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The effect of binocular eye position on stereopsis with double images[1]

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Abstract: We examined the hypothesis (Kaufman, 1976) that perceived relative depth between a stereoscopically fused stimulus and two nonfused stimuli (or double images) is due to vergence-induced disparity (or disparity between the fixation plane and the fused stimulus). Twenty-four observers reported their perceived depth between fused and non-fused stimuli with seven different vergence-induced disparities, the sizes of which were controlled using Nonius alignment. We found that the magnitude of perceived depth covaried with the vergence-induced disparity size and that it also depended on the binocular disparity size of the stereoscopic stimuli. This finding suggests that both vergence-induced disparity and binocular disparity can be depth cues in stereopsis with double images.

Key words: double images, vergence-induced disparity, stereopsis, perceived depth, binocular disparity.

The effect of binocular eye position on stereopsis with double images

Binocular stereopsis is a sensation of relative depth between stereoscopic stimuli having binocular disparity. For example, when an observer views a stereogram consisting of upper and lower bars as seen in Figure 1a and the binocular disparity between the upper bar pair and lower bar pair is relatively small, two bars of each bar pair might fuse. Furthermore, between the two (upper and lower) fused bars there might be relative depth and the magnitude of this might covary with the binocular disparity between the two bar pairs (e.g., Ogle, 1952; Richards, 1971). However, when the binocular disparity between two bar pairs is relatively large, one of the two bar pairs might fuse but the other bar pair might not, and there might be relative depth between the fused and nonfused bars (double images). In this stereopsis with double images, the magnitude of the perceived depth does not necessarily covary with the binocular disparity between the two bar pairs, while the direction of the perceived depth might correspond with the sign of a given binocular disparity (crossed or uncrossed; e.g., Ogle, 1952;

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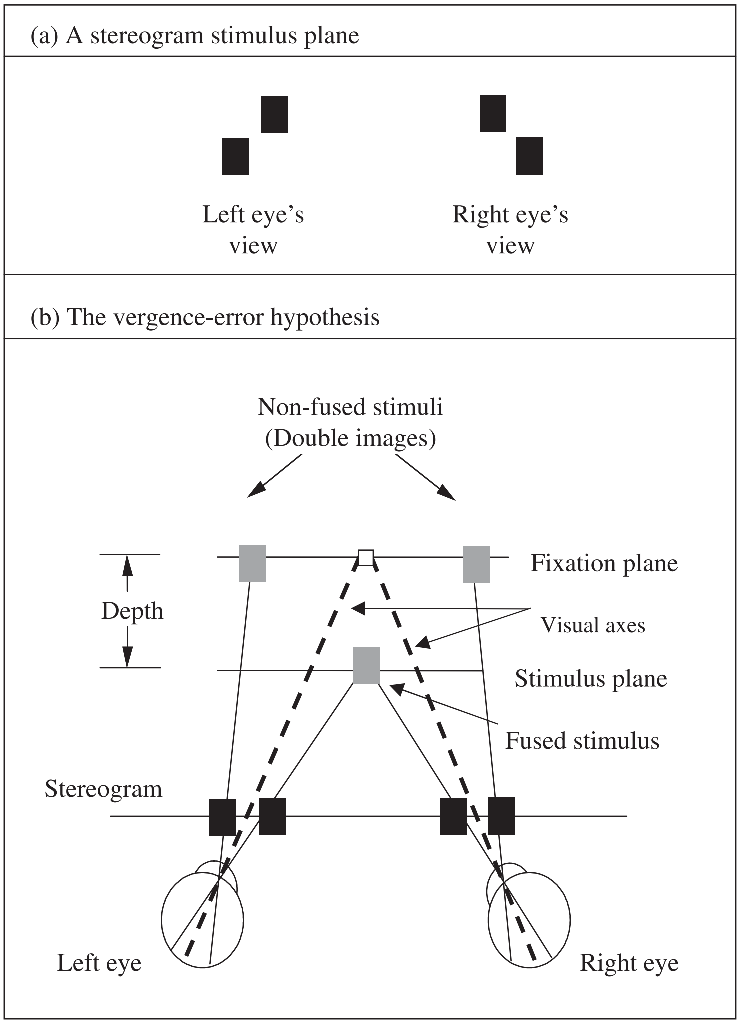

Figure 1. (a) An illustration of a stereogram and (b) an explanation of how depth is perceived on the basis of the vergence-error hypothesis. Please refer to the main text for details.

