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Three elemental illusions determine the Zöllner illusion

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We have discovered an apparent contraction illusion of acute angles in a special form of the Zöllner figure at the intersecting angles between 36º and 83º (i.e., a reversal of the Zöllner illusion). The necessary condition for this illusion is that inducing lines are long enough and the induced line (test line) is single. When an illusory line is used as the induced line, the magnitude of contraction increases. Short inducing lines give no illusion or a slight expansion of acute angles at the intersecting angle of 45º. We have ascertained that the source of this expansion is the narrow region in the vicinity of the induced line, whereas the source of the contraction is much broader regions. Furthermore, we have discovered another expansion mechanism, which is generated by the symmetrical configuration of the standard Zöllner figure.

When two lines of different orientations are drawn closely to each other or when they cross each other, the acute angle formed by them tends to appear larger than it really is. This apparent expansion of the acute angle occurs at the angles between 0º and 90º in the Zöllner illusion (Morinaga, 1933; Wallace & Crampin, 1969). On the other hand, in the tilt illusion, the acute-angle expansion appears at the angles between 0º and 50º, and, to the contrary, the acute-angle contraction, called the *indirect effect*, occurs at the angles between 50º and 90º (Gibson & Radner, 1937; O'Toole & Wenderoth, 1977; Over, Broerse, & Crassini, 1972). These illusions are illustrated in Figure 1.

What conditions make the difference between the two illusions? First, the figure of the Zöllner illusion is characterized by the abundance of inducing lines, whereas the figure of the tilt illusion includes one or a few inducing lines. Second, inducing lines are relatively short for the former, whereas they are long for the latter. Third, the Zöllner figure includes more than two induced lines, each intersected by inducing lines of different orientations symmetrical to each other, whereas the tilt figure contains a single induced line.

In this study, we explored the source of the difference between the Zöllner illusion and the tilt illusion, and we found that three elemental illusions determined these two illusions.

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EXPERIMENT 1

To examine whether or not the acute-angle contraction also occurs in the Zöllner figure, we changed the second and third conditions described in the introduction. We modified the Zöllner figure with long inducing lines and a single induced line (see Figure 2a). Intersecting angles examined were 27º, 36º, 45º, 53º, 63º, 76º, 83º, and 90º.

Method

Subjects. The subjects were the authors and 8 students who were not aware of the purpose of this study. All had normal or corrected-to-normal vision. All of them participated in the following experiments.

Test figures. Test figures were drawn with a graphics software and printed out onto pieces of white cardboard of fine quality (28 cm high × 22 cm wide) by a printer (RICHO SP-10PS Pro II/6F Laser Printer, 1200 dpi). The thickness of a line was about 0.3 mm. Each of the test stimuli was drawn in the center of a surrounding rectangular frame (16 cm high × 8 cm wide), which was placed in the center of the card. Each comparison figure was composed of a single vertical line or tilted line (each 4 cm long), which deviated from the vertical with angles between −5º and 5º in steps of 0.5º. Each comparison line was drawn in the center of the rectangular frame, which was of the same size as that of the test figure. One of the test figures and one of the comparison figures were simultaneously placed on a hand-made stand, side by side. The figures were illuminated (340 lx) by ceiling fluorescent lamps mounted 2.0 m above the stand. The luminance was 14 cd/m^2 for the (black) figures and 228 cd/m^2 for the card; the contrast, $(L_{max} - L_{min})/(L_{max} + L_{min})$, was 0.88. These conditions were identical throughout the following experiments.

In this experiment, there were two types of the test figures: one including a real line as the induced line, and the other using an illusory line as the induced line (Figure 2a). The former was composed of a 4-cm vertical line (= the induced line) and nine inducing lines that sloped down to the left and periodically intersected the induced line with a 0.5-cm interval; the horizontal width of each line was

