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Evidence for the correcting-mechanism explanation of Kanizsa amodal shrinkage

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Abstract

An object phenomenally shrinks in its horizontal dimension when illustrated on a 2-D plane as if the central portion of the object is partially occluded by another vertical one in 3-D space (Kanizsa amodal shrinkage). We examined the predictions of the correcting-mechanism hypothesis proposed by Ohtsuka and Ono (2002), which states that an inappropriate operation of the mechanism that corrects a phenomenal increase in monocularly visible areas accompanied by a stereoscopic occluder gives rise to the illusion. In this study we measured the perceived width (or height in Experiment 3) of a square seen behind a rectangle, while controlling other factors which potentially influence the illusion, such as the division of space or depth stratification. The results of five experiments showed that (a) the perceived width was not influenced when the occluder had a relatively large binocular disparity, but was underestimated when the occluder did not have disparity, and that (b) the shrinkage diminished when the foreground rectangle was transparent, was horizontally oriented, or contained no pictorial occlusion cues. These results support the hypothesis that the correcting mechanism, triggered by pictorial occlusion cues, contributes to Kanizsa shrinkage.

Evidence for the correcting-mechanism explanation of Kanizsa amodal shrinkage

1. Introduction

When one opaque object located in three-dimensional (3-D) space partially occludes another one, binocularly unpaired regions inevitably arise in the occluded object along the vertical occluding edges (Figures 1A and 1B). Recent theories of binocular depth perception have emphasized the role of the unpaired regions in producing apparent depth (eg Anderson and Nakayama 1994; Howard and Rogers 2002; Liu et al 1994; Nakayama and Shimojo 1990). Several studies, using various stimulus configurations, have demonstrated that the unpaired regions are effective in producing depth, even when no binocular disparity of the paired features is presented (Gillam and Nakayama 1999; Grove et al 2002; Hakkinen and Nyman 2001; Howard 1995; Pianta and Gillam 2003).

On the other hand, unpaired regions create a serious problem regarding shape perception in 3-D space. Figure 1B shows an occlusion configuration in which the binocularly paired and unpaired regions are formed. The *paired* regions of the occluded square are denoted as *a* and *c* in Figure 1B; the *unpaired* regions are denoted as *b* and *b*' (*b* is seen only by the right eye, while *b'* is seen only by the left eye.) When this stereogram (Figure 1A) is seen fused, one can perceive *both* unpaired regions (*b, b'*) as well as the paired regions (*a, c*) of the occluded square behind the occluding rectangle. This observation was noted by Ohtsuka and Ono (2002) and van Ee and Erkelens (2000). Thus, the binocularly visible (modally perceived) areas of the occluded object in the fused image are the sum of the areas *a, b, b'*, and *c* (Figure 1C). This implies the expansion of the width of the occluded object by the area *b* or *b'* in the cyclopean view, because each monocular image contains the area of only either *b* or *b'*. Despite this implication, however, the perceived width of a partially occluded square is nearly *veridical* in stereoscopic presentation (Ohtsuka and Ono 2002; van Ee and Erkelens, 2000).

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Insert Figure 1 about here

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To solve this discrepancy between the predicted expansion and the veridical perception in the width of a stereoscopically occluded object, Ohtsuka and Ono (2002) proposed the hypothesis that the visual system has a mechanism that corrects the increase of visible areas[1] of the occluded object, by laterally *compressing* the expanded object in the shape dimension (see also Howard and Rogers 2002; Ono et al 2002). According to Ohtsuka and Ono (2002), Kanizsa shrinkage (Kanizsa 1975, 1979; Vezzani 1999), in which a square apparently shrinks when depicted as partially occluded by an opaque rectangle on a two-dimensional (2-D) plane (Figure 1D, left panel), can be explained by the “correcting-mechanism” hypothesis. Since this illusion disappears when the occluder is viewed stereoscopically in front of the occluded object (Figure 1A, Ohtsuka and Ono 2002; van Ee and Erkelens 2000), Ohtsuka and Ono speculated that inappropriate operation of the correcting mechanism, which is triggered by pictorial occlusion cues being included not only in 3-D but also in 2-D images, produces Kanizsa shrinkage.

However, several observations do not support the correcting-mechanism hypothesis. First, this hypothesis predicts that shrinkage disappears with a *horizontally* oriented occluder, because it does not produce monocular areas around its horizontal edges. However, shrinkage also seems to be evident in this case: the occluded square appeared to shrink in its vertical dimension (van Ee and Erkelens 2000)[2]. Second, Kanizsa (1975) found that the illusion does not always require pictorial occlusion cues (ie T-junctions): the shrinkage occurred with a pattern in which the pictorial cues had been eliminated by removing the upper and lower parts of the occluding rectangle. Vezzani (1999), therefore, argued that this illusion is the by-product of some other shrinkage illusion, such as the division of space into several parts (ie the Oppel-Kundt illusion) or empty space.

The observations described above, which seem to contradict the correcting-mechanism hypothesis, lack experimental verification. Despite these reported difficulties with the correcting-mechanism hypothesis, the aim of the present study is to examine whether the correcting mechanism contributes to Kanizsa shrinkage. In this study we focused on isolating the shrinkage produced by the inappropriate operation of the correcting mechanism from shrinkage produced by other factors.

In a series of experiments presented in this study, we tested predictions from the correcting-mechanism hypothesis by measuring the perceived width (or height in Experiment 3) of a square seen behind a rectangle with the use of the method of adjustment. If the hypothesis is true, then the following predictions should be confirmed: Kanizsa shrinkage will disappear or be reduced (a) when the opaque occluder is replaced by an illusory transparent one, in which the binocularly *unpaired* regions are interpreted as belonging to *both* foreground and background surfaces, (b) when the vertical occluder is replaced by a horizontal occluder, whose horizontal contours do not produce unpaired regions, and (c) when pictorial occlusion cues are removed. Experiment 1 examined the perceived width of the occluded square as a function of binocular disparity of the occluder with respect to the occluded square. Experiments 2, 3, and 4 tested the above predictions (a), (b), and (c), respectively. Experiment 5, carried out with a view to complementing the results of Experiment 2, examined the effects of perceived transmittance of the foreground rectangle on the perceived width of a background square.

2. General method

2.1 Participants

Thirty-four graduate and undergraduate students at Kyushu University participated in Experiments 1-5. Eight of the observers were initially assigned to each experiment, with six of observers participating in two of the experiments. All were naive to the purpose of the experiments. Before each experiment, all participants were confirmed as being able to see stereoscopic depth by the anaglyph method.

2.2 Apparatus

All experiments were conducted on an Apple iBook with a 12.1-inch liquid crystal display. Stimulus presentation and data collection were controlled with a program written in C, except for Experiment 2. In Experiment 2, PsyScope software (Cohen et al 1993) was used.

2.3 Stimuli

The stimuli (Figure 1D) were composed of a test stimulus and a matching stimulus which were simultaneously presented on the display (background luminance, 72.0 cd/m^2, without red-green spectacles). The test stimulus was composed of a dark-gray square (luminance, 34.1 cd/m^2; visual angle, 4.9° x 4.9°) and an outlined rectangle (visual angle, 3.0° x 7.3°; line width, 0.05°). In each experiment we manipulated the perceived transmittance (from completely transparent to opaque) of the rectangle, by varying the luminance of the overlapped region of the square and the rectangle. The matching stimulus, whose width was adjustable, was a dark-gray rectangle (luminance, 34.1 cd/m^2). The height was identical to that of the test stimulus. The distance between the center of the test stimulus and that of the matching stimulus was constant (visual angle, 7.3°).

