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Localization of monocular stimuli in different depth planes

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Abstract

We examined the phenomenon in which two physically aligned monocular stimuli appear to be non-collinear when each of them is located in binocular regions that are at different depth planes. Using monocular bars embedded in binocular random-dot areas that are at different depths, we manipulated properties of the binocular areas and examined their effect on the perceived direction and depth of the monocular stimuli. Results showed that (1) the relative visual direction and perceived depth of the monocular bars depended on the binocular disparity and the dot density of the binocular areas, and (2) the visual direction, but not the depth, depended on the width of the binocular regions. These results are consistent with the hypothesis that monocular stimuli are treated by the visual system as binocular stimuli that have acquired the properties of their binocular surrounds. Moreover, partial correlation analysis suggests that the visual system utilizes both the disparity information of the binocular areas and the perceived depth of the monocular bars in determining the relative visual direction of the bars.

Keywords: Relative visual direction; Stereo-depth; Capture phenomenon; Monocular stimuli

1. Introduction

It is generally believed that both eye position and the retinal location that is being stimulated determine the visual direction of a monocular stimulus. This belief is reflected in the monocular rule of visual direction (e.g., Howard & Rogers, 2002; Ono & Mapp, 1995). However, recently, a number of studies showed that the visual direction of a monocular stimulus does not always follow the monocular rule of visual direction, particularly, when it is presented in or near a binocular area (e.g., Domini & Braunstein, 2001; Erkelens, Muijs, & van Ee, 1996; Erkelens & van de Grind, 1994; Erkelens & van Ee, 1997a, 1997b; Ono, Wade, & Lillakas, 2002; Shimono, Ono, Saida, & Mapp, 1998; Shimono & Wade, 2002; van Ee, Banks, & Backus, 1999). In these studies, the visual direction of the monocular stimulus was closer to that predicted by the binocular rule of visual direction (than the monocular rule of visual direction) which asserts that the visual direction of a binocularly fused stimulus is midway between that of each monocular component of the binocular stimulus (e.g., Howard & Rogers, 2002; Ono & Mapp, 1995). This finding can be explained by assuming that the visual direction of the monocular stimulus was "captured" by that of the binocular stimulus (Erkelens & van Ee, 1997a, 1997b) or that the visual system treated the monocular stimulus as if it were part of the binocular stimulus (Shimono et al., 1998; Shimono & Wade, 2002).

If the monocular stimulus can be treated as the binocular stimulus in the direction domain of perception, what would happen to the monocular stimulus in the depth domain? Will the perceived depth of the monocular stimulus correspond to that of the binocular stimulus? Shimono and Wade (2002) addressed this question and found that when a monocular vertical bar was presented inside each of two binocularly fused but disparate areas,

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the relative depth between the two monocular bars changed as a function of the binocular disparity of the two fused areas. In addition, the depth magnitude of the monocular bars corresponded to that of the binocular areas in which they were embedded. These findings suggest that a monocular stimulus can be treated as a binocular stimulus in the depth domain of perception.

Shimono and Wade (2002) further found that when the disparity of the binocular areas was relatively large the relative direction of the monocular stimuli did not covary with their perceived relative depth. This finding suggests that the relative visual direction and the relative depth of a monocular stimulus are not necessarily processed by the same mechanism. Nevertheless, how and under what conditions the visual direction and the perceived depth of the monocular stimuli might be mediated separately in the visual system and what might be the underlying mechanism(s) are not clear.

In the present study, we manipulated properties of the binocular stimuli to further our understanding of the conditions and the underlying process or processes that might be involved in determining the visual direction and the perceived depth of the monocular stimuli. We reasoned that if a monocular stimulus is treated by the visual system as part of a binocular stimulus in which it is embedded, manipulation of the binocular stimulus could change the likelihood that the monocular stimulus are treated as part of the binocular stimulus. In addition, if perceived depth and visual direction of the monocular stimulus are mediated via different mechanisms, the changes could be different in the direction domain compared to that in the depth domain. In this vein, we manipulated the dot density of the binocular stimulus in Experiment 1 and the width of the binocular stimulus in Experiment 2 to investigate their effect on both the visual direction and the perceived depth of the monocular stimulus. We manipulated dot density because we hypothesized that if a binocular stimulus (or area) consisted of fewer dots, for example, only 10% coverage, there would be more "vacant" space around each fused dot and this might hinder the visual system from interpreting the monocular bar stimulus as part of the binocular stimulus. In the other case, we manipulated the width of the binocular stimulus (area) because we reasoned that as the width is increased, it would be more difficult for the visual system to interpret the monocular stimulus as being part of the surrounding binocular stimulus. That is, the monocular stimulus would more likely be treated as a figure than as part of the "background" binocular stimulus.

To infer the underlying mechanism(s) that are involved in the phenomenon under study, we applied partial correlation analysis to the results of the experiments. Partial correlation is a method that is used to determine the causal chain among physical and perceptual variables (Higashiyama & Shimono, 1994, 2004; Oyama, 1974, 1977; van der Meer, 1979). It is the correlation of two variables while controlling for a third or more other variables. It requires the usual assumptions as for Pearson correlation.

2. Method

2.1. Stimuli and apparatus

The stimuli were generated with a computer (Gateway Solo 5300) and displayed on a color monitor (Gateway EV700). The stimuli, similar to those used in Shimono and Wade (2002) and shown in Fig. 1 here, consisted of a set of random-dot stereograms each with an upper and a lower rectangular area as binocular areas for fusion. The rectangular areas were separated from each other by 3.3 deg arc from center to center and each of the two areas consisted of picture elements, each subtending 1.5 × 1.5 min arc. In each of the rectangular areas within one half-field, there was a monocular stimulus consisting of a vertical red bar. The center of the monitor was set at eye level, 106 cm away from the corneal plane. Matching polarizing filters in front of the eyes and the monitor 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 40 cm and a −1.5D lens was placed in front of each eye of an observer to match the required accommodation to the convergence distance.

