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Influence of Exclusive Binocular Rivalry on Perceived Depth in the 'Sieve Effect'

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An impression of a surface seen through holes is created when one fuses dichoptic pairs of discs with one member of each pair black and the other white. This is referred to as the 'sieve effect'. This stimulus contains no positional disparities. The impression of depth in the sieve effect is most evident when the size, contrast, and rim thickness of rivalrous patterns are such as to produce exclusive rivalry. I investigated how long it took for the sieve effect to recover from exclusive rivalry suppression. The magnitude of perceived depth in the effect was measured after exclusive rivalry suppression of one half-image of the sieve-effect stimulus. The results showed that the sieve effect takes approximately 630 ms to recover from exclusive rivalry suppression, compared with 200 ms for disparity-based stereopsis. Considered together with the previous report [Matsumiya and Howard: Invest. Ophthalmol. Visual Sci. **42** (2001) S403] that the sieve effect is positively correlated with the rate of exclusive rivalry, these findings suggest that the effect and exclusive rivalry are processed in the identical channel.

Key words: binocular vision, stereopsis, binocular rivalry, depth perception, the sieve effect

1. Introduction

It has been proposed that stereopsis and binocular rivalry are distinct processes in parallel channels.[1–3] This is referred to as the two-channel theory.[3] According to this theory, stereopsis and rivalry can coexist in the same location of the visual field. Some studies, using a stereogram in which binocular disparity generated a form in depth, showed that depth is perceived even when the stereogram is superimposed on a background of rivalrous stimuli.[4–8] These studies support the two-channel theory. In contrast, other studies have presented evidence that rivalry depends on depth perception from image features unmatched between the left and right eyes in the absence of spatial disparity, which is inconsistent with the two-channel theory.[9,10] For example, Shimojo and Nakayama[9] showed that opto-geometrically valid unmatched features create impressions of depth and escape binocular rivalry, whereas invalid unpaired features create few impressions of depth and generate binocular rivalry. Thus, *disparity-based* stereopsis and binocular rivalry seem to be processed in parallel channels. Also, it has been suggested that the channel mediating rivalry interacts with that mediating disparity-based stereopsis.[2,11] The threshold of stereoacuity from disparity rises after rivalry suppression only for a short period of 150 – 200 ms, suggesting that disparity-based stereopsis rapidly recovers from rivalry suppression.[11]

On the other hand, Howard[12] reported a novel stereoscopic effect which is directly related to binocular rivalry without spatial disparity. The effect seems to be inconsistent with the two-channel theory. When one fuses dichoptic pairs of discs with one member of each pair black and the other white as shown in Fig. 1(a), the impression of a black-and-white dotted surface seen through holes in a near surface is created. The impression of depth is created between the black-and-white dotted surface and the near surface; this is referred to as the sieve effect. Figure 2 illustrates the surface layout simulated by the stereogram shown in Fig. 1(a). In the latter, there are no spatial disparities of luminance edges