2.4 Procedure

Observers viewed the display in a binocular fashion through red-green spectacles. In with-disparity conditions, to introduce horizontal retinal disparity of the rectangle relative to the square in the test stimulus, red-green test stimuli were used. RGB values in the stimuli were set to avoid crosstalk[3] between the two images projected to the two eyes. The display was located on the fronto-parallel plane at a distance of 56 cm from the observer's eyes. The observer's head was stabilized with a chin-and-forehead rest.

The observer's task was to adjust the width (or height in Experiment 3) of the matching stimulus so that it appeared to be equal to the width (or height in Experiment 3) of the test stimulus. A starting width of the matching stimulus was selected at random within the ranges of 4.2° to 4.4° or 5.4° to 5.6°, except for Experiment 2.[4] At these starting points, the matching stimulus was perceived definitely narrower or wider than that of the test stimulus. During each trial, the width of the matching stimulus could be increased or decreased by repeatedly pressing the "1" or "2" keys[5] on the extended keyboard (the step size of the width was 0.05°). Both test and matching stimuli were visible until observers pressed the "space" key. The pressing of this key also triggered the next trial. In each trial, no fixation mark was presented.

To avoid observer's biased adjustments not based on their width perception (eg an adjustment based on the space between the test and matching stimuli), a narrower (visual angle, 4.7°) or wider (visual angle, 5.1°) test stimulus was presented in one out of every seven trials. The test stimuli used in these catch trials were randomly selected from the six test stimuli used in each experiment. No feedback on the adjustment was provided. After 14 practice trials, each observer underwent 84 trials which were separated into three blocks. In each block, six test conditions and one catch trial were repeated twice in randomized order. The location of the test and matching stimuli and the adjusting keys were counterbalanced across observers.

2.5 Data analysis

In each experiment, data analyses were based on the mean width of the matching stimulus averaged over 12 trials for each condition of each observer. If the mean width for the catch trials was outside the physical width of the test stimulus ±5% (ie less than 4.66° or more than 5.14°), then his/her data were excluded from further analyses (two observers for Experiment 1; one observer for each of Experiments 3, 4, and 5).

3. Experiment 1

The experiment was aimed (a) to confirm the previous findings (Ohtsuka and Ono 2002; van Ee and Erkelens 2000) that the perceived width of the occluded object is nearly veridical when the occluding rectangle is presented stereoscopically in front of the occluded object, and if this is the case, (b) to examine what extent of disparity of an occluder produces the veridical perception of an occluded object. We measured the perceived width of an occluded square as a function of the extent of horizontal retinal disparity (ranging from 0° to 0.69°) of the occluding rectangle.

3.1 Method

The test stimulus was a filled square depicted as partially occluded by a vertically oriented opaque rectangle (Figure 1D). The luminance of the overlapped region of the rectangle and the square was identical to that of the background (72.0 cd/m^2). Horizontal retinal disparities of the occluder with respect to the occluded square were 0°, 0.10°, 0.25°, 0.34°, 0.49°, and 0.69°of visual angle.

3.2 Results and Discussion

Figure 2 shows the mean perceived width averaged over six naive observers as a function of disparity. Perceived widths are expressed as a percentage of the physical width of the test stimuli. One-way repeated-measures analysis of variance (ANOVA) was performed on the perceived width with the factor of disparity. The main effect was significant, $F(1, 5) = 10.47$, $p < .0001$. Planned pairwise comparisons showed that perceived widths between two abutting disparity subconditions significantly differed only between the 0°- and 0.10°-disparity conditions, $F(1, 5) = 7.26$, $p < .05$.

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Insert Figure 2 about here

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The results confirmed previous findings that shrinkage occurs only with a 0°-disparity occluder, but not with with-disparity occluders (Ohtsuka and Ono 2002; van Ee and Erkelens 2000). Moreover the results showed that when disparity was larger than 0.1°, it did not affect the perceived width of the occluded square[6]. One possible interpretation of the shrinkage observed in the 0°-disparity condition is an inappropriate operation of the correcting mechanism, which appropriately operates for stereoscopic occluders (depicted by the downward arrow in Figure 2).

However, the obtained results, as well as the findings of Ohtsuka and Ono (2002), are insufficient to support the hypothesis that the correcting mechanism, triggered by pictorial occlusion cues, contributes to Kanizsa shrinkage. That is, since we used only a vertical *opaque* occluder in this experiment as in the previous studies (Ohtsuka and Ono 2002; van Ee and Erkelens 2000), we cannot safely conclude that pictorial occlusion cues are critical for Kanizsa shrinkage. It is possible that pictorial cues to depth *stratification* may trigger shrinkage since pictorial occlusion cues also imply the depth order of two surfaces. Indeed, Gerbino (1975) reported that a transparent object can trigger Kanizsa shrinkage. The previous study, however, was not conclusive about the correcting mechanism since it used only without-disparity stimuli.

In addition, one might think that it is inappropriate to directly compare perceived width in a with-disparity condition to that in a without-disparity condition, since several studies have reported that geometrical illusions disappear with binocular disparity, even in the absence of pictorial occlusion cues (eg Gregory and Harris 1975). To examine the two possibilities, we conducted Experiment 2.

4. Experiment 2

The experiment examined whether the results of Experiment 1 can be explained by pictorial cues to depth stratification or by the binocular disparity itself. To that purpose, we added two stimulus conditions and measured the perceived width of an occluded square with or without occluder disparity (for the with-disparity condition, occluder disparity was constant: visual angle, 0.34°).

First, to examine the effect of pictorial cues to depth stratification on the perceived width, we used a perceptually *transparent* rectangle (Figure 3A, center panel) instead of an opaque one. Since pictorial cues to transparency imply that binocularly unpaired regions belong to both occluding (foreground) and occluded (background) objects, from the viewpoint of the correction-mechanism hypothesis its operation is unnecessary for a transparent foreground object. Thus, if the correcting mechanism contributes to Kanizsa shrinkage, then no shrinkage for the transparent type should be observed under each of the disparity conditions.

Second, to eliminate the potential effects of binocular disparity itself on the perceived width, we employed a baseline condition in which an outlined rectangle (Figure 3A, right panel) was overlapped with the test square. Thus, for each disparity condition we defined shrinkage as subtraction of the perceived width in the baseline (ie outlined) condition from that in the experimental (ie opaque or transparent) condition. If the correcting-mechanism hypothesis is true, then shrinkage for the opaque type should be larger in the without-disparity condition than in the with-disparity condition, even when the effect of the disparity itself was removed.

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Insert Figure 3 about here
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4.1 Method

We used six test stimuli, which comprised combinations of three types of foreground rectangle and two types of binocular disparity. The three foreground rectangles were opaque, transparent, and outlined types: the luminances of the overlapped region [7] of the square and the rectangle were 72.0, 55.2, and 34.1 cd/m^2, respectively.[8] The outlined rectangle served as a baseline control. Each rectangle had two disparity conditions, with and without disparity. In the with-disparity condition, the binocular disparity of the foreground rectangle relative to the square was 0.34° of visual angle; in the without-disparity condition, no disparity was presented.