Richards, 1971; Westheimer & Tanzman, 1956). It has usually been believed that the perceived depth between the stereoscopic stimuli is due to binocular disparity, irrespective of its size (e.g., Bishop & Henry, 1971; Dodwell, 1970; Foley, Applebaum, & Richards, 1975; Ogle, 1952; Richards, 1971).

However, stereopsis with double images can also be explained using the hypothesis that was provided by Kaufman (1976). The hypothesis asserts that the perceived depth between the fused and nonfused stimuli is a result of misconvergence. According to the hypothesis, when an observer views a stereoscopic stimulus as shown in Figure 1a, (1) one of the two bars on one retina fuses with one of the two bars on the other retina and the fused bar is located in the stimulus plane, (2) the other bar on one eye does not fuse with its remaining one on the other retina because of large binocular disparity and the nonfused bars (double images) are located on the fixation plane, (3) there is misconvergence of the fused bar, and (4) the fused bar appears in depth relative to the fixation plane (see Figure 1b). Thus, the perceived depth between the fused bar and the nonfused bar would be determined by the disparity between the stimulus plane and the fixation plane (or vergence-induced disparity).[3] If this was the case, stereopsis with double images could be due to the vergence-induced disparity, but not to binocular disparity.

Recently, it was found that the vergence-induced disparity can be a depth cue between a fused stimulus and a monocular stimulus (Howard & Rogers, 1995, pp. 521–523; Shimono, Tam, & Nakamizo, 1999). Shimono et al. (1999) examined the vergence-error hypothesis (Kaufman, 1976) on the perceived depth in the Wheatstone–Panum limiting-case stereogram, which consisted of two stimuli in one half-field and one stimulus in the other half-field. When one of the two stimuli in one half-field fuses with the single stimulus in the other, an observer can perceive depth between the fused stimulus and the remaining monocular stimulus. Shimono et al. (1999) found that the perceived depth covaried with the vergence-induced disparity. This finding suggests that if each of stereoscopic double images is effectively "monocular," stereopsis with double images can be due to the vergence-error, but not to the binocular disparity. However, it has not been examined yet whether or not the vergence-error can play a role in binocular stereopsis with double images, although researchers seem to have believed its effect (e.g., Foley et al., 1975; Richards, 1971). If we can control the size of the vergence-induced disparity, the magnitude of perceived depth in stereopsis with double images would covary with it.

In the present study, we examined the vergence-error hypothesis using a Nonius method that is often used to control binocular eye positions (e.g., Jaschinski, Bröde, & Griefahn, 1999; Ogle, Martens, & Dyer, 1967; Shimono, Ono, Saida, & Mapp, 1998; Shimono et al., 1999). Stimuli used for the Nonius method usually consist of a pair of nonfusible monocular lines, often called Nonius lines. In this method, it is assumed that when the Nonius lines are aligned, the binocular eye position is at the desired position.

[3] Note that the vergence-induced disparity is defined with respect to a fused stimulus, but not with respect to nonfused stimuli, and that when the fixation plane is in front of (behind) the stimulus plane, the sign of the vergence-induced disparity is uncrossed (crossed). Furthermore, note that the fused stimulus is not necessarily to be fixated in defining the vergence-induced disparity.

Methods

Stimuli and apparatus

The stimuli were generated using an NEC PC-9801 computer, and were displayed on an NEC color monitor (PC-KD853). The stimuli were stereograms consisting of bars, one above another, as shown in Figure 1a. The height of the bars was an 18.2-min arc and the width of the bars was an 26.0-min arc, and the vertical separation between the upper and lower bars was an 26.0-min arc. There was binocular disparity between the upper bar pair and the lower bar pair. The center of the monitor was at eye level, and the viewing distance was 100 cm. Polarized filters made the left half of the screen visible only to the right eye and the right half-field visible only to the left eye. The convergence distance was approximately 40 cm, with a –1.5-D lens placed in front of each eye to match accommodation to the convergence distance. In addition, a variable diopter prism was positioned in front of the right eye, allowing image location to be adjusted on the retina.