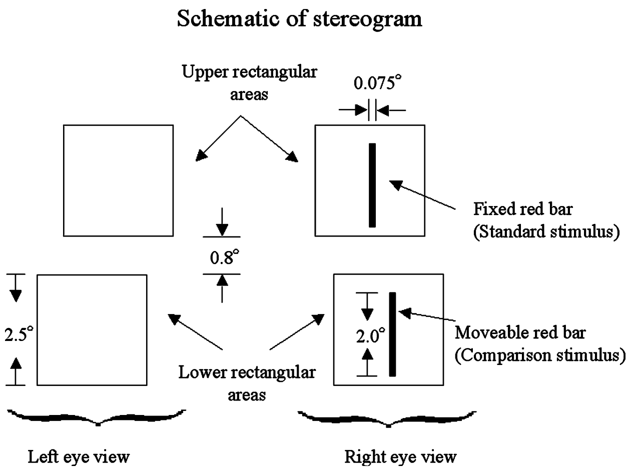

Fig. 1. Schematic of an example of the random-dot stereogram used in Experiments 1 and 2. A vertical (red) bar was presented in the upper rectangular area and another in the lower rectangular area. Note that in the actual experiment the lines enclosing the rectangular areas were not visible and that the bounded areas were filled with "dots". In both experiments, the distance between the upper and lower rectangular areas, their height, and the width and height of the monocular bar were kept constant. However, dot density of the rectangular areas was varied in Experiment 1, ranging from 0.03% to 100%, while it was kept constant at 50% in Experiment 2. The width of the rectangular areas was varied in Experiment 2, ranging from 0.4 to 3.7 deg arc, while it was kept constant at 2.5 deg arc in Experiment 1.

In Experiment 1, the dot density of each rectangular area was varied but its size was kept constant (2.5×2.5 deg arc). The size of the monocular bar was also kept constant (0.075×2.0 deg arc). There were five dot densities: 0.03%, 0.125%, 5%, 10%, 50%, 75%, and 100%.[1] The horizontal disparity between the upper and lower rectangular areas was zero, 6.0, 11.9, 23.8 min arc, either crossed or uncrossed.

In Experiment 2, the width of the random-dot rectangular areas was varied but its height was kept constant at 2.5 deg arc. There were five widths: 0.4, 0.6, 1.2, 2.5, and 3.7 deg arc. For the first three widths, the disparities of the binocular areas were manipulated at four levels: 0, 3.0, 6.0, and 11.9 min arc crossed and uncrossed. For the remaining wider stimuli, the disparities were also manipulated at four levels but the magnitudes were slightly different: 0, 6.0, 11.9, and 23.8 min arc crossed and uncrossed. The range of disparities for the three narrower stereograms was smaller than that for the two wider stereograms because observers reported difficulties in getting stable fusion when the disparity was 23.8 min arc, either crossed or uncrossed, for the narrower stereograms. The dot density of the stereogram was fixed at 50%. The size of the monocular bar was the same as in Experiment 1.

2.2. Procedure

At the end of each trial, the observer was asked (a) to report whether the two perceived red bars appeared in the same plane and, if they were not, which bar appeared closer, (b) to report verbally the perceived depth between the two red bars in mm or cm, and (c) to adjust the lower red bar (the comparison stimulus) to appear aligned with the upper reference bar (the standard). Each of the red bars was presented in each of the rectangular areas of the left half-field of the stereogram on the screen, that is, to the right eye. The position of the standard in the upper area was fixed and that for the comparison in the lower area could be shifted horizontally, either left or right, by an observer. For all trials, the standard was located at the center of the upper area and the comparison was located initially at the center of the lower area. 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 take a rest at any time during the sessions.

There were three practice trials before the actual experimental trials in each Experiment. For the practice trials, stimulus disparities were selected randomly from 0, 6.0 min arc crossed and uncrossed, with dot density fixed at 50%. For the experimental trials, stimulus disparity was selected from the different levels of binocular disparities and dot densities in Experiment 1, and from the different levels of binocular disparities and widths of the binocular stimuli in Experiment 2. Thus, each observer underwent a total of 49 trials in Experiment 1, and 35 trials in Experiment 2. Eight observers participated in Experiment 1 and seven in Experiment 2.

2.3. Data analysis

The procedure used to code the data with respect to relative visual direction[2] and perceived depth was like that by Shimono and Wade (2002). With respect to visual direction, we coded the difference in horizontal position between the adjusted comparison bar and the fixed standard bar. A value of zero was assigned when there was no difference in the horizontal position. When the comparison was on the left side of the standard, a negative value was given. Conversely, a positive sign was given when the comparison was on the right side of the standard. With respect to depth, we coded the reported depth between the two red bars. A value of zero was given when there was no depth between them, a negative value was given to the reported value when the lower bar appeared in front of the upper bar, and a positive value was given when the upper bar appeared in front of the lower bar. With this notation, if the red bars were treated as a part of their surrounding binocular areas, the difference value and the depth value would be negative for the crossed disparity condition and they would be positive for the uncrossed disparity condition.