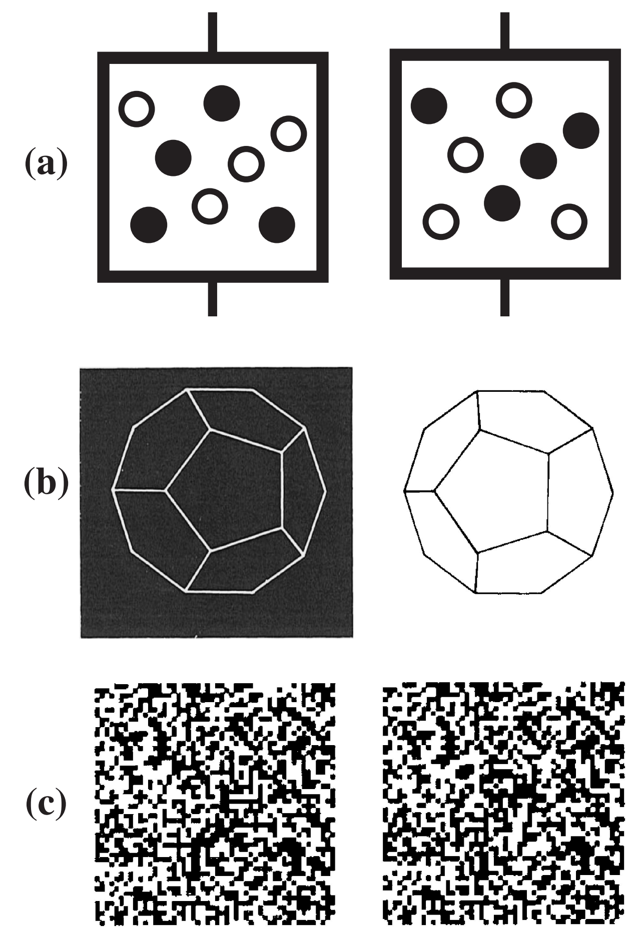

Fig. 1. Three stereograms. (a) The sieve effect. (b) Stereogram with opposite luminance polarity. (c) Rivaldepth.

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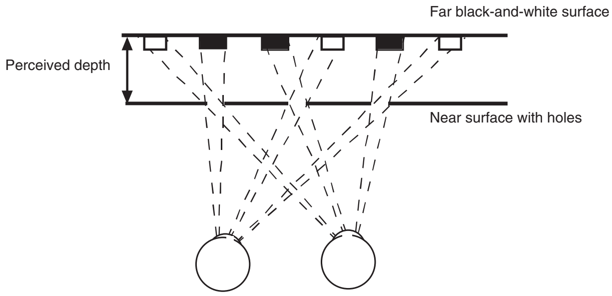

Fig. 2. A far black-and-white surface seen through holes in a near surface.

and no monocular cues to depth. The only disparity is one that the visual system may infer from the rivalrous contents of the discs. That is, luminance rivalry is serving as a cue to depth. The sieve effect is not related to depth produced by disparity between thin lines with opposite luminance polarity as shown in Fig. 1(b)[13] because opposite-polarity lines have a disparity between edges with the same sign of contrast. Nor is the sieve effect related to depth created by binocular combination of random-dot displays that are uncorrelated between the two eyes, as shown in Fig. 1(c)—an effect known as rivaldepth.[14] This is because misconvergence induces positional disparity into the non-rivalrous region in the central square on the O'Shea and Blake stereogram [Fig. 1(c)].[14]

Howard[12] noted that the impression of depth in the sieve effect is most evident when the size, contrast, and rim thickness of rivalrous patterns are such as to produce exclusive rivalry. In exclusive rivalry, the whole of a stimulus in one eye alternates with the whole of a stimulus in the other eye.[15] Matsumiya and Howard[16] also found that the magnitude of perceived depth in the sieve effect is at a maximum when the rate of exclusive rivalry is highest. These findings suggest that the sieve effect and exclusive rivalry may be processed in the same channel. Thus, the two-channel theory may be valid for disparity-based stereopsis but not for the sieve effect.

If the sieve effect and exclusive rivalry were processed in the same channel, one would predict that it takes a longer time for the sieve effect to recover from exclusive rivalry suppression, compared with the time (200 ms) it takes for disparity-based stereopsis to recover from rivalry suppression.[11] I designed the following experiment to ascertain how long after exclusive rivalry suppression the magnitude of perceived depth in the sieve effect is reduced. In this experiment, effects of rivalry suppression per se were distinguished from masking effects associated with the rivalry-inducing target.

2. Experiment

2.1 Methods

Visual stimuli were presented on a CRT monitor with a refresh rate of 75 Hz controlled by an Apple iBook computer. A half image of a stereo target to the left eye was presented on the left side of the display and the other half image of the stereo target was presented on the right side of the display. The subject viewed the display (17×26 deg) from 63 cm through mirrors. The display created a stereoscopic surface in the frontal plane of the subject when fused by the mirrors. The room lights were extinguished and all surfaces surrounding the display were covered by black cloth or black paper. The subject's head was fixed with a chin rest.

To produce the sieve effect, the binocularly combined stimulus consisted of an array of rivalrous black and white squares on a random-dot texture, as shown in Fig. 3(a). In the basic stimulus, each square had a black rim 3 arcmin thick that was visible only around the white squares. The size of the squares was 12 arcmin in width and height. The white squares had a luminance of 7.0 cd/m^2. The random-dot texture subtended 6 deg in width and 6 deg in height and was correlated in the two eyes. Nonius lines (3 arcmin wide and 22 arcmin long) were presented in the center of the display to avoid possible artifacts related to misconvergence. Figure 3(b) illustrates the perceived surface layout in the sieve-effect stereogram.

