < p < 0.10$, and zero, $t(11) = -1.43$, $p > 0.1$, respectively, is consistent with the idea that the monocular lines are treated like the surrounding binocular stimulus.

Then, we calculated the difference of the horizontal position between the comparison and standard. The difference was coded as in Experiment 1; the value of zero was given when there was no difference, a negative value was given when the comparison appeared to the left of the standard and a positive value was given when the comparison appeared to the right of the standard. As with the depth data, the difference for the left and right initial positions of the comparison was averaged as a score. We performed one way repeated measures ANOVA (9 disparities) on the scores and found that the main factor was statistically significant, $F(8, 80) = 7.86$, $p < 0.0001$. Tukey HSD tests showed that the score in each of four uncrossed disparity conditions was statistically significantly different from that in its respective crossed disparity condition ($p < 0.05$). Fig. 4 shows the mean score over 11 observers as a function of binocular disparity.

As shown in Fig. 4, the extent of the difference of the horizontal position did not covary with the binocular disparity between the upper and lower rectangular areas. Within the small range of disparities (between −5 and 5 min arc), however, the visual direction of the monocular stimulus appears to be the same as predicted from the law of the visual direction for the binocularly fused stimulus. This can be seen in Fig. 4 where the dotted line indicates the value predicted from the law; it corresponds to half of the difference of the horizontal physical position between upper and lower rectangles (or binocular disparity between them). Note that the monocular spatial distortion found in Experiment 1 was also

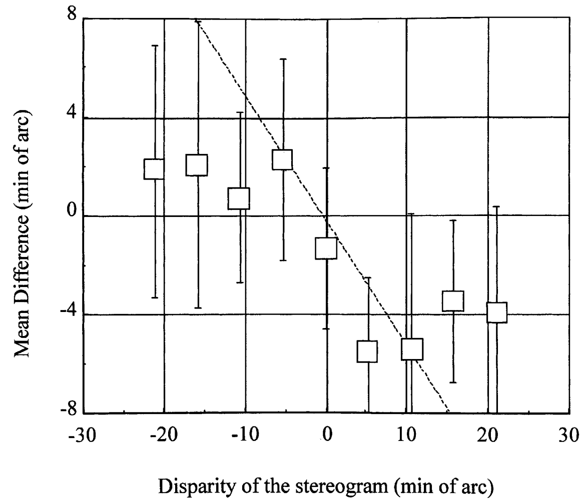

Fig. 4. Mean difference of the horizontal position between the comparison and standard as a function of the binocular disparity between the upper and lower rectangular areas. Each open square represents the mean of 11 observers. The vertical lines attached to the data points indicate the SDs. Dotted lines show the difference of the physical positions, predicted from the law of visual direction for the binocularly fused stimulus.

displayed in Fig. 4. Outside the disparity range, the difference between the physical position of the two aligned lines was less than the predicted value. [The present results suggest that because binocular disparity (10.4 min arc) used in Experiment 1 was outside of the range, and so the obtained difference was less than predicted.] However, even outside the range, the difference of the physical position for each of the 10.4, 15.8 and 21.1 min arc uncrossed disparity conditions was larger than that for its respective crossed disparity condition. These differences are contrary to the idea that the retinal local sign is fixed, which is the assumption based on the law of visual direction for the monocular stimulus.

The obtained disparity range in the present study, where monocular stimuli behave as if they follow the law for the binocularly fused stimulus, differs from that reported in Erkelens and van Ee (1997a,b). This could be due to differences between the disparity types and the stimuli used in the two studies. In the present study, monocular lines were embedded on different depth planes and, thus, the range was that of "relative" disparity between the depth planes (between −5 and 5 min arc) (see Fig. 4). In Erkelens and van Ee (1997a,b), a monocular line was embedded on a single depth plane moving in depth and thus, the range was that of vergence-induced disparity or "absolute" disparity between the eye position and the depth plane (−1 and 1 deg arc) (see Fig. 2 in Erkelens & van Ee, 1997a and Fig. 6 in Erkelens & van Ee, 1997b). The amount of the absolute disparity is known to become larger when the eyes track the fused random-dot stereogram, simulated to move in depth (Erkelens & Collewijn, 1985; Ono et al., 2000) than when the eyes fixate the stationary stimulus (Schor, 1979). [2]