4.2 Results and Discussion

For each observer, we calculated the perceived width change by subtracting the mean perceived width in the outlined type from that in the opaque or transparent type, separately for the with- and without-disparity conditions. (As in Experiment 1, perceived widths were calculated as a percentage of the physical width of the test stimuli.) Figure 3B shows the mean width changes averaged over eight naive observers. Two-way repeated-measures ANOVA was performed for the width changes, with the factors of rectangle type (opaque, transparent) and disparity (with, without). The main effect of rectangle type was significant, $F(1, 7) = 21.15$, $p < .005$. More importantly, for the opaque type, a planned pairwise comparison revealed that the width decrease was significantly larger in the without-disparity condition than in the with-disparity condition, $F(1, 7) = 12.74$, $p < .01$. For the transparent type, on the other hand, there was no significant difference in the width change between the with- and without-disparity conditions, $F(1, 7) = 2.51$, $p > .1$.

These results confirmed the prediction from the correcting-mechanism hypothesis: when an opaque occluder was replaced by a transparent one, Kanizsa shrinkage disappeared. We found a significant difference for the opaque type but not for the transparent type. These results can be interpreted as being due to the difference between opaque and transparent objects arising from ecological constraints on forming their image: in 3-D space an opaque surface inevitably forms binocularly unpaired regions, whereas a transparent one does not. To strength this argument, we measured the perceived width, varying the degree of transparency (perceived transmittance) in Experiment 5.

Furthermore, the results of Experiment 2 exclude the possibility that the difference in perceived width between the with- and without-disparity conditions in Experiment 1 is due to the binocular disparity itself, since we used a baseline condition for each of the with- and without-disparity conditions. The larger shrinkage for the without-disparity opaque occluder than for the with-disparity one is consistent with the correcting-mechanism hypothesis.

Even if the correcting-mechanism hypothesis can explain the difference between the with- and without-disparity conditions for the opaque type, what causes the small but evident shrinkage for the with-disparity opaque occluder? This can be accounted by the contrast-energy hypothesis[9], which was introduced by Kanizsa (1979). In this hypothesis, shrinkage increases with the luminance contrast and the area size of the overlapped region of occluded and occluding objects relative to the rest of the occluded object. Since the contrast was higher for the opaque type than for the control type, the contrast-energy hypothesis can explain the shrinkage for the with-disparity opaque occluder. A further attempt to experimentally separate shrinkage based on the correcting-mechanism from that based on the contrast energy was made in Experiment 5.

Support for the correcting-mechanism hypothesis can be strengthened by the width-change scatter plot of the individual data which compares the without-disparity condition to the with-disparity condition (Figure 3C: abscissa, the with-disparity condition; ordinate, the without-disparity condition). The correcting-mechanism hypothesis predicts that the plot of the width change in the without-disparity condition as a function of that in the with-disparity condition should be distributed within the area under the line of the slope of 1 (Figure 3C) for the opaque type, but not for the transparent type. As can be seen in Figure 3C, the results supported this prediction: the individual data for the opaque type were distributed under the diagonal line; in addition, there was no correlation between the with- and without-disparity conditions not only for the transparent type (r^2, 0.095; slope, 0.26) but for the opaque type (r^2, 0.015; slope, –0.21).

5. Experiment 3

We further tested the correcting-mechanism hypothesis by using a horizontally oriented occluder. According to this hypothesis, the shrinkage triggered by pictorial occlusion cues depends upon the orientation of the occluding edges. That is, in stereoscopic viewing, since a horizontally oriented occluder does not produce monocular regions along its horizontal edges, no correction should be required; thus shrinkage based on the correcting mechanism will not be observed. To test this prediction, we measured the perceived *height* of an occluded object, using stimuli in which the stimulus configuration used in Experiment 2 was rotated by 90° in the image plane. If the correcting mechanism contributes to Kanizsa shrinkage, then no difference in perceived height will be observed between the with- and without-disparity conditions, either for the opaque type or for the transparent type.

5.1 Method

The stimuli were identical to those in Experiment 2, except for a 90° rotation (in the image plane) of both the test and matching stimuli (ie the test and matching stimuli were aligned vertically). As in Experiment 2, in the with-disparity condition, the horizontal binocular disparity of a foreground rectangle was 0.34° of visual angle. Observers were required to adjust the height of the matching stimulus.

5.2 Results and Discussion

We applied the same analyses as used in Experiment 2. For each disparity condition we calculated the height change by subtracting the mean perceived height in the outlined type from that in the opaque or transparent type. Figure 4A shows the mean height changes averaged over seven naive observers. Planned pairwise comparisons revealed that there was no significant difference between the with- and without-disparity conditions either for the opaque type or for the transparent type [$F(1, 6) = 1.21, p > .3$; $F(1, 6) = .79, p > .4$, respectively].

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Insert Figure 4 about here
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The results with the horizontal occluders confirmed the predictions based on the correcting-mechanism hypothesis.[10] That is, the larger shrinkage for the without-disparity opaque occluder which was observed in Experiment 2, was weakened when the occluder was simply rotated by 90°; we found a modest positive correlation in perceived height between the with- and without-disparity conditions, for both the opaque (r^2, 0.84; slope, 0.89) and the transparent (r^2, 0.45; slope, 0.48) types (Fig. 4B). The small shrinkage for both the with- and without-disparity occluders can be attributed to the contrast energy, because the amount was highly consistent with that for the with-disparity opaque occluder in Experiment 2.

Although the results of Experiments 2 and 3 suggest that the operation of the correcting mechanism requires *vertical* occluding edges, it is still possible that the results of Experiment 2 could be explained by the presence of unpaired regions per se, rather than an occlusion interpretation. That is, since no monocular region along the horizontal edges was formed for each of the with- and without-disparity occluders in Experiment 3, no difference in perceived height could be observed between the with- and without-disparity conditions. To examine this possibility, we conducted the next experiment.

6. Experiment 4

In this experiment we eliminated pictorial occlusion cues (ie T-junctions) from the stimuli used in Experiment 2 and measured the perceived width of the square. Such cues were eliminated by removing the upper and lower extremities of the occluding rectangle from the test stimuli (Figure 5A). If the correcting mechanism requires pictorial occlusion cues, then no difference in perceived width will be observed between the with- and without-disparity conditions.

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Insert Figure 5 about here
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6.1 Method

The stimuli were identical to those used in Experiment 2, except for the removal of the upper and lower extremities of the rectangle in each test stimulus (Figure 5A). Although these stimuli did not produce an impression of either occlusion or transparency, for the sake of clarity we used the same labels as those used in Experiments 2 and 3.

6.2 Results and Discussion

We applied the same analyses as used in Experiments 2 and 3. Figure. 5B shows the mean width changes averaged over seven naive observers. Planned pairwise comparisons revealed that there was no significant difference in width change between the with- and without-disparity conditions either for the opaque type or for the transparent type [$F(1, 6) = 5.65$, $p > .05$; $F(1, 6) = .37$, $p > .5$, respectively].

Removing pictorial occlusion cues disrupted the shrinkage, which occurred selectively for the without-disparity opaque occluder, observed in Experiment 2. Although the unpaired regions in this experiment were identical to those of Experiment 2, the width change in the without-disparity condition was positively correlated with that in the with-disparity condition, not only for the transparent type (r^2, 0.33; slope, 0.68) but also for the opaque type (r^2, 0.92; slope, 1.29), as shown in Figure 5C. Indeed, a few observers showed a relatively strong shrinkage for both the with- and without-disparity conditions, indicating that the correcting mechanism operate precisely when pictorial occlusion cues are removed. This tendency is similar to that observed in Experiment 3, and is clearly different from that observed in Experiment 2: in Experiment 2, the shrinkage triggered by occlusion cues was restricted to the without-disparity occluder. These results therefore suggest that the presence of unpaired regions is not sufficient to explain the results of Experiments 2 and 3; a vertical occluder is critical for Kanizsa shrinkage.