In Experiment 1, we performed a partial correlation analysis on the coded direction and depth data using two perceptual variables (perceived depth, PD', and visual direction, VD') and two physical variables

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[1] While the percentage of dot density can be calculated in terms of the "white" dots or the "black" dots, note that in this study the light intensity of the background of the whole screen was that of the "black" dots. Thus, the condition with 5% "white" dots, for example, is not entirely equivalent to the condition with 95% "white" dots (i.e., 5% "black" dots). In the former case, there would be an apparent sparse area of "white" dots amidst a black background, whereas in the latter case, there would be an apparent "white square" made up of a dense distribution of "white" dots speckled with "black" dots. In short, for this study, we manipulated the density of the "white" dots and also presented the results based on the "white" dots.

[2] One might think that because we did not ask observers to maintain a fixed binocular eye position, the (absolute) visual direction of the monocular stimulus would have changed because it is known to depend on binocular eye position (e.g., Ono & Mapp, 1995) and, thus, the eye positions would have played a role in the results of the present experiments. Note, however, that we measured the relative visual direction and not the absolute visual directions of the monocular bars. Thus, although the binocular eye position may have affected the absolute visual directions of the upper and lower monocular bars, the effect should have been the same for either bar and there should have been no or little effect of eye position on their relative visual direction.

(disparity of the binocular stimulus, BD, and dot density, DD). In Experiment 2, the same two perceptual variables (PD′ and VD′) and the disparity of the binocular stimulus (BD) were used in addition to the physical variable, width of the binocular stimulus (WBS). The partial correlation is a net correlation between two variables when the influence of other variable(s) is eliminated. If the partial correlation approaches zero, the inference is that the original correlation is spurious and that there is no direct causal link between the two original variables. If the partial correlation is significantly different from zero, a given pair of variables has a direct relation, although it does not indicate the direction of causality (Oyama, 1974). Nevertheless, we can apply the analysis to the present data to look for causality because in the present study it is assumed that physical variables can determine perceptual variables and that there is no causal relation between the physical variables. Specifically, in calculating the partial correlations, we assumed that (1) perceived depth can be influenced by the two physical variables and by perceived visual direction, and that (2) visual direction can be influenced by the same two physical variables as well as by perceived depth.

3. Results

3.1. Experiment 1: Effects of dot density of binocular stimuli

Fig. 2A shows the mean coded direction score based on the data from eight observers as a function of binocular disparity. Data for the different dot density conditions are presented separately. We performed a two-way repeated measures ANOVA (7 disparities × 7 dot densities) on the score. The analysis showed that the main effect of disparity and the interaction between disparity and dot density were statistically significant, $F(6,42) = 36.93$, $p < .001$ and $F(36,252) = 4.27$, $p < .001$. The main effect of dot density was not statistically significant, $F(6,42) = 1.38$, $p > .1$. The significant main effect of disparity can be seen in Fig. 2A—the difference in horizontal position between the two bars covaried with the disparity of the binocular stimuli, for each dot density condition. The significant interaction between disparity and dot density can also be seen in Fig. 2A—at the largest disparity conditions (23.8 min arc crossed and uncrossed), differences in horizontal position between the two monocular bars for the stereograms with dot densities of 0.03%, 0.125%, and 100% were smaller than those for the stereograms with other dot densities.

To examine further the effect of dot density on relative visual direction, we calculated the slopes of the regression lines for the different dot densities for each observer and then performed a one-way ANOVA on the slopes. The results show that the main effect of slope was significant, $F(6,42) = 14.08$, $p < .001$. A multiple-pairwise Tukey HSD test shows that the slopes for the 0.03% and 0.125% dot density conditions were significantly shallower than those for the 5%, 10%, 50%, and 75% dot density conditions ($p < .05$). As well, the slope for the 100% dot density condition was significantly shallower than the slope for the 10%, 50%, and 75% dot density conditions ($p < .05$). The filled trian-

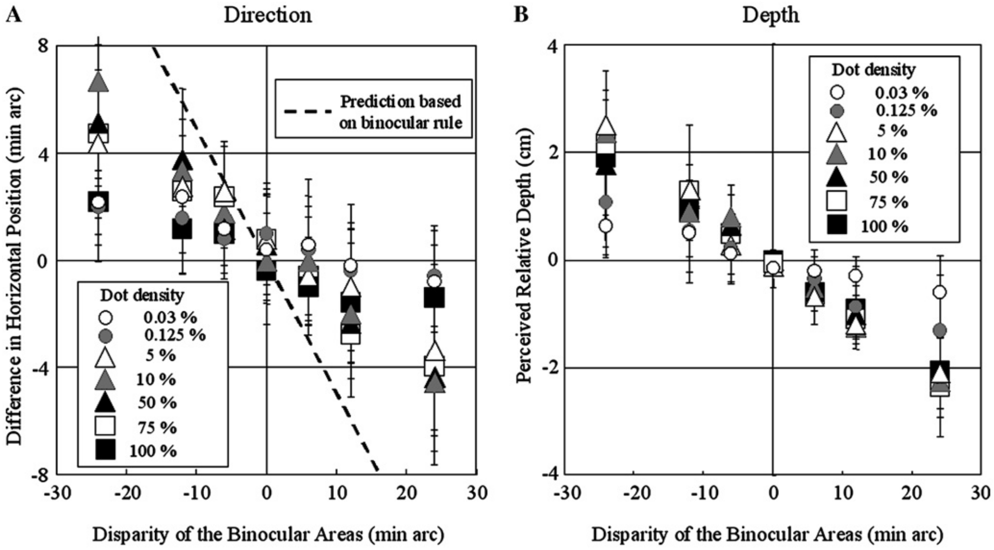

Fig. 2. Mean difference of the horizontal position (A) and mean perceived depth (B) between the comparison and the standard monocular stimuli as a function of the disparity of the binocular areas, for different levels of dot density. The vertical lines attached to the data points indicate standard deviations. The broken line depicted in (A) indicates the difference in horizontal position between the upper and the lower monocular bars as predicted using the binocular rule of visual direction.