4. General discussion

The results of Experiment 1 showed that two vertical monocular lines, which differed in their horizontal physical positions, appeared aligned when they were presented at different depth planes that are defined by random-dot patterns. The results of Experiment 2 indicated that the difference in the horizontal position of the aligned monocular lines depended on the binocular disparity between the depth planes. These results suggest that when the monocular stimulus is presented in the binocular area, the stimulus does not follow the monocular law of the visual direction. Our stimuli may be added to the list of those that are now known not to follow the monocular law of visual direction (Erkelens & van Ee (1997a,b); Erkelens & van de Grind, 1994; Ono et al. (1998, 2002); Popple & Findlay, 1998; Shimono et al., 1998; van Ee et al., 1999).

Furthermore, the results of Experiment 2 suggested the relationship between depth and direction perception for a monocular stimulus. In particular, comparison of Fig. 3B (depth data) with Fig. 4 (direction data) indicates that the difference of the physical positions of the monocular lines did not covary with the disparity of the stereogram as their relative depth did. Fig. 4 shows that although the difference of the physical position covaried with the disparity of the stereogram within a relatively small disparity range (about from -5.0 to 5.0 min arc), the difference was relatively constant over the disparity range. In contrast, Fig. 3B shows that the perceived depth between the two monocular lines changed like that between the two depth planes, at least, within the disparity range from -21.1 to 21.1 min arc. These results suggest that the visual direction and the perceived depth for a monocular stimulus, presented on a random-dot stereogram may be processed differently. [3]

[2] Although the results of Erkelens and van Ee's studies can be understood with the idea that a monocular stimulus can behave as a binocular stimulus, there is another possible explanation for them. Because there was no relative motion between the binocular and monocular stimuli in their stimulus configuration, the visual system had "judged" the monocular stimulus to be stationary. According to Swanston and Wade (1992), relative motion of a stimulus is critical to perceive motion and therefore, if there were no relative motion (or no patterncentric signal in the stimulus configuration) no motion will be perceived. Furthermore, Wade, Swanston, and de Weert (1993) suggested that patterncentric signals are mostly extracted before the level of binocular combination of each eye's information in the sequence of the visual processing. If the visual system can use the "no-relative motion" information extracted monocularly after the binocular combination, Erkelens and van Ee's (1997a,b) results can also be understood in terms of the lack of the patterncentric signal in their stimuli.

[3] The obtained relationship between depth and direction perception for monocular stimuli is similar to that for binocular stimuli. For binocular stimuli, it is well known that the range of disparity where their relative visual directions follow the law for the binocularly fused stimulus (Panum's fusional area) is generally smaller than that where depth covaries with the disparity. Accordingly, one might think that the obtained relationship for the monocular lines can be explained by the small size of Panum's fusional area for our stimulus. Because we did not control eye positions we cannot infer its size in the present study, although our informal observations showed that within the range of the disparity we used, at least, contours of elements of the two fused rectangular areas were clearly seen while adjusting. This suggests that both rectangular areas might had been in the Panum's fusional area.

Acknowledgements

The first author worked on this study in 2000, while he was at the University of Dundee, Dundee, Scotland, as a visiting researcher from Tokyo University of Mercantile Marine. Part of the present study was supported by grant-in-aids for Scientific Research (10610069) provided by the Japanese Ministry of Education, Science, and Culture. The authors wish to thank two anonymous reviewers and Dr. H. Ono for their helpful comments on an earlier version of this paper. Correspondence concerning this article should be addressed to Koichi Shimono, Department of Information Processing Engineering and Logistics, Tokyo University of Mercantile Marine, Ettchujima 2-1-6, Koto-ku, Tokyo, Japan, 135-8533, shimono@ipc.tosho-u.ac.jp.

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