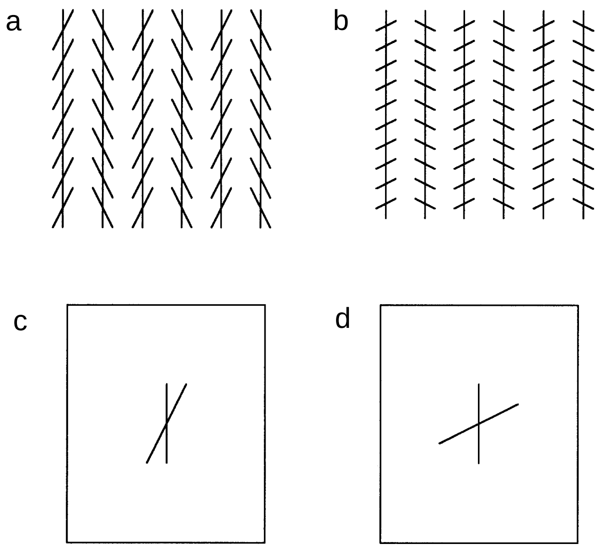

Figure 1. Examples of the Zöllner illusion (a and b) and the tilt illusion (c and d). (a) The Zöllner illusion in which the intersecting angles between the vertical lines and the oblique lines are 27º. In this case, the vertical ones do not appear to be parallel to each other, though they really are. The illusional shift is an acute-angle expansion. (b) The Zöllner illusion with the intersecting angles being 63º. In this case, the parallel vertical lines show a distorted and unstable appearance, but an acute-angle expansion was reported (Morinaga, 1933). (c) The tilt illusion with the intersecting angles being 27º, in which the vertical line appears to tilt counterclockwise. This illusional shift is an acute-angle expansion. (d) The tilt illusion with the intersecting angles being 63º. In this case, the vertical line appears to tilt clockwise. This illusional shift is an acute-angle contraction and is called the *indirect effect* (Gibson & Radner, 1937; O'Toole & Wenderoth, 1977).

constant (5 cm), so that the length of the inducing line varied according to the intersecting angles (27º, 36º, 45º, 53º, 63º, 76º, 83º, and 90º). The latter was composed of half-cycle phase-shifted abutting gratings forming a vertical illusory line (4.5 cm long) in the center; the other conditions were identical to those of the former.

Procedure. The subjects were instructed to estimate the orientation of the induced line in the test figure placed on the frontal plane with a 57-cm viewing distance; 1 cm on the test figures thus corresponded to 1º of visual angles. The subjects' task was to select a comparison stimulus from a stack of cards of single lines, place it in the stand next to the test figure, and continue selecting in this way until they achieved a satisfactory match. They were allowed to shift their position so that they could keep the perpendicular viewing distance. Each test figure was tested once for each subject. The testing order was randomized.

Results and Discussion

We found the acute-angle contraction at angles between 36º and 90º [$F(7,63) = 11.95, p < .01$] (Figure 2b). This result is surprising since it has been believed so far that the Zöllner illusion is an acute-angle expansion illusion. We thus conclude that the Zöllner illusion depends not only on the acute-angle expansion mechanism but also on the acute-angle contraction mechanism.

It is also surprising that the lower limit of the angle giving the contraction (36º) was much lower than that observed in the tilt illusion (50º). This result suggests that the contraction also occurs at much smaller angles where the acute-angle expansion is predominant. Furthermore, this result disagrees with the idea that the contraction is the weak "indirect effect" of the expansion rendered by the "virtual axis" orthogonal to the real axis (Wenderoth, van der Zwan, & Williams, 1993).

Two reviewers simultaneously pointed out that the contraction might be an extension of the reversal of the Zöllner illusion at small angles (5º–15º) or the Fraser illusion (Fraser, 1908; Tyler & Nakayama, 1984) (Figure 3). This idea is attractive. We therefore speculate that an acute-angle contraction mechanism may underlie the Zöllner illusion at small angles through large angles and that the contraction illusion may appear where the expansion illusion is relatively weak.