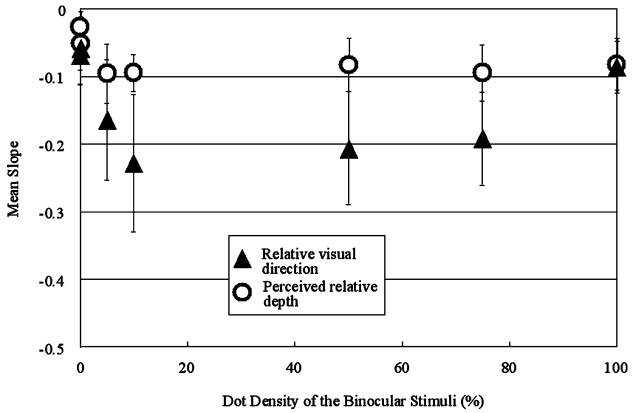

Fig. 3. Mean slopes for the direction and depth data from Experiment 1. Filled triangles indicate the slopes for the direction data of the aligned monocular bars, and open circles the slopes for the depth data of the monocular bars, respectively. The vertical lines attached to the data points indicate standard deviations.

gles in Fig. 3 show the mean slopes, averaged over the data from the eight observers, as a function of dot density. The figure shows that the slope drops rapidly as the dot density is increased between 0.03% and 10%. Beyond this range, the slope changes gradually upwards until at the highest dot density of 100% the slope reaches almost the same level as that at the lowest dot density condition of 0.03%. This pattern of results indicate that the likelihood a monocular stimulus is treated as a binocular stimulus is less at the two lower dot densities (0.03% and 0.125%) and at the highest dot density (100%), than at the other dot density conditions. However, note that the slopes at these three densities are still larger than zero, $t(7) = 4.74$, $p < .001$; $t(7) = 3.03$, $p < .001$; and $t(7) = 6.24$, $p < .001$, for the 0.03%, 0.125%, and 100% dot densities, respectively. This indicates that there is still an influence of the disparity of the binocular areas on the relative visual directions of the monocular stimuli at these dot density conditions.

Another important aspect of the results is that the slopes obtained in this experiment are less than what is predicted from the binocular rule of visual direction (see Fig. 2A). According to the rules, the visual direction of a binocularly fused stimulus is midway between that of each monocular stimulus. If the visual system treats the monocular red bar used in the present experiment as a binocular stimulus with features of the surrounding binocular area, the angular difference between the aligned upper and lower red bars should be half the binocular disparity between the two rectangular areas. That is, the slope of the direction data should be 0.5. The slopes that were obtained were smaller than this value, ranging from 0.06 to 0.23. We will discuss why this might be the case in Section 3.2 and Section 4.

Fig. 2B shows the mean coded depth score based on the data of eight observers as a function of binocular disparity. The data are shown separately for the different dot density conditions. We performed a two-way repeated measures ANOVA (7 densities × 7 disparities) and the analysis showed that the main effect of disparity and the interaction between disparity and dot density were statistically significant, $F(6,42) = 36.44$, $p < .001$ and $F(36,252) = 6.50$, $p < .001$, respectively. The main effect of dot density was not statistically significant, $F(6,42) = 0.31$, $p > .05$. The significant main effect of disparity can be seen in Fig. 2B—the reported depth covaried with the disparity of the binocular areas for each dot density condition. The significant interaction between disparity and dot density can also be seen in Fig. 2B. At the largest disparity conditions (23.8 min arc crossed and uncrossed) the magnitude of the relative depth of the monocular stimuli for the stereograms with dot densities of 0.03% and 0.125% was smaller than those for the stereograms with dot densities of 5%, 10%, 50%, 75%, and 100%.

With respect to the depth data, we also calculated the slope of the regression lines for each observer's data and a one-way ANOVA on the slopes was completed. It showed a significant main effect of slope, $F(6,42) = 16.11$, $p < .001$. A multiple-pairwise Tukey HSD test shows that the slopes of 0.03% and 0.125% dot density were significantly shallower than those of the 5%, 10%, 50%, 75%, and 100% dot density conditions ($p < .05$). This difference is also reflected in Fig. 3 where the open circles indicate the mean slopes as a function of dot density. The figure shows that the slope dropped rapidly between the first two dot density conditions (0.03% and 0.125%) before reaching the level at the 5% dot density condition the slopes remained relatively constant. In general, the results are consistent with the idea that the dot density of the binocular areas in a stereogram can have an effect on the perceived depth of the monocular stimuli that are embedded in the binocular regions.

Comparing the curves produced by the visual direction data and by the depth data in Fig. 3, we note also that the effect of dot density is different for the two sets of data. The data for visual direction drops quickly between 0.03% and 5% dot density conditions and then gradually increase such that at the 100% dot density condition the slope reaches a value that is comparable to that at 0.03% dot density. For the depth data, the drop is as dramatic between 0.03% and 5% dot density conditions, however, the slopes remain relatively constant beyond the 5% and up to the 100% dot density conditions. We interpret this as additional evidence that the binocular areas can change the likelihood that a monocular stimulus is treated as binocular stimuli differently in the direction and depth domains. Recall that Shimono and Wade (2002) found that when the disparity of the binocular area was relatively large the relative direction of the monocular stimuli did not covary with their perceived relative depth.