7. Experiment 5

The experiment was a control for the transparent type used in Experiment 2. Although the results of Experiment 2 showed the differential effect of rectangle type (opaque or transparent) on the perceived width of the occluded square, this difference could be explained by the contrast-energy hypothesis (Kanizsa, 1979). That is, since luminance contrast of the overlapped region relative to the remaining regions of the background square was simply lower for the transparent type than for the opaque one, a reliable shrinkage for the transparent type could not be obtained in the without-disparity condition.

To examine this possibility, we measured the perceived width of the square seen behind a transparent rectangle with or without binocular disparity, varying the transmittance of the rectangle. Perceived transmittance was varied by manipulating the luminance of the overlapped region in the test stimulus. Since the difference in the perceived widths between the with- and without-disparity conditions reflects how the correcting mechanism operates, we focused on examining whether or not the disparity manipulation influences the *slope* of luminance-contrast x perceived-width function.

7.1 Method

The stimuli comprised variations of the transparent type used in Experiment 2. We used three transmittance conditions (high, middle and low), in which the luminance of the overlapped region of the rectangle and the square in the test stimulus varied (42.9, 55.2, and 65.3 cd/m^2, respectively). Each of the three rectangles had two binocular disparity conditions: with- and without-disparity. As in Experiments 2-4, in the with-disparity condition the binocular disparity was constant (visual angle, 0.34°).

7.2 Results and Discussion

Figure 6 shows the mean perceived width as a function of Michelson contrast of the overlapped region relative to the rest of the test square for each condition averaged over seven naive observers. As in Experiment 1, perceived widths were expressed as a percentage of the physical width of the test stimuli. In Figure 6, a higher contrast corresponds to a lower transmittance. Slopes of linear regression of perceived width against Michelson contrast were calculated for each observer. One-way repeated-measures ANOVA was performed on the slope with the factor of disparity. There was no significant difference in slope between the with- and without-disparity conditions (mean slopes, –7.3 and –6.5 %/contrast, respectively), $F(1, 6) = .10$, $p > .7$.

In addition, two-way within-observers ANOVA was performed on the perceived width, with the factors of transmittance (high, middle, low) and binocular disparity (with, without). The main effects of both transmittance and binocular disparity were significant [$F(2,12) = 9.53$, $p < .005$; $F(1,6) = 15.98$, $p < .01$, respectively], but the interaction was not, $F(2,12) = .12$, *n.s.*

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Insert Figure 6 about here

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Whereas the monotonic decrease linked to the increase of the luminance contrast (or to a decrease in perceived transmittance) of the foreground object for each of the with- and without-disparity conditions is consistent with the contrast-energy hypothesis, this hypothesis cannot explain the constant *difference* in the perceived width between the with- and without-disparity conditions irrespective of the transmittance change. (This small but significant constant difference seems to be partly due to the binocular disparity itself, since we also found a similar tendency even for the outlined control type of Experiments 2-4. See Appendix.) The results indicate that the operation of the correcting mechanism is not influenced by the luminance contrast, but is influenced by the perceptual interpretation of an occluding (foreground) object.

8. General discussion

In the five experiments, we found that Kanizsa shrinkage is selectively large only when using a vertical occluder without disparity (Experiment 1), and that the large shrinkage diminishes when the occluder is transparent (Experiments 2 and 5), is horizontally oriented (Experiment 3), or has no pictorial occlusion cues (Experiment 4). These results qualitatively confirmed the prediction of the correcting-mechanism hypothesis (Ohtsuka and Ono 2002), which states that the inappropriate operation of the mechanism, triggered by pictorial occlusion cues, contributes to Kanizsa shrinkage. This implies that other hypotheses regarding on Kanizsa shrinkage are incomplete; in the next two paragraphs, we will discuss the conclusion that the independent-processing hypothesis (van Ee and Erkelens 2000) and the contrast-energy hypothesis (Kanizsa 1979; Gerbino 1975) are insufficient to explain all the results of the present study.

Van Ee and Erkelens (2000) argued that the perceived shape of an object is processed independently of its visible areas, which also include the monocularly visible ones (accompanied by a stereoscopic occluder). This independent-processing hypothesis relies on their experiments using stimuli defined by *stereoscopic* contours, which showed that (a) binocular disparity of a vertical occluder does not influence the perceived width of the occluded object, and that (b) a without-disparity occluder does not cause shrinkage. In addition, they stated that the correcting-mechanism hypothesis is not applicable for Kanizsa shrinkage, by presenting a demonstration in which (c) shrinkage can still be observed with a horizontal occluder. While (a) is consistent with the results for the large-disparity conditions of Experiment 1, (b) is not consistent with the shrinkage observed in the without-disparity condition of Experiments 1 and 2. Since the essential assumption of the correcting-mechanism is that the correction is triggered by pictorial information (coded directly by each monocular image), then the lack of shrinkage for a without-disparity occluder observed in van Ee and Erkelens can be explained by the absence of pictorial occlusion cues as defined by monocular contours in their experiments. In addition, (c) is not true because Experiment 3 showed that Kanizsa shrinkage is reduced with a horizontal occluder. Thus, the present results support the correcting-mechanism hypothesis, rather than the independent-processing hypothesis.

The contrast-energy hypothesis (Kanizsa 1979; Gerbino 1975) has provided a good description of this illusion: shrinkage increases with the *width* or the *opacity* of an occluder. However, this hypothesis is not consistent with two findings of the present study. First, Vezzani (1999) pointed out that this description can be applied for weaker shrinkage for with-disparity occluders (van Ee and Erkelens 2000; Ohtsuka and Ono 2002), as used in the present study. According to Vezzani (1999), since a phenomenal increase in monocular areas accompanied by such occluders causes a decrease in the width ratio of the occluder relative to the whole object, shrinkage will be weaker when the occluder has binocular disparity than when it has not. If this view is true, the perceived width would linearly increase with disparity, since visible areas of an occluded object increase proportionally with disparity. This prediction, however, was not supported by the results of Experiment 1: the perceived width was almost constant with relatively large disparities (> 0.25°, Figure 2). Second, Gerbino (1975) stated that Kanizsa shrinkage can occur not only in the case of *amodal* completion (ie opaque occluder), but also in the case of *modal* completion (ie transparent occluder). This explanation, however, cannot predict the differential effect of occluder type on the difference between the two disparity conditions (with and without), observed in Experiments 2 and 5. The contrast-energy hypothesis therefore fails to explain the present results.

The present results with Kanizsa shrinkage provide evidence for a well-documented, but rarely convincing idea that geometrical illusions are caused by inappropriate operation of mechanisms for recovering 3-D representations (eg Gregory and Harris 1975). In the case of linear-perspective stimuli such as the Muller-Lyer and Ponzo illusions, experimental data do not always support this hypothesis (eg DeLucia and Hochberg 1991). However, in the case of monocular occlusion cues such as Kanizsa shrinkage (Ohtsuka and Ono 2002; the present study) and the Poggendorff illusion (Gillam 1971; Spehar and Gillam 2002), experimental data support this hypothesis. We speculate, therefore, that distinguishing pictorial depth cues is important when applying depth-recovering theories to geometrical illusions.