The stimuli consisted of 112 test stereograms and 14 reference stereograms. Fifty-six test stereograms had 0.5°, 1.0°, 2.0°, and 3.0° arc crossed disparities with respect to the upper or lower bar pair, and the other 56 had 0.5°, 1.0°, 2.0°, and 3.0° arc uncrossed disparities with respect to the upper or lower bar pair. The test stereograms also had vergence-induced disparities, 2.6-, 7.8-, and 13.0-min arc crossed, zero, and 2.6-, 7.8-, and 13.0-min arc uncrossed. The reference stereograms had relatively small binocular disparities, 5.2-, 10.4-, and 20.8-min arc crossed, zero, and 5.2-, 10.4-, and 20.8-min arc uncrossed.

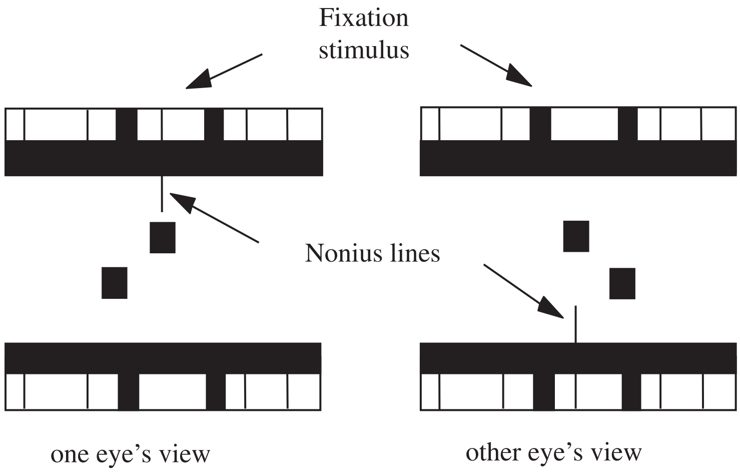

Figure 2. Example of a stereogram used (not drawn to scale).

Aside from the bars of interest, both half-fields of each test and reference stereogram were bounded on the top and bottom by a band-like pattern as shown in Figure 2. We assumed that the bands facilitated binocular fusion and helped "lock" convergence, as in Ono, Shimono, and Shibuta (1992) and Shimono et al. (1999). A Nonius line (3.9×53.3-min arc) was placed at the center of the top band in one half-field, and at the center of the bottom band in the other half-field. The vertical separation between the upper and lower Nonius lines was a 52.8-min arc.[4]

Procedure

Observers were asked on each trial: (a) to report whether or not the upper and lower bars appeared in the same fronto-parallel plane and, if they were not, which bar appeared closer; and (b) to report the magnitude of depth between the upper and lower bars in millimeters or in centimeters. Observers were also asked to align the Nonius lines at each trial. For each trial, the stereograms were presented for as long as the observers needed to align the Nonius lines and respond with confidence. If the observers had difficulty in adjusting their convergence to make the Nonius lines collinear, the variable diopter prism in front of the right eye was adjusted until the lines appeared collinear.

The observers were given two or three blocks of trials as practice. Each block consisted of 14 reference stereograms presented in a random order. During practice, the observers were given feedback as to the correct direction of depth. The observers who responded correctly for all 14 stereograms in the last block of trials were allowed to proceed in the study.

The experiment consisted of two sessions: one session with 14 reference stereograms and the other session with 56 test stereograms with crossed (or uncrossed) disparities. The presentation order of the reference and test sessions was pseudo-randomized. Within each session, the stereograms were presented in a random order, with one repetition of each stereogram. During the experimental session, feedback as to the correct direction of depth was not given to the observers. The observers took a rest three times during the experiment: the first between the reference session and the test session, the second after the first 20 trials in the test session, and the third after the next 20 trials in the test session.