3.2. Experiment 2: Effects of width of binocular stimuli

Fig. 4A shows the mean direction data of the monocular red bars as a function of binocular disparity, for different widths of the binocular area. Fig. 4B shows the corresponding data for perceived relative depth. For each plot, the results were obtained by averaging the data from the seven observers. As can be seen in Fig. 4, the mean horizontal difference and the mean depth covary with binocular disparity; the data fall along a diagonal rather than a horizontal line.

To scrutinize the effect of the width of binocular stimuli, we calculated the slopes of the regression lines for the direction data for each observer and a one-way ANOVA was performed on the slopes. The analysis showed that the main effect of slope was significant, $F(4,24) = 11.46$, $p < .001$. Multiple-pairwise Tukey HSD test showed that the slope (−0.41) for the narrowest stereogram was significantly steeper than each of the intermediate 1.2, 2.5, and 3.7 deg arc stereograms, and the slope (−0.34) for the 0.6 deg arc stereogram was significantly steeper than that for the widest stereogram ($p < .05$).

The significant main effect of slope can be observed in Fig. 5 in which the filled triangles indicate the mean slopes for the direction data, averaged over seven observers, as a function of the width of the binocular stimulus. As can be seen in Fig. 5, as the width of the binocular stimulus is increased the slope decreases. This result suggests that the monocular stimulus is less likely to be treated as being part of its surrounding binocular area when the width of the binocular area is increased. Nevertheless, another possible explanation is that instead of the width of the binocular stimulus per se, it is the ratio of the width of the monocular stimulus to that of the binocular stimulus that may have played a role in effecting a change in the perceived direction of the monocular stimulus. To distinguish these two possibilities, an experiment in which the width of the monocular stimulus is manipulated is needed. This supplementary experiment will be presented in Section 3.3.

Fig. 5 also shows that most of the mean slopes for the direction data are less than that predicted from the rules of binocular visual direction. As mentioned in Experiment 1, the rules predict that the slope of the direction data ought to be 0.5. Therefore, a test was conducted to examine the significance of the difference between the mean slope and the slope predicted from the rules of binocular visual direction. A multiple-pairwise Tukey test showed that the difference between the mean slope (0.41) for the narrowest stereogram (0.4 deg arc) and the predicted slope was not significant, $t(7) = 1.94$, $p > .10$, while that between the mean slope of the four other stereograms of widths 0.6, 1.2, 2.5, and 3.7 deg arc and the predicted slope were significant, $t(7) = 4.55$, $p < .001$; $t(7) = 7.91$, $p < .001$; $t(7) = 9.69$, $p < .001$; $t(7) = 12.67$, $p < .001$, respectively. It is as if the capture phenomenon (Erkelens & van Ee, 1997a, 1997b) had occurred only for the narrowest stereogram,

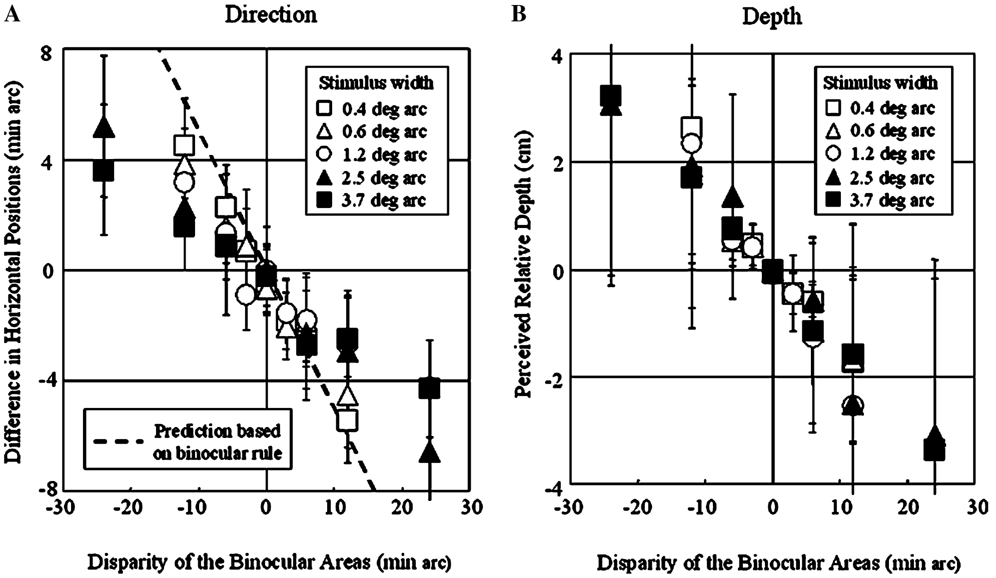

Fig. 4. Mean difference of the horizontal position (A) and mean perceived depth (B) between the comparison and the standard monocular stimuli as a function of the disparity of the binocular areas, for different widths of the binocular areas. The vertical lines attached to the data points indicate standard deviations. The broken line depicted in (A) indicates the difference in horizontal position between the upper and lower monocular bars as predicted using the binocular rule of visual direction.

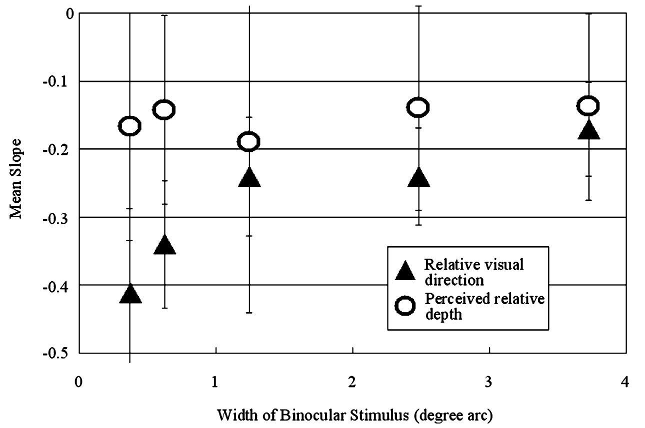

Fig. 5. Mean slopes for the direction data and depth data from Experiment 2. Filled triangles and open circles indicate the slopes for the direction data and the depth data of the monocular bars, respectively. The vertical lines attached to the data points indicate standard deviations.

and "partial" capture for the others. In Section 4, we will discuss possible reasons as to why there is partial capture and why the extent of capture decreased as a function of the width of the binocular stimulus.