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Authors' Note

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Footnotes

[1] Strictly speaking, Ohtsuka and Ono (2002) also used the concept of displacement of monocular regions in a visual direction, instead of that a phenomenal increase in visible regions. This formulation, based on visual direction, seems to contain some inconsistency when explaining Kanizsa shrinkage, since several studies have suggested that visual direction and shape perception are independent of each other (van Ee andErkelens 2000; Ono et al 2003). Because we thought that conceptual introduction of the correcting mechanism is possible without referring to the visual direction, we did not use the concept of visual direction in the Introduction section.

[2] However, van Ee and Erkelens (2000) did not measure the extent of shrinkage in a horizontal occluder.

[3] To confirm that our anaglyphic method was effective in producing a surface in depth, we measured the perceived depth of the opaque occluder in the practice block in Experiment 1, with the use of a reproduction method. In this task, observers were asked to reproduce the depth of the occluder by indicating the depth on a straight measure (the scale was not visible to an observer). Measurements were made twice for each disparity condition. A high positive correlation between theoretical depth and perceived depth was found for each of eight observers (mean correlation coefficient, .93; standard deviation, .076). Thus, we can say that our anaglyphic display was effective in producing a 3-D image.

[4] In Experiment 2, the starting width was 4.2° or 5.4° due to a program limitation.

[5] In Experiment 2, observers were unable to return to the previous state of the matching width in each trial due to a program limitation. If the matching stimulus with a narrower (or wider) starting point became wider (or narrower) than the test stimulus, the trial was then repeated at the end of the experiment.

[6] When the disparity was larger than 0.25°, the perceived widths seemed to be slightly but constantly larger than its physical width. This tendency was also observed for the control conditions for Experiments 2-4 (Appendix), as well as by Kanizsa (1979). This constant error was not considered in this paper, since differences between with- and without-disparity conditions, but not absolute widths, were enough to provide information relevant to our interest.

[7] In an effort to minimize shape assimilation of the square to the rectangle, varying only the luminance of the overlapped region has an advantage over varying that of *all* regions (eg Gerbino 1975) of a foreground rectangle. This is because in the former manipulation, additional elements (ie the upper and lower extremities), which potentially influence the perceived

shape of the square, were constant.

[8] This type of configuration for triggering transparency (ie a transparent surface defined only by outline) was reported by Kanizsa (1979). The luminance relation for the transparent type satisfied the Metelli's rule for transparency (Metelli 1974); therefore the depth order (ie the rectangle is seen in front of the square) for the transparent type was identical to that for the opaque type.

[9] Although Kanizsa's definition of the term "energy" is relatively ambiguous, a more precise definition of "energy" (eg Pelli and Farell 1999), the square of luminance contrast of the central region relative to the rest of the occluded object, seems to be adequate for describing the two variables (ie the width and the opacity of an occluder).

[10] Similar results were previously reported in a conference abstract (Ono et al 1999).

Figure Captions

Figure 1. A: Kanizsa shrinkage disappears in stereoscopic viewing (left two images: crossed viewing; right two images : uncrossed viewing). B: Schematic representation of binocularly unpaired regions in the left two images of Figure 1A. The unpaired regions are denoted as *b* and *b'*. C: The (cyclopean) view expected with the visible (including unpaired) regions in Figure 1B. D: Test and matching stimuli used in the experiments. In Experiment 3, these stimuli were rotated 90°, while maintaining their relative relation constant.

Figure 2. The results for Experiment 1. Mean perceived widths averaged over six naive observers as a function of binocular disparity. The horizontal line depicts the physical width of the test stimuli. Vertical bars represent standard errors.

Figure 3. The stimuli and results for Experiment 2 (vertical occluder). A: The three test stimuli. B: Mean width changes averaged over eight naive observers. Open bars represent data from the with-disparity occluder; Filled bars represent data from the without-disparity occluder. Error bars represent 95% confidence intervals. C: The scatterplot of width-changes for the individual observers. Filled circles represent data from the opaque type; Open circles represent data from the transparent type. The oblique line depicts a prediction based on a *non*-correcting mechanism.

Figure 4. The results for Experiment 3 (horizontal occluder). A: Mean height changes averaged over seven naive observers. Open bars represent data from the with-disparity occluder; Filled bars represent data from the without-disparity occluder. Error bars represent 95% confidence intervals. B: The scatterplot of height-changes for the individual observers. Filled circles represent data from the opaque type; Open circles represent data from the transparent type. The oblique line depicts a prediction based on a *non*-correcting mechanism.

Figure 5. The stimuli and results for Experiment 4 (vertical occluder without pictorial cues). A: The three test stimuli. B: Mean width changes averaged over seven naive observers. Open bars represent data from the with-disparity occluder; Filled bars represent data from the without-disparity occluder. Error bars represent 95% confidence intervals. C: The scatterplot of width-changes for the individual observers. Filled circles represent data from the opaque type; Open circles represent data from the transparent type. The oblique line depicts a prediction based on a *non*-correcting mechanism.

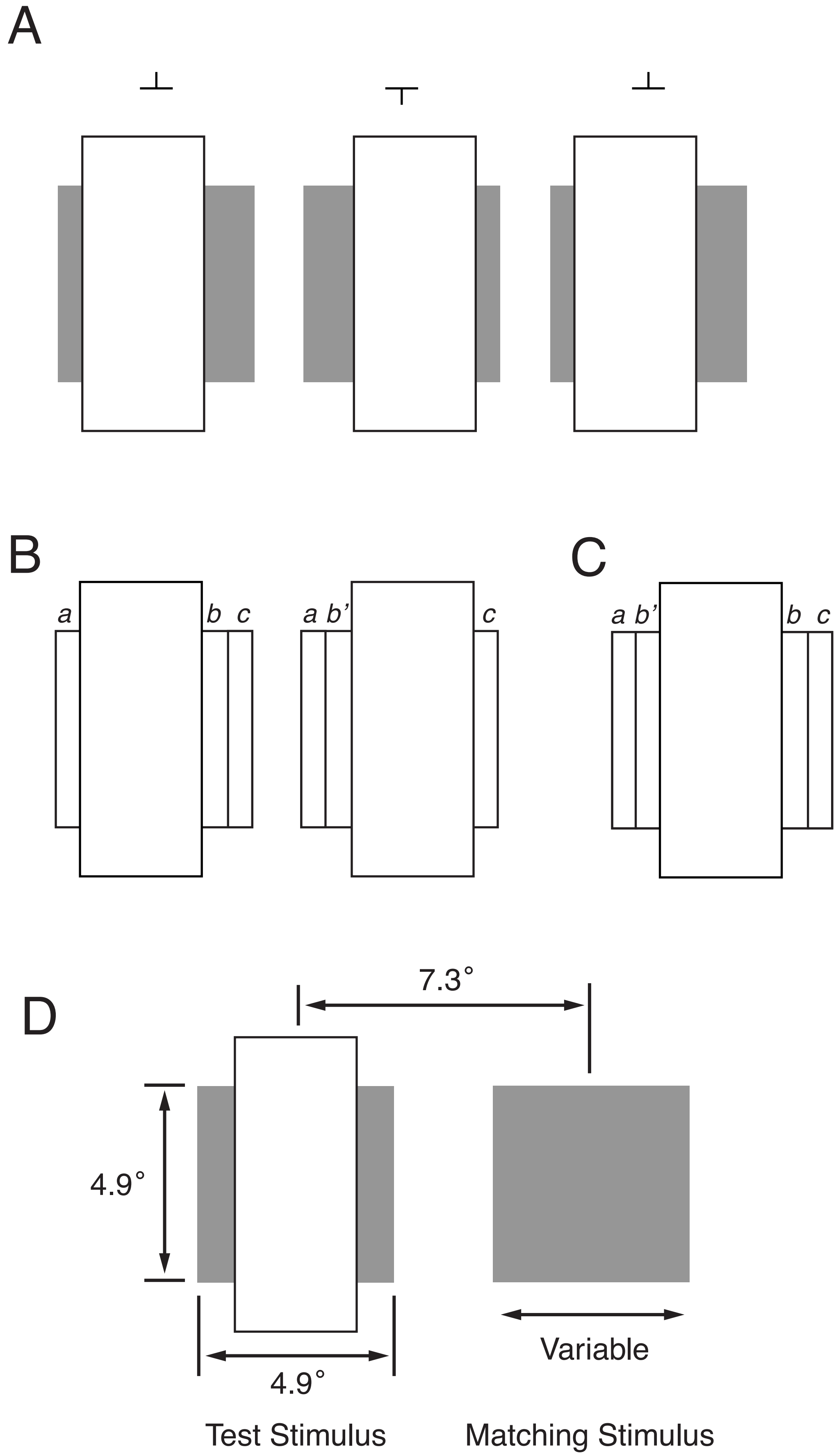
Figure 6. The results for Experiment 5. Mean perceived widths as a function of Michelson contrast of the overlapped region relative to the rest of the test square averaged over seven naive observers. A high-contrast value corresponds to a low-transmittance value. Filled circles represent data from the without-disparity rectangles; Open circles represent data from the with-disparity rectangles. Vertical bars represent standard errors.