I employed two test conditions and one control condition. I refer to the first test condition as the rivalry condition. To produce rivalry suppression, an oblique sinusoidal grating was presented to the right eye. The spatial frequency of the grating was 2.0 cpd, and the mean luminance was 3.5 cd/m^2. Figure 4(a) shows the sequence for the rivalry condition. The subject fixated the nonius lines in the center of the display and pressed a button to start a trial. Just after the button was depressed, the right half image of the random-dot display was replaced by the oblique grating, and the left half image was replaced by a half image of the sieve-effect stimulus. The subject pressed a button when perceiving the exclusive dominance of the grating. Five hundred seven msec after the button was depressed, the grating was replaced by the other half image of the sieve-effect stimulus. The eight small rivalrous squares producing the sieve effect were presented for the duration selected randomly from 40, 93, 253, and 627 msec. Three hundred seven msec after the disappearance of the rivalrous squares, probe stimuli consisting of random-dots were presented in some regions of the random-dot background. The subject's task was to adjust the horizontal disparity of the probe stimuli using a track-ball until these stimuli appeared at the same depth as the surface perceived through the rivalrous squares.

I refer to the second test condition as the masking condition. Figure 4(b) shows the sequence of stimulus presentations in this condition. This stimulus sequence was similar to the rivalry condition except for the following. In the masking condition, the binocular random-dot display was replaced by the binocular oblique grating after the button was depressed. The binocular grating remained present until the subject pressed a button, after which, the eight small rivalrous squares producing the sieve effect were briefly presented for the duration selected randomly from 40 to 627 ms.

In the control condition, 507 ms after the subject pressed a button to start a trial, the eight small rivalrous squares

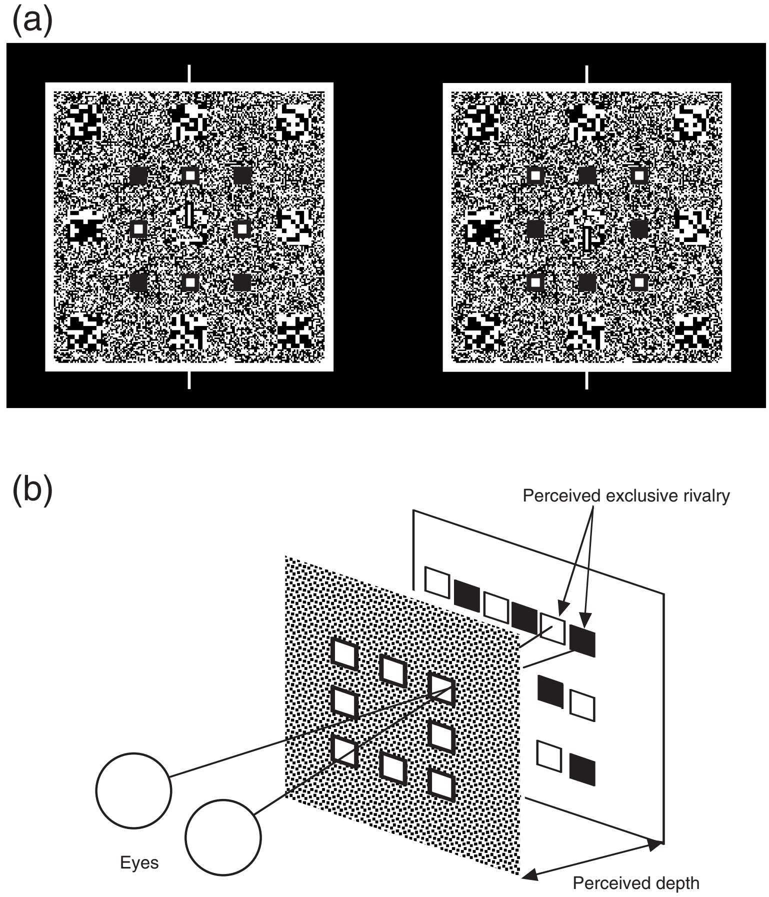

Fig. 3. Visual Stimuli. (a) Arrangement of visual stimuli to produce the sieve effect. (b) Illustration of the perceived surface layout generated by the sieve-effect stereogram.

producing the sieve effect were briefly presented for the duration selected randomly from 40 to 627 ms [Fig. 4(c)].