Next, we discuss the slopes for the depth data. In Fig. 5, the open circles indicate the mean slopes for the depth data over seven observers as a function of the width of the binocular stimulus. We performed a one-way ANOVA on the slopes, which showed that the main effect of the width of the binocular stimuli was not significant, $F(4,24) = 1.38$, $p > .05$. As can be seen in Fig. 5, the slope is relatively constant as the width of the binocular stimuli is increased. This result suggests that the width of the binocular area had no effect on the perceived depth of the monocular stimulus, at least, within the range of disparities that were used in the present experiment. This is in contrast to the direction data in which the width of the binocular area did have an effect on the slopes.

3.3. Supplementary experiment: Effects of widths of monocular stimuli

A supplementary experiment was conducted to determine whether it was the ratio of the width of the monocular stimulus to that of the binocular stimulus, rather than the width of the binocular stimulus, that played a role in effecting a change in the perceived direction of the monocular stimulus. We manipulated the width of the monocular bars at four levels, corresponding to 3.0, 29.8, 59.6, and 119.2 min arc, with the height fixed at 2.5 deg arc. The size of the stereogram was the same as that used in Experiment 1 with the disparity of the binocular stimuli at one of four levels: 0, 6.0, 11.9, and 23.8 min arc, either crossed or uncrossed. The dot density of the binocular stimulus was fixed at 50% and eight observers were recruited for this experiment.

Fig. 6A shows the mean direction data averaged over the data of eight observers as a function of binocular disparity. The data are presented as separate plots for different widths of the monocular stimuli. We performed

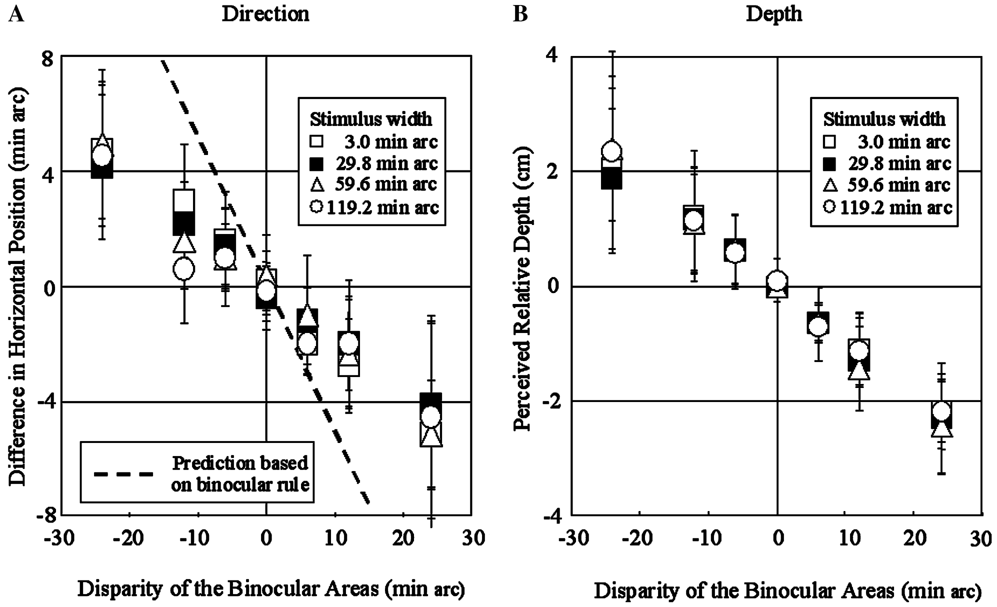

Fig. 6. Mean difference of the horizontal position (A) and mean perceived depth (B) between the comparison and the standard monocular stimuli as a function of the disparity of the binocular areas, with the width of a monocular stimulus as a parameter. The vertical lines attached to the data points indicate standard deviations. The broken line depicted in (A) indicates the difference in horizontal position between the upper and lower monocular bars as predicted using the binocular rule of visual direction.

a two-way repeated measures ANOVA (4 densities × 7 disparities) on the mean data. The analysis showed that the main effect of disparity was statistically significant, $F(6,42) = 32.11$, $p < .001$, while the main effect of width and the interaction between the two main effects were not statistically significant, $F(3,21) = 0.47$, $p > .1$ and $F(18,126) = 0.831$, $p > .1$, respectively.

The fact that the width of the monocular stimulus did not affect relative visual direction suggests that the direction data in Experiment 2 is probably due to the width of the binocular area and not the ratio of the width of the monocular stimulus to that of the binocular area. As discussed in Experiment 2, if the latter were the case, the relative visual direction would have depended on the width of the monocular stimulus in this supplementary experiment. The present results show that the width of the monocular stimulus has no noticeable effect on the relative visual directions of the monocular stimuli. Thus, it is the features of the binocular area, specifically its disparity and its width, that can affect the visual direction of monocular stimuli embedded in binocular regions.