[4] According to McKee and Levi (1987), the precision of Nonius alignment is relatively constant (approximately a 40-s arc) until vertical separation between Nonius stimuli is beyond 1.0°. Thus, it is reasonable to assume that the precision of Nonius alignment used in the present experiment is good enough to monitor the binocular eye position.

Observers

Twenty-eight university students who reported having normal or corrected-to-normal visual acuity participated. After screening for correct responses as to the direction of depth in the reference stereograms, 24 students (8 female and 16 male, ranging in age from 18 to 23 years) were allowed to continue in this experiment. Nine observers participated in the section for crossed disparities, another nine observers participated in the section for uncrossed disparities, and the remaining six observers participated in the two sessions. Thus, 15 observers participated in each session.

Ancillary measure

One ancillary measure was made to confirm that the observers reported the perceived depth between the fused and nonfused stimuli. In the trial of the test stereogram, the observers were asked to report whether they saw one or two bars for each of the upper and lower bars, before reporting the magnitude of perceived depth. When the observers reported "two bars" (double images), it was assumed that the bars did not fuse.

Our analysis of the ancillary measure showed that the observer reported the single upper (lower) and the two lower (upper) bars in most of the trials for the test stereogram, except for those for the test stereogram with 0.5° arc disparity. The percentage of the trials at which observers reported the double images was 40%, 92.9%, 99.5%, and 100% for 0.5°, 1.0°, 2.0°, and 3.0° arc crossed disparities, respectively, and 17%, 92.3%, 99.1%, and 100% for 0.5°, 1.0°, 2.0°, and 3.0° arc uncrossed disparities, respectively. In almost all trials except for those for 0.5° arc crossed and uncrossed disparity conditions, double images had occurred. Thus, we proceeded with further analysis except for the 0.5° arc disparity condition.

Data analysis

The estimates of perceived depth obtained with the reference stereograms were used to normalize the estimates of perceived depth obtained with the test stereograms; a preliminary study showed that there can be large individual differences in estimates of depth based on the test stereograms. Details of the normalization were similar to those used in Shimono et al. (1999). The reported depth values obtained with the test stereograms were assigned a positive or negative sign, depending on whether the nonfused bar was perceived to be behind or in front of the fused bar, respectively. Then the signed values were divided by the reported depth values obtained with the reference stereograms. Specifically, positively signed values were divided by the reported depth values for reference stereograms with uncrossed disparities, and negatively signed values were divided by the reported depth values for reference stereograms with crossed disparities. (Usually, observers saw one fused and two nonfused bars in a trial for a test stereogram. When each of the two nonfused bars appeared at different depth planes, their depth values were averaged.)

Results

The basic unit for analysis was the average between the normalized depth between the upper fused bar and the lower nonfused bars and that between the lower fused bar and the upper nonfused bars, for each experimental condition and observer. In calculating the normalized depth values, the reported depth value obtained for a given test stereogram was divided by the reported depth value obtained with the reference stereogram with a 5.2-min arc crossed or uncrossed disparity.

We carried out two-way repeated measures ANOVA (7 vergence-induced disparities × 3 binocular disparity sizes) on the depth values separately for crossed and uncrossed disparity conditions. For the crossed disparity condition, the main effect of vergence-induced disparity was significant, $F(6,28) = 16.52$, $p < 0.001$, the main effect of binocular disparity size was marginally significant, $F(2,14) = 3.20$, $0.05 < p < 0.06$, and no interaction was significant, $F(12,168) = 1.32$, $p > 0.10$. For the uncrossed disparity condition, the main effects of vergence-induced disparity and of binocular disparity size were statistically significant, $F(6,28) = 12.07$, $p < 0.001$ and $F(2,14) = 3.85$, $p < 0.05$, respectively. Furthermore, the