Twelve stimulus conditions [4 (durations for the rivalrous squares) $\times$ 3 (display conditions)] were presented in random order, and each duration was repeated four times in random order in a session. Subjects performed two sessions for a total of eight trials in each condition.

Two females and one male served as subjects. Their ages ranged from 26 to 32 years, and they had corrected-to-normal vision. Subjects YN and HI were experienced in other psychophysical experiments, but were naive with respect to the purpose of this study. Subject KM was the author.

2.2 Results

Figure 5 shows the mean depth settings for each of the three subjects as a function of duration. The fourth graph is the mean data of all three subjects. The solid, open, and cross symbols represent the rivalry, masking, and control conditions, respectively. Perceived depth was attenuated for about 90–630 ms in the rivalry condition, compared with the masking and control conditions. An analysis of variance (ANOVA) was performed on the group mean data using three display conditions (rivalry, masking, and control) and four duration levels (40, 93, 253, and 627 ms) for each display condition. This revealed the significant effect of display condition [$F(2,24) = 5.213$, $p < 0.05$] and of duration level [$F(3,24) = 80.472$, $p < 0.0001$]. Separate analyses were performed to reveal differences in disparity settings of the probe (disparities matched with the sieve-effect depth) between each pair of display conditions. Disparity settings of the probe for the rivalry condition were significantly different from those for the control condition [$F(1,16) = 8.015$, $p < 0.05$]. There was a significant effect of duration level in the pair of the rivalry and control conditions [$F(3,16) = 36.425$, $p < 0.0001$]. Disparity settings for the masking condition were not significantly different from those for the control condition [$F(1,16) = 0.00675$, $p = 0.938$ ns]. There was a significant effect of duration level in the pair of the masking and control conditions [$F(3,16) = 104.572$, $p < 0.0001$], but there was no significant interaction between display condition and duration level [$F(3,16) = 0.552$, $p = 0.657$ ns]. These results suggest that the magnitude of the sieve-effect depth is reduced after rivalry suppression for a period of more than 200 ms.

An additional experiment was conducted to examine how the magnitude of the sieve-effect depth is affected by rivalry suppression for the longer duration of the sieve effect stimulus. The procedure for this experiment was identical to

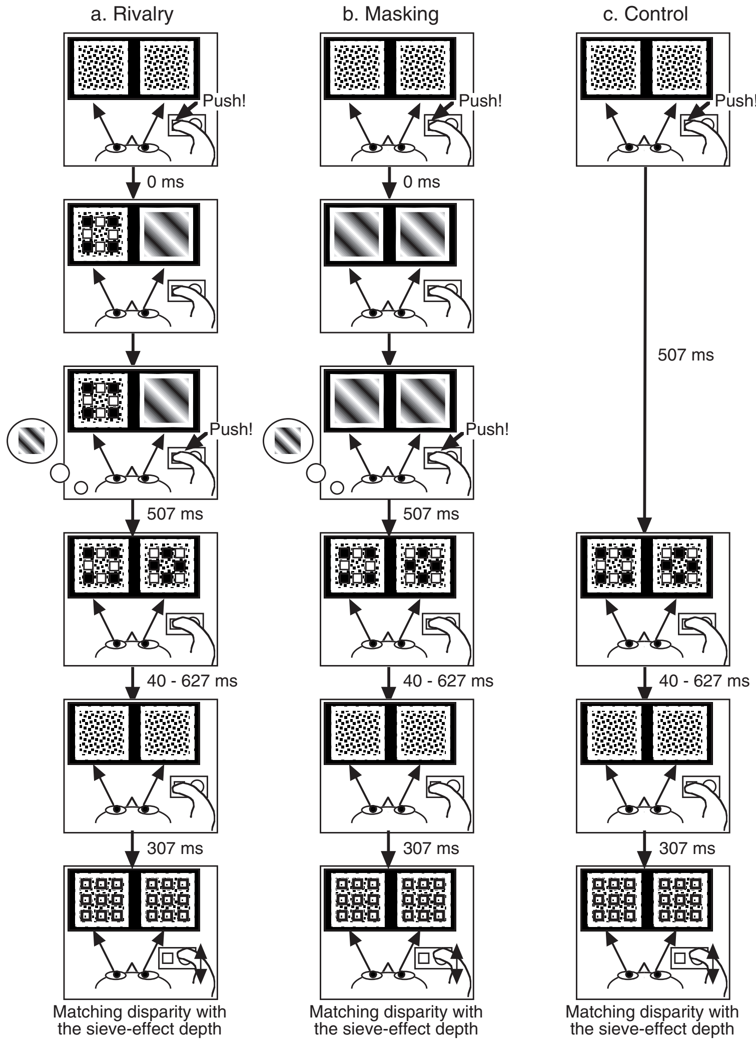

Fig. 4. Stimulus sequence in experiment. (a) Rivalry condition. (b) Masking condition. (c) Control condition.