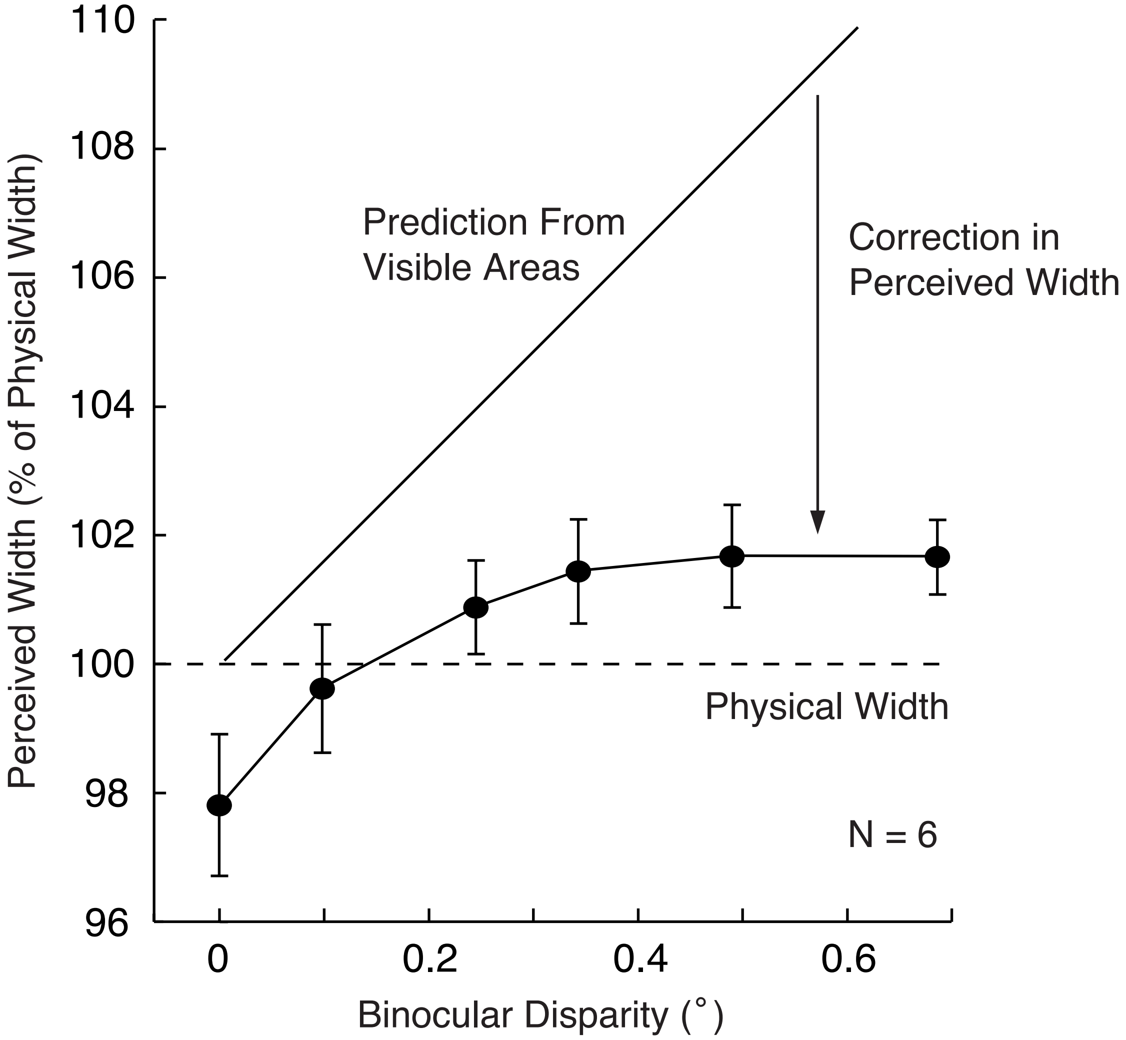
Appendix

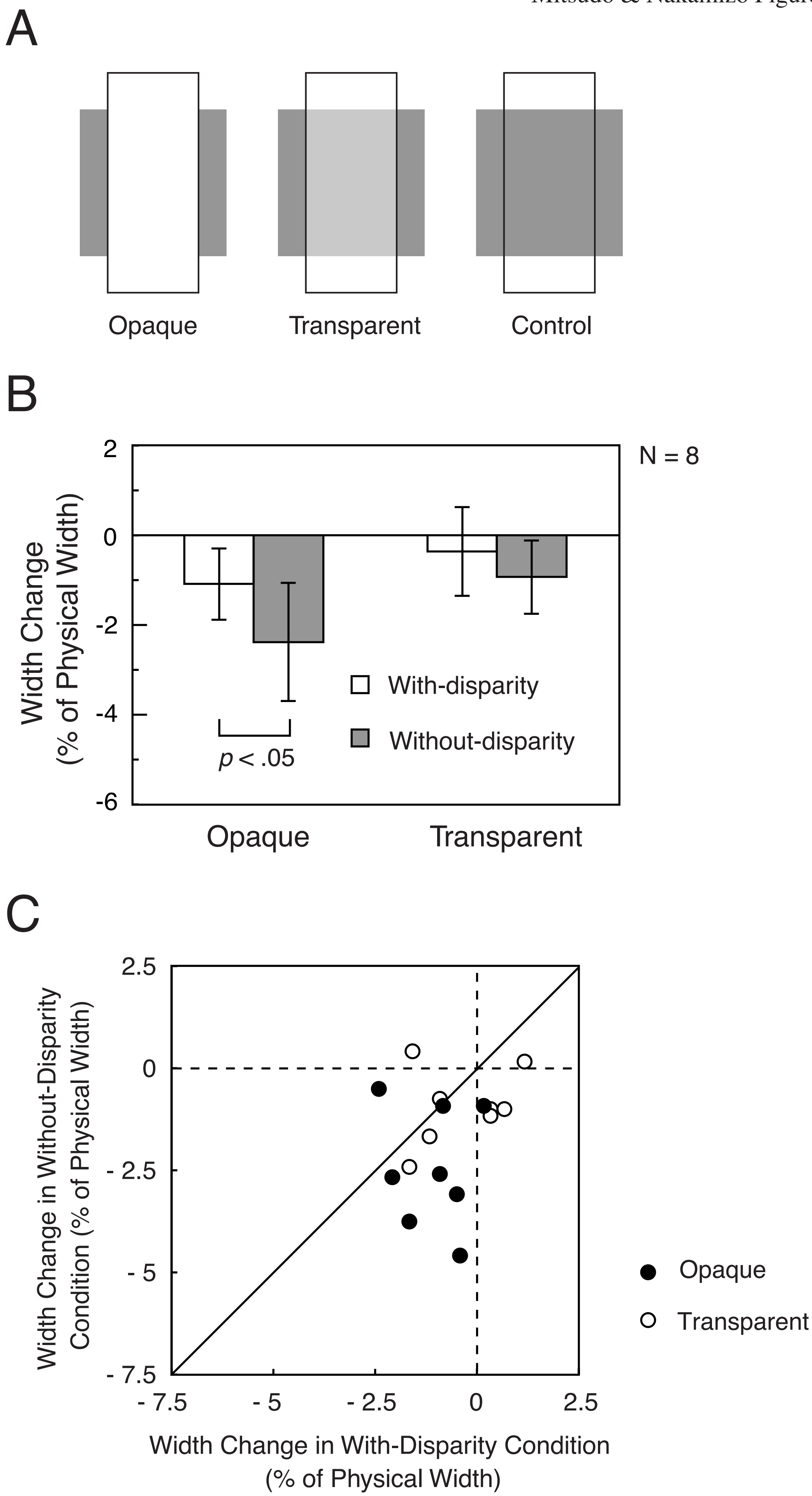
Mean matching widths (height in Experiment 3) for Experiments 2-4

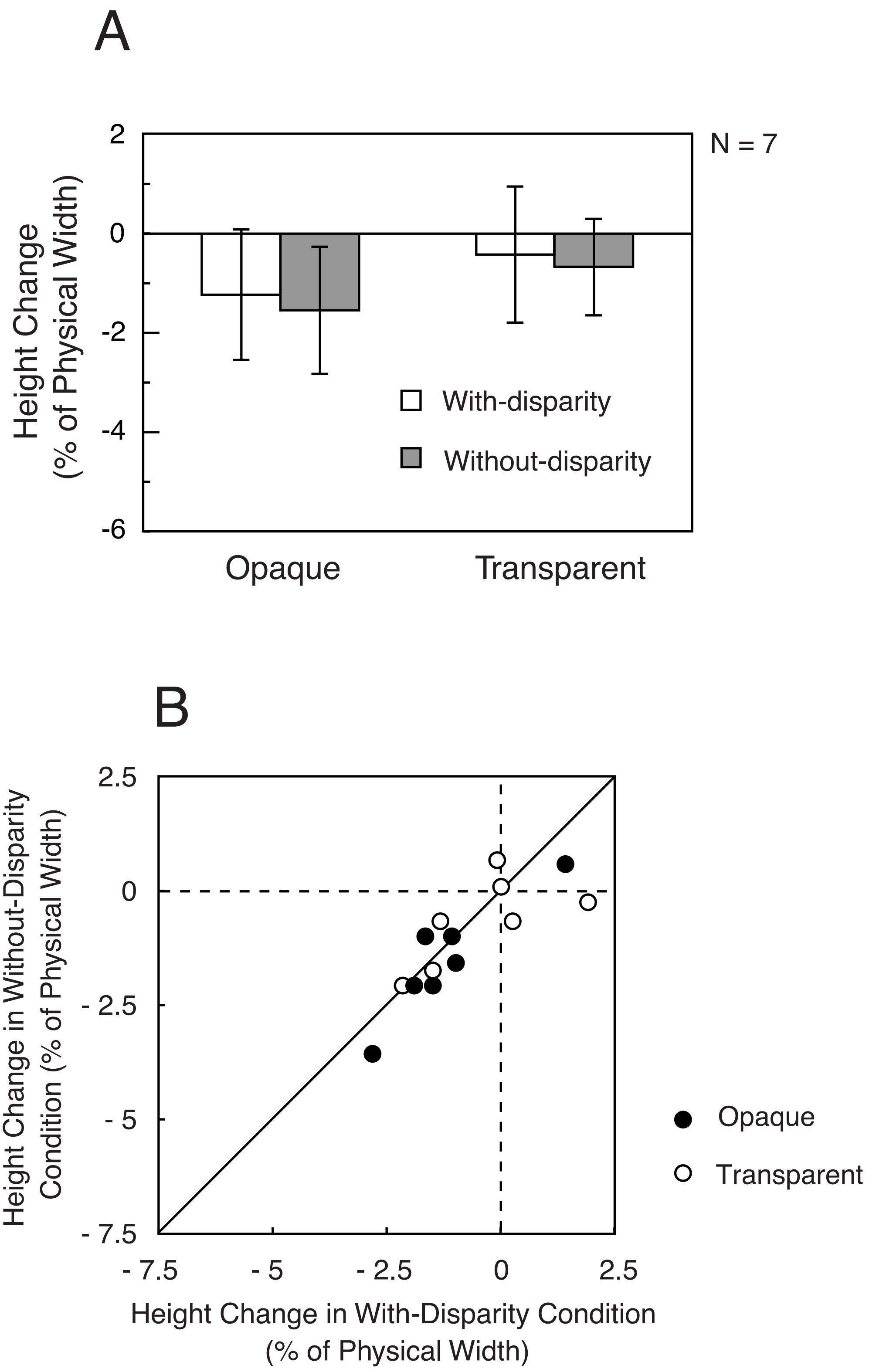
Experiment	*n*	Occluder type		
		Opaque	Transparent	Control
Experiment 2				
Without disparity	8	97.97	99.42	100.34
With disparity		99.59	100.32	100.68
Experiment 3				
Without disparity	7	100.45	101.32	101.99
With disparity		101.23	102.04	102.45
Experiment 4				
Without disparity	7	98.21	100.11	100.25
With disparity		99.32	100.17	100.52