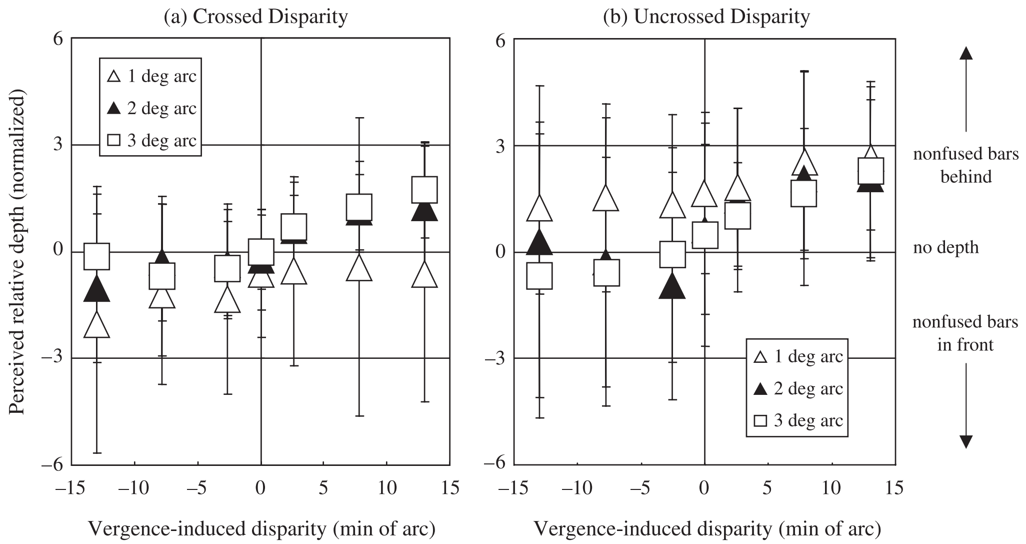

Figure 3. Normalized depth value as a function of the vergence-induced disparity between the fused and nonfused bars with binocular disparity as the parameter. Separate panels show (a) the perceived depth for the crossed disparity and (b) that for the uncrossed disparity. Each symbol represents the mean of 15 observers. The vertical lines attached to the data points indicate the *SD*. We assigned a negative sign and a positive sign to uncrossed vergence-induced disparity and crossed vergence-induced disparity, respectively.

interaction of these main effects was statistically significant, $F(12,168) = 2.27$, $p < 0.05$.

The significant main effect of vergence-induced disparity can be seen in Figure 3, which shows the mean normalized values over 15 observers as a function of the vergence-induced disparity, with binocular disparity as the parameter. The left and right panels show the results for the crossed and uncrossed disparity conditions, respectively. As shown in each panel, the mean normalized depth values covaried with the vergence-induced disparity as a whole. The obtained covariation is consistent with the prediction based on the vergence-error hypothesis (Kaufman, 1976; Shimono, Nakamizo, & Higashiyama, 2000). The present result is also compatible with the results of Shimono et al. (1999), that the vergence-induced disparity can provide the depth-order and depth-magnitude information.

The main effect of binocular disparity size in the uncrossed disparity condition can be seen in the right panel in Figure 3. The nonfused bars with the small disparity (1.0° arc) appeared further than those with the middle disparity (2.0° arc) or large disparity (3.0° arc) at each vergence-induced disparity condition. The marginal main effect of binocular disparity size in the crossed disparity condition can also be seen in the left panel in Figure 3. The nonfused bars with the small disparity appeared closer than those with the middle disparity or large disparity at each vergence-induced disparity condition.

The significant interaction between the binocular disparity size and the vergence-induced disparity in the uncrossed disparity condition can be seen in the right panel in Figure 3. The difference in the mean depth value among the three binocular disparity sizes in the uncrossed vergence-induced disparity condition was larger than that in the crossed vergence-induced disparity condition. We do not have a definitive answer as to why the significant interaction between the binocular disparity size and the vergence-induced disparity emerged in the uncrossed disparity condition, but not in the crossed disparity condition. The result, however, is consistent with an idea that there are separate mechanisms in the processing of crossed and uncrossed disparities (e.g., Patterson, Cayko, Short, Flanagan, Moe, & Taylor, 1995; Richards, 1971; Shimono, 1984).