the first experiment, except that the eight small rivalrous squares were presented for the duration selected randomly from 40, 93, 253, 627, 1600, 4000, and 10000 ms. Two subjects, KM and YN, participated in this additional experiment.

Figure 6(a) shows the mean sieve-effect depth for the two subjects as a function of duration. The solid, open, and cross symbols represent the rivalry, masking, and control conditions, respectively. In the masking and control conditions, the magnitude of the sieve-effect depth saturated at the matched disparity of about 15 to 17 arcmin for a period of more than 4000 ms, as shown by the horizontal dashed lines in Fig. 6(a). For subject KM, the magnitude of the sieve-effect depth decreased for about 90–4000 ms in the rivalry condition, compared with the other conditions. For subject YN, the magnitude of the sieve-effect depth decreased for about 250–630 ms in the rivalry condition, compared with the other conditions. Also, for subject KM, the data for matched disparities of about 1–15 arcmin in the rivalry condition tended to be parallel to those in the control condition. As a result, one might consider that this supports the idea that a constant delay is required to switch from the processing of rivalry to that of the sieve-effect depth. However, this trend indicates that the differences in duration between the rivalry and control conditions are not constant over the matched disparities of about 1–15 arcmin because the horizontal axis represents the logarithm of duration in Fig. 6(a). For subject YN, on the other hand, the data for matched disparities of more than 10 arcmin in the rivalry condition did not differ from those in the control conditions, indicating that the differences between these two conditions are at approximately zero arcmin before the magnitude of the sieve-effect depth reaches maximum. Thus, these results cannot be explained by the idea that it takes a constant delay to switch from the processing of rivalry to that of the sieve-effect depth.

Figure 6(b) shows differences in the mean sieve-effect depth relative to the control condition as a function of duration. The solid and open symbols represent the rivalry and masking conditions, respectively. In the rivalry condition, the differences in magnitude of the sieve-effect depth were large for about 200–630 ms, which is highlighted by the gray zone. For subject KM, these differences gradually approached zero arcmin for a period of more than 630 ms,