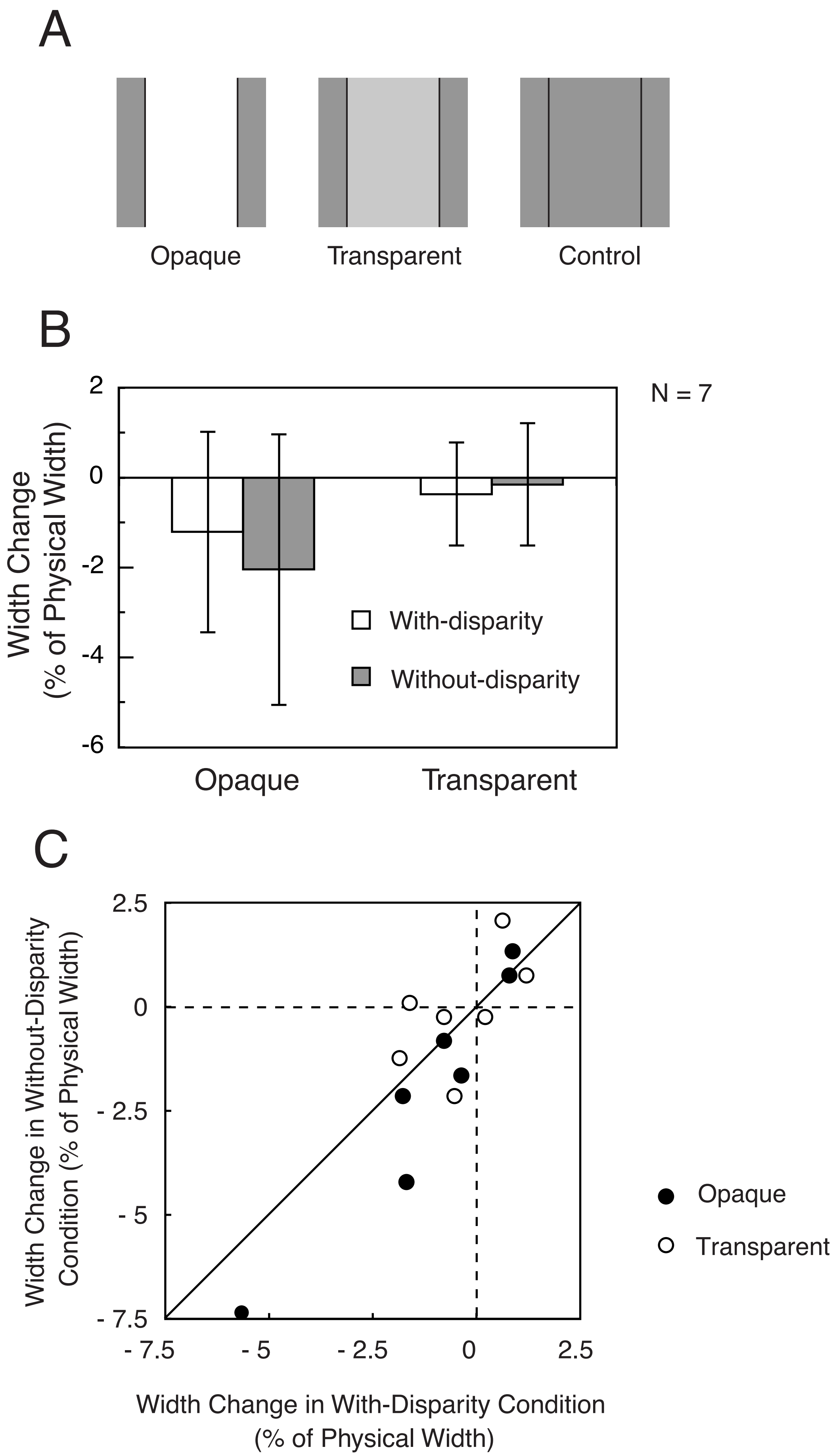
Note. Widths are expressed as a percentage of the physical width of the test stimuli (visual angle, 4.9°).

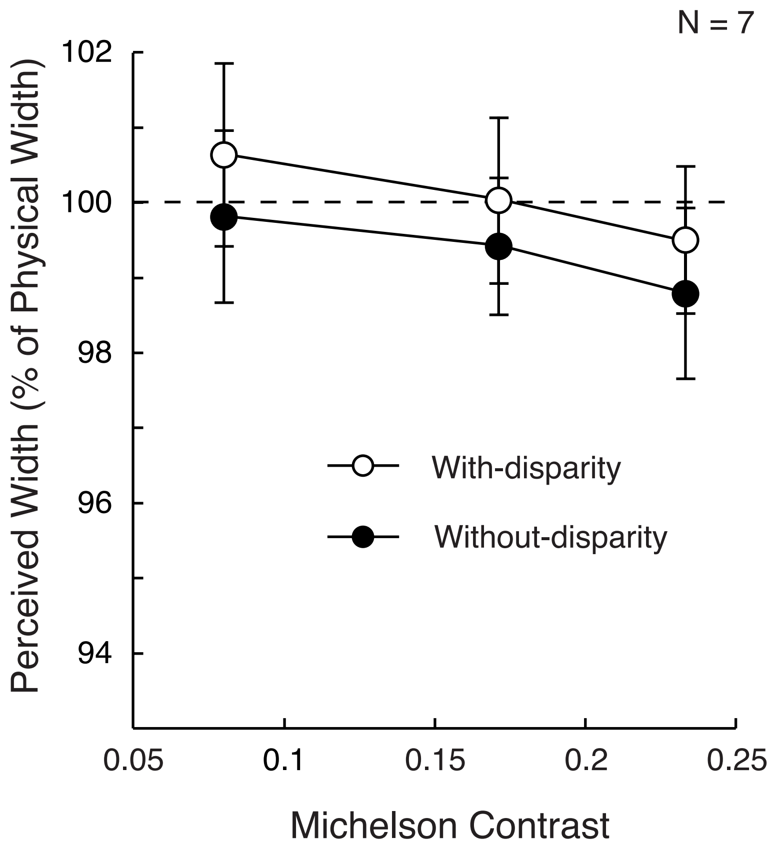

A
B
a
b
c
a
b'
c
C
a
b'
b
c
D
7.3°
4.9°
4.9°
Variable
Test Stimulus
Matching Stimulus


110
108
106
104
102
100
98
96
Perceived Width (% of Physical Width)
0
0.2
0.4
0.6
Binocular Disparity (°)
Prediction From
Visible Areas
Correction in
Perceived Width
Physical Width
N = 6


A
Opaque
Transparent
Control
B
N = 8
2
0
-2
-4
-6
Width Change
(% of Physical Width)
With-disparity
Without-disparity
p < .05
Opaque
Transparent
C
2.5
0
- 2.5
- 5
- 7.5
- 7.5
- 5
- 2.5
0
2.5
Width Change in Without-Disparity Condition (% of Physical Width)
Width Change in With-Disparity Condition (% of Physical Width)
Opaque
Transparent


A
N = 7
Height Change
(% of Physical Width)
2
0
-2
-4
-6
With-disparity
Without-disparity
Opaque
Transparent
B
Height Change in Without-Disparity
Condition (% of Physical Width)
2.5
0
- 2.5
- 5
- 7.5
- 7.5
- 5
- 2.5
0
2.5
Opaque
Transparent
Height Change in With-Disparity Condition
(% of Physical Width)


A
Opaque
Transparent
Control
B
N = 7
2
0
-2
-4
-6
Width Change
(% of Physical Width)
With-disparity
Without-disparity
Opaque
Transparent
C
2.5
0
- 2.5
- 5
- 7.5
- 7.5
- 5
- 2.5
0
2.5
Width Change in Without-Disparity
Condition (% of Physical Width)
Opaque
Transparent
Width Change in With-Disparity Condition
(% of Physical Width)



N = 7
102
100
98
96
94
Perceived Width (% of Physical Width)
0.05
0.1
0.15
0.2
0.25
Michelson Contrast
With-disparity
Without-disparity