To examine the effect of the vergence-induced disparity further, we compared the slopes of the regression lines for the normalized depth values in the test stereogram with those in the reference stereogram. We assumed that the effect of the vergence-induced disparity and that of the (small) binocular disparity can be reflected by the slopes of the regression lines (Shimono et al., 1999). The comparison of the slopes showed that the vergence-induced disparity is not a "strong" depth cue relative to binocular disparity, as found in Shimono et al. (1999). The slopes of the regression lines calculated for the data shown in Figure 3 were –0.056, –0.091, and –0.090, for the small, middle, and large crossed-disparity conditions, respectively, and –0.058, –0.101, and –0.123, for the small, middle, and large uncrossed-disparity conditions, respectively. For the crossed-disparity condition, the mean value (–0.079) of the three slopes was much smaller than that (–0.197) calculated for the reference stereogram.[5] For the uncrossed disparity condition, the mean value (–0.094) of the three slopes was much smaller than that (–0.171) calculated for the reference stereogram. The smaller values of the slopes of the test stereograms suggest that the vergence-induced disparity is a weaker cue than small binocular disparity (Shimono et al., 1999).

As discussed above, the slope of the test stereogram with the middle or large disparity size is larger than that with the small disparity size. This suggests that the effect of the vergence-induced disparity on the perceived depth increases as the binocular disparity size increases. This result is also compatible with that of Shimono et al. (1999). They found that the magnitude of the perceived depth between the fused and monocular stimuli increased when the monocular stimulus was presented at a more peripheral retinal location. Similarly, in this experiment, each one of the two nonfused bars, which may have been effectively monocular, was presented at a more peripheral retinal location as the binocular disparity increased.

Discussion

The results of the present study show that the magnitude of the perceived depth between the fused and the nonfused stimuli (double images) can covary with the vergence-induced disparity. The results are consistent with the prediction from the vergence-error hypothesis (Kaufman, 1976; Shimono et al., 2000) and suggest that the vergence-induced disparity is one of depth cues in stereopsis with double images. However, the results also show that the binocular disparity has an effect on the perceived depth, supporting the well-established idea that stereopsis with double images is due to binocular disparity (Biship & Henry, 1971; Dodwell, 1970; Foley et al., 1975; Ogle, 1952; Richards, 1971; Ziegler & Hess, 1997). These results suggest that it is difficult to explain the present results using only the vergence-error hypothesis. It might be that both the vergence-induced disparity and the binocular disparity are depth cues in stereopsis with double images.

Furthermore, the present results show that the effect of the vergence-induced disparity cue increases as the binocular disparity size increases. The results are consistent with the idea that "stereopsis may depend on a process in which the outputs from many disparity detectors are pooled, with perceived depth depending on the relative activity in a small number of such pools" (Foley et al., 1975, p. 417). If the activity of the pools decreases as binocular disparity size increases in stereopsis with double images, the effect of binocular disparity on the perceived depth might decrease. Thus, the vergence-induced disparity can have an effect on perceived depth more effectively for larger disparity, if the vergence-induced disparity and binocular disparity are depth cues.

The present result that the vergence-induced disparity can be a depth cue suggests that a caveat is necessary when researchers measure

[5] In calculating the slope for the reference stereogram, we normalized the reported values with the value obtained for the smallest disparity (5.2-min arc), taking into account the sign of disparity (crossed or uncrossed) for each observer. We computed the slopes of the regression lines using data from the four disparity conditions (three crossed and zero, or three uncrossed and zero).

the magnitude of perceived depth between fused and nonfused stimuli. Recently, it is found that the perceived depth between the fused and nonfused stimuli can vary qualitatively (e.g., Forte, Peirce, & Lennie, 2002; Gillam & Nakayama, 1999). In Gillam and Nakayama (1999) and Forte et al. (2002), however, the binocular eye position did not control well and thus, it is possible to argue that their results were due to the vergence-induced disparity. To avoid such argument, researchers should take into account the effect of the vergence-induced disparity and pay attention to controlling the binocular eye position in measuring the depth between fused and nonfused stimuli (see Krol & van de Grind, 1983, 1986; Shimono et al., 1999; for similar discussions).

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