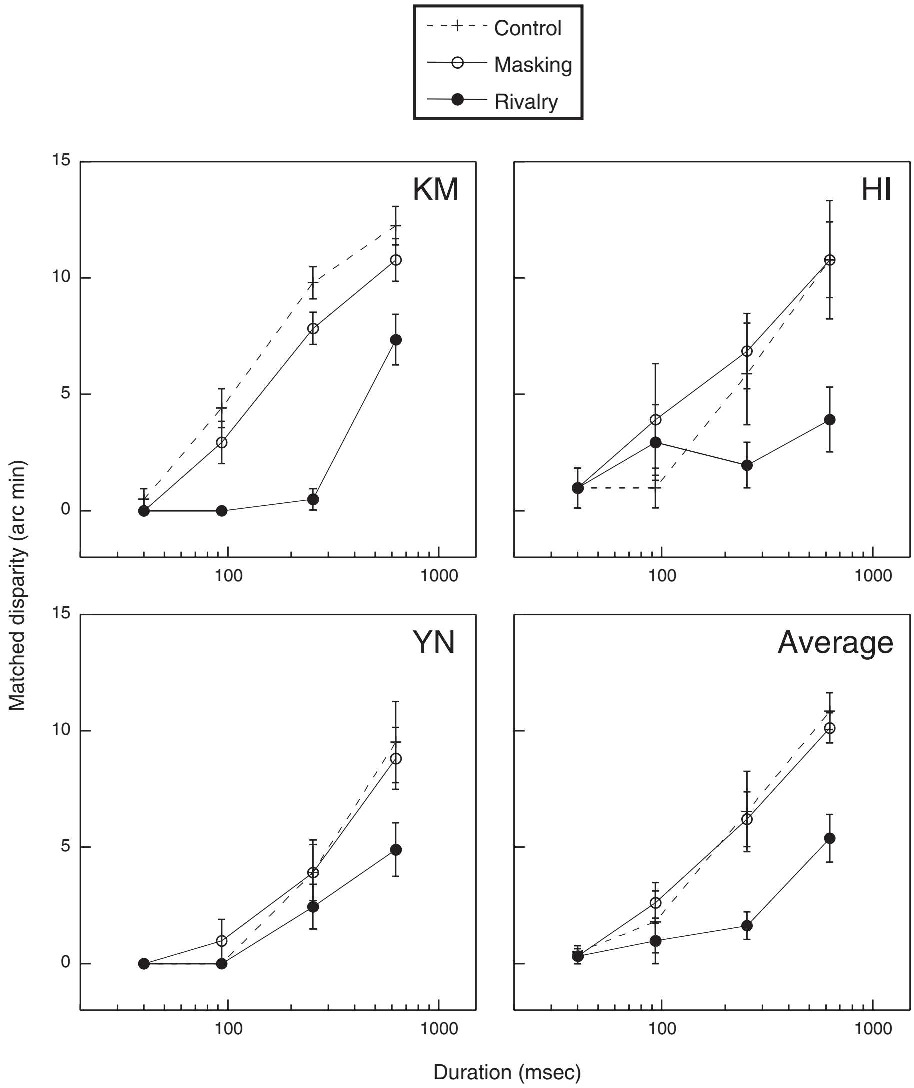

Fig. 5. Perceived depth as a function of the duration for the rivalrous squares to produce the sieve effect for the three subjects and the average of the three subjects. Error bars plot S.E.

and reached zero arcmin at the period of 10000 ms. For subject YN, the differences in the magnitude of the sieve-effect depth tended to disappear for a period of more than 630 ms. In the masking condition, these differences tended to be approximately constant around zero arcmin over the duration period for both subjects. Thus the magnitude of the sieve-effect depth appears to be greatly reduced after rivalry suppression for the period of 200–630 ms.

3. Discussion

The present study investigated the influence of exclusive rivalry suppression on the magnitude of perceived depth in the sieve effect. I found that this magnitude is largely reduced after exclusive rivalry suppression for the period of 200–630 ms. I controlled for the possible impact of simple masking on the magnitude of perceived depth in the sieve effect and demonstrated that the masking had no effect on this magnitude. These findings suggest that it takes time for the sieve effect to recover from rivalry suppression.

According to the two-channel theory of stereopsis and binocular rivalry, stereopsis occurs at the same time and in the same location of the visual field as binocular rivalry. Rivalry and disparity-based stereopsis are seen as distinct processes that occur in separate channels.[1–3] Harrad *et al.*[11] showed that disparity processing was disrupted for 150–200 ms after a period in which one of the images had been suppressed by rivalry. This suggests that, although the channel mediating rivalry interacts with that mediating perceived depth for the short period of time, depth from disparity rapidly recovers from rivalry suppression.

In the sieve effect, depth and rivalry occur at the same time and in the same location as well. In this case, however, the impression of depth is most evident when the stimulus configuration produces exclusive rivalry.[12] The magnitude of perceived depth in the sieve effect is positively correlated with the rate of exclusive rivalry for changes in the contrast, size, and relative sizes of rivalrous regions.[16] Moreover, the present study revealed that it takes a relatively long time