For the depth data the pattern of results obtained in the supplementary experiment were similar to those obtained for the direction data. The mean depth averaged over the eight observers are plotted as a function of binocular disparity data in Fig. 6B, separately for the different widths of the monocular stimuli. A two-way repeated measures ANOVA (4 sizes × 7 disparities) was performed on the data and it showed that the main effect of disparity was statistically significant, $F(6,42) = 46.93$, $p < .001$. However, the main effect of size and the interaction between size and disparity were not statistically significant, $F(3,21) = 0.34$, $p > .1$ and $F(18,126) = 1.01$, $p > .1$, respectively. The significant main effect of disparity can be seen in Fig. 6B; the reported depth covaried with the disparity of the binocular areas for each of the plots for the different widths of the monocular stimuli.

As for the results in Experiment 1, slopes of the regression lines for the direction data (filled triangles) and the depth data (open circles) were calculated and are shown in Fig. 7, as a function of the width of the monocular stimulus. The figure shows that both the direction data and the depth data are relatively constant over the widths used in the present experiment, indicating that the width has no effect on the slopes of the regression lines. These results are interpreted as indicating that the width of the monocular stimulus has no influence on the likelihood that it would be treated by the visual system as part of the binocular stimulus or area in which it is embedded. This observation was confirmed by a one-way ANOVA on the slopes that showed the main effect of width was not significant either for the direction data, $F(3,21) = 1.13$, $p > .05$, or for the depth data, $F(3,21) = 1.14$, $p > .05$.

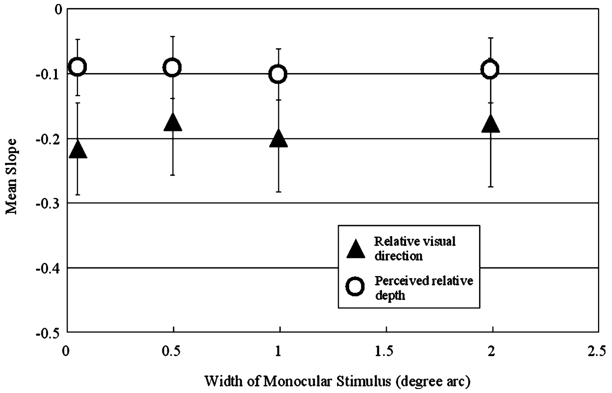

Fig. 7. Mean slopes for the direction data and the depth data from the supplementary experiment. Filled triangles and open circles indicate the slopes for the direction data and the depth data of the aligned monocular bars, respectively. The vertical lines attached to the data points indicate standard deviations.

3.4. Partial correlation analysis

Table 1 shows the results of the correlation analysis for Experiments 1 and 2. We obtained significant partial correlations between BD and PD′ and between VD′ and PD′ in Experiment 1. Recall that if a partial correlation of a given pair of variables is significantly different from zero, it would mean that there is a direct relationship between the variables. In particular, for the present study, the direction of causality can be assessed because it is reasonable to assume that physical variables can determine perceptual variables and that there is no causal relation between the physical variables examined. Thus, given the significant partial correlation between binocular disparity (BD) and perceived depth (PD′), we can say that binocular disparity affected perceived depth. Also, from the significant partial correlation between visual direction (VD′) and perceived depth (PD′), we can either say that visual direction affected perceived depth or that perceived depth affected visual direction. However, based on the conclusion of a related study that "visual directions of monocular stimuli can be determined after the perceived depth planes (*of monocular stimuli*) are determined" (Shimono & Wade, 2002, p.1131; italics ours), we suggest that perceived depth affected visual direction rather than the other way around with respect to the current results. That is, we believe that binocular disparity indirectly affected visual direction through perceived depth.

In comparison to the results of Experiment 1, those of Experiment 2 and the supplementary experiment indicate significant partial correlations between BD and PD′ *and* between BD and VD′. The significant partial correlations suggest that binocular disparity affected both perceived depth and visual direction directly, leading one to conclude that the localization of a monocular

Table 1
Simple and partial correlations between physical variable (binocular disparity, BD; dot density, DD; width of a binocular stimulus, WBS; or width of a monocular stimulus, WMS) and perceptual variable (perceived depth, PD′ or visual direction, VD′) and between PD′ and VD′

Paired values	Experiment 1		Experiment 2		Supplementary experiment	
	Simple	Partial	Simple	Partial	Simple	Partial
(DD, PD′)	.003	.218	—	—	—	—
(WBS, PD′)	—	—	−.015	−.067	—	—
(WMS, PD′)	—	—	—	—	.220	.194
(BD, PD′)	−.946**	−.686**	−.980**	−.824**	−.990**	−.728**
(VD′, PD′)	.940**	.683**	.937**	.154	.978**	.170
(DD, VD′)	−.107	−.317	—	—	—	—
(WBS, VD′)	—	—	−.020	−.051	—	—
(WMS, VD′)	—	—	—	—	−.045	−.279
(BD, VD′)	−.894**	−.008	−.946**	−.402*	−.984**	−.542*

* $p < .05$.
** $p < .001$.

stimulus is determined by only one single physical variable, namely, the disparity of the surrounding binocular stimuli. This conclusion based on partial correlation analysis is inconsistent with that based on the results of Experiment 1 and in Section 4 we will discuss how the two apparently inconsistent results can be reconciled. Keep in mind that the property of the binocular stimulus that was manipulated in Experiment 1 was dot density, whereas it was stimulus width that was manipulated in Experiment 2.