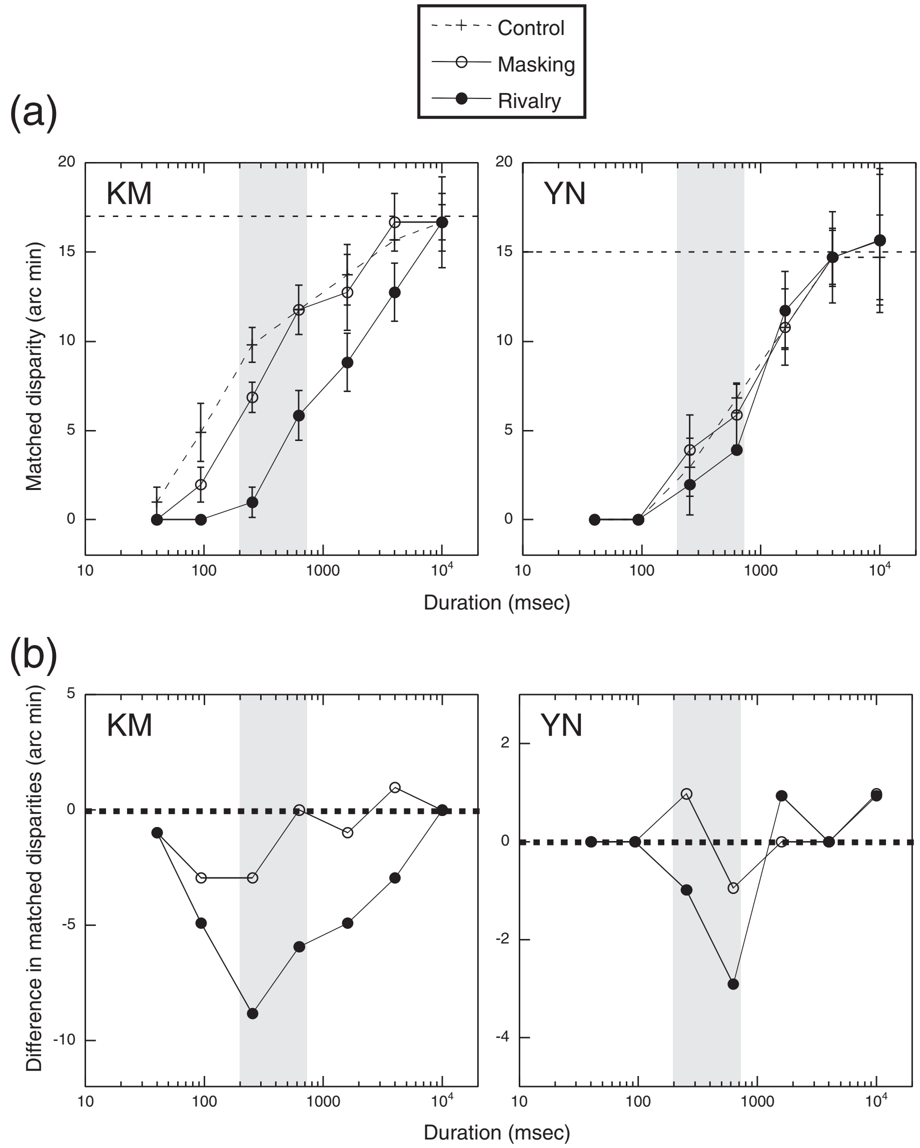

Fig. 6. Results of the additional experiment. (a) Perceived depth in the sieve effect as a function of duration for two subjects. Error bars plot S.E. (b) Differences in the magnitude of perceived depth in the sieve effect relative to the control condition. The solid and open circles represent the rivalry and masking conditions, respectively.

(200–630 ms) for the sieve effect to recover from exclusive rivalry suppression. In the sieve effect, therefore, the channel responsible for processing binocular rivalry also appears to be responsible for generating an impression of depth. This is consistent with the proposition of Hayashi *et al.*[10] that rivalry arises from a stereopsis mechanism for depth from unmatched image features without spatial disparity.

Also, Tsai and Victor[17] found the lower precision of depth judgments in the sieve effect compared with judgments of depth from disparity. The present study shows that it takes considerably longer time for the magnitude of depth judgments in the sieve effect to recover from rivalry suppression compared with judgments of depth from disparity. These findings suggest that, for both the precision and magnitude of depth judgments, the mechanism of the sieve effect is different from that of disparity, implying that the two-channel theory is valid for disparity-based stereopsis but not for the sieve effect.

Alternatively, it is possible that the sieve effect and rivalry are processed in separate channels but the former interacts with rivalry for a long period of time. However, the sieve effect arises under conditions that produce a high rate of exclusive rivalry.[16] Thus, it seems unlikely that the results from the present study can be attributed to the idea that the sieve effect and rivalry are processed in separate channels.

In conclusion, I have demonstrated that the magnitude of perceived depth in the sieve effect is reduced after exclusive rivalry suppression for a significantly longer time than for disparity-based depth, allowing me to conclude that the sieve effect and exclusive rivalry are processed in the same channel, whereas disparity-based stereopsis and rivalry are processed in parallel channels.

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