4. General discussion

The results of the present study showed that when two objectively aligned monocular bars are presented separately in two binocularly disparate regions of a random-dot stereogram, the perceived direction and depth of the two monocular bars depended on features of the binocular regions. Experiments 1 and 2, as well as the supplementary experiment, showed that both the extent of misalignment of the two bars and the magnitude of perceived depth covaried with binocular disparity. These results are consistent with the idea that when a monocular stimulus is embedded within a binocular area or stimulus, the visual system "regards" the monocular stimulus as part of its binocular surround by taking on specific characteristics of the binocular stimulus (e.g., Domini & Braunstein, 2001; Erkelens & van Ee, 1997a, 1997b; Shimono et al., 1998; Shimono & Wade, 2002).

From an ecological point of view, the assignment of properties of the binocular stimuli (depth and direction) to the monocular stimuli is parsimonious for the visual system because monocular stimuli are unlikely to be surrounded by binocular stimuli in the natural environment, except when an object is partially occluded by a nearer binocular object. Thus, the visual system does not have to develop a specific system or process to deal with a monocular stimulus that is surrounded by a binocular stimulus. This point of view is also useful in helping us understand why manipulation of the property of the monocular stimulus (stimulus width) in the supplementary experiment did not have an effect on the direction and the depth data, whereas, manipulation of the property of the binocular stimulus did have an effect.

Aside from providing further evidence of this "capture" phenomenon, results of the present study provide some insights into the mechanisms involved. One interesting result is that the binocular stimulus does not affect the perceived visual direction of the two bars in the same way as it affects the magnitude of their perceived depth. Experiment 1 showed that the extent of misalignment of the monocular stimuli using binocular stimuli with 100% dot density was comparable to that obtained using a sparse dot density (0.03% or 0.125%). On the other hand, the magnitude of perceived depth of the monocular stimuli obtained using binocular stimuli with 100% dot density was comparable to that obtained using the middle range of dot densities (5%, 10%, 50%, or 75%), rather than that with the sparse densities. Furthermore, Experiment 2 showed that the extent of misalignment of the monocular stimuli depended on the width of the binocular stimuli. In contrast, the magnitude of perceived depth did not. The differential results for the direction and the depth data suggest that the visual direction and the perceived depth of the monocular stimuli are processed differently. This idea was also suggested before (Shimono & Wade, 2002).

The results of the partial correlation analyses provide further insights as to the process(es) involved in mediating visual direction and perceived depth of the monocular stimuli. With respect to perceived depth, the results of the analyses for all three experiments were the same, showing a significant partial correlation between binocular disparity and perceived depth. This indicates that binocular disparity had a direct influence on the perceived depth of the monocular stimuli. With respect to visual direction, while Experiment 1 showed a significant partial correlation between visual direction and *perceived depth*, Experiment 2 and the supplementary experiment showed a significant partial correlation between visual direction and *binocular disparity*. These apparently inconsistent results between Experiment 1 and Experiment 2 for visual direction can be understood if it is assumed that the stimulus property of the surrounding binocular area helps control whether it is the perceptual variable (perceived depth) or the physical variable (disparity of the binocular areas) that determines relative visual direction directly. We manipulated the dot density of the binocular areas in Experiment 1 and, for a fixed binocular disparity, the perceived depth of the monocular stimuli depended on the dot density. However, manipulation of the width of the binocular areas in Experiment 2 did not have an effect on the perceived depth of the monocular stimuli. One can view these results as indicating that binocular disparity was "less effective" in determining perceived depth in Experiment 1 than in Experiment 2. In the case where binocular disparity is less effective, it is plausible to assume that the visual system may utilize the perceived depth information but not the disparity information to determine the relative direction of the monocular stimulus. We speculate that manipulations of different features of the binocular stimuli can help influence which of the two variables (perceived depth or binocular disparity) is used to determine the perceived direction of the monocular stimuli.

The present study also shows that besides binocular disparity and perceived depth the width of a binocular stimulus is also a factor that can affect the visual direction of a monocular stimulus (see Experiment 2). A similar finding from a different study was reported by Shimono et al. (1998). They found that the extent of misalignment of a pair of monocular Nonius lines that were adjusted such as to be perceptually aligned decreased as the width of a "dot-free" zone of a random-dot stereogram was increased (see Fig. 5 in Shimono et al., 1998). This result shows that the visual direction of a monocular stimulus depends on the width of the dot-free zone where no "explicit" binocular features exist. Shimono et al.'s (1998) study and the present study indicate that the visual direction of a monocular stimulus depends on the width of the binocular stimulus in which it is embedded irrespective of whether the binocular stimulus is filled inside with dots or not. This can be interpreted to mean that the horizontal separation between the right and left edges of the binocular stimulus is important for the visual system to "complete" the plane where the monocular stimulus is localized. It seems that there might be an optimal horizontal separation of the edges of a binocular stimulus for the monocular stimulus to be regarded as binocular. The result of Experiment 1 in this study and that of Experiment 3 in Shimono et al. (1998) suggest that the optimal separation is approximately 20 min arc.

The result of the present study that the extent of misalignment of two monocular bars covaried with binocular disparity of its surround indicates that the visual direction of the monocular bars does not necessarily follow the rule of visual direction for a monocular stimulus. The rule would have predicted that the extent of misalignment should be zero (e.g., Howard & Rogers, 2002; Ono & Mapp, 1995). Our result is consistent with recent findings for the condition in which the monocular stimulus is partially occluded by a binocular stimulus (Erkelens et al., 1996; Ono et al., 2002; van Ee et al., 1999) and when the monocular stimulus is embedded in a binocular stimulus that is either stationary (Shimono et al., 1998; Shimono & Wade, 2002) or moving in depth (Erkelens & van Ee, 1997a, 1997b). These studies suggest that the monocular rule of visual direction does not hold under some conditions and, therefore, should be revised.

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