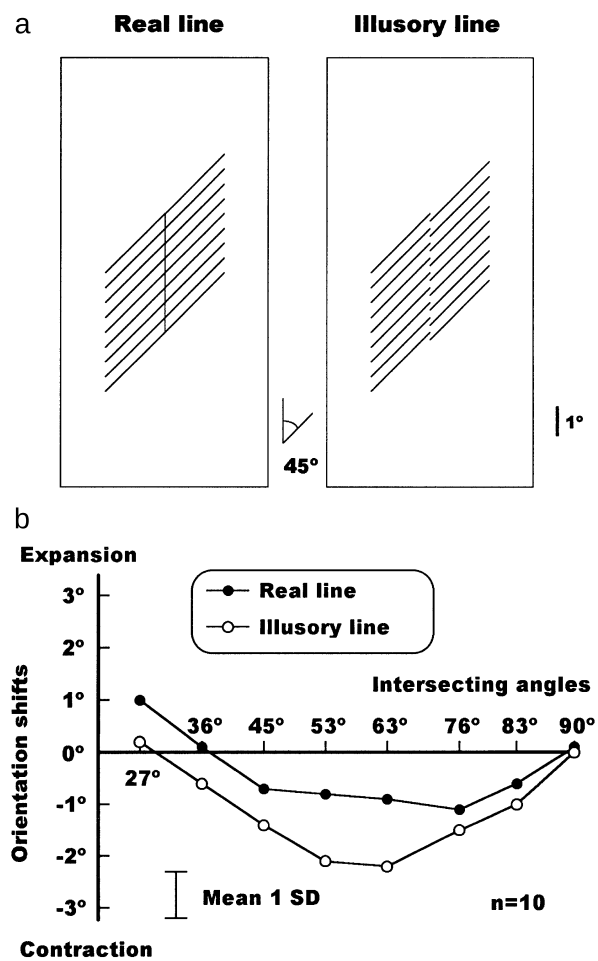

Figure 2. Experiment 1. (a) Examples of the test figures. The inducing line is a real line for the left figure and an illusory line (the border of half-cycle phase-shifted abutting gratings) for the right figure. The intersecting angle is 45º in these figures. (b) The results. The apparent tilt of the vertical induced line was shown. The result showed that the apparent contraction of acute angles (clockwise tilts of the induced line) appeared at the intersecting angles between 36º and 90º. The contraction was greater for the illusory-line figures than for the real-line figures.

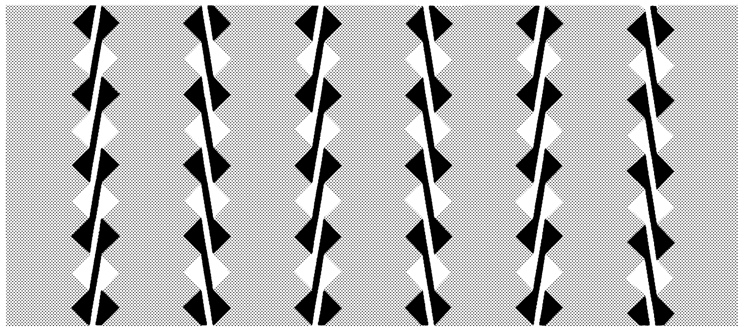

Figure 3. An example of the Fraser illusion. The black and white oblique lines, which deviate with 9.5º from the vertical in this figure, are aligned vertically, but the global lines appear to tilt with the same orientation as those of the oblique lines. This illusional shift is an acute-angle contraction.

Figure 4 shows a model, in which the expansion illusion gradually increases in magnitude as the intersecting angle increases from 0º, shows a peak at angles of 20º–30º, and decays to zero at large angles. On the other hand, the contraction illusion rapidly increases in magnitude as the intersecting angles increases from 0º, but keeps a constant magnitude through large angles, and decays to zero at 90º. Furthermore, it is assumed that the peak magnitude of the expansion illusion is much larger than that of the contraction illusion. This model not only fits the obtained curves of the present experiment but also explains the Fraser illusion. As described later, we presume that the expansion illusion arises at a low level in the visual system, whereas the contraction illusion arises at a higher level.

Finally, the contraction illusion was greater for the illusory-line figures than for the real-line figures [$F(1,9) = 14.14$, $p < .01$] (Figure 2b). This characteristic was also observed in Experiment 2.

EXPERIMENT 2

To determine the characteristics of the two opposite mechanisms, further experiments were implemented. Since the indirect effect was thought to arise at a higher level in the visual system than the acute-angle expansion illusion (Wenderoth & Johnstone, 1988), we first examined the effect of the lengths of inducing lines.

Method

Subjects. The subjects were the same as those who participated in Experiment 1.

Test figures. The intersecting angle was fixed at 45º, and the length of inducing lines was changed. The lengths from the line end to the intersecting point, or the wing length, were 4, 2, 1, 0.5, and 0.25 cm. The other conditions were identical to those in Experiment 1.

Procedure. The procedure was the same as that in Experiment 1.

Results and Discussion

We found that the magnitude of the acute-angle contraction was reduced when the inducing lines were shortened [$F(4,36) = 10.67$, $p < .01$] (Figure 5). This result is quite consistent with O'Toole's (1979) report, though he examined the angle of 70º. Furthermore, we found that the shortest inducing lines gave no illusion in average or a slight expansion for some subjects. These results confirm our hypothesis that there are two opposite illusory mechanisms underlying the Zöllner illusion.

Furthermore, these results suggest that the contraction is rendered by broader regions than is the expansion. This suggestion quite agrees with the results of Wenderoth and Johnstone's (1988) study, which suggested that "indirect effects (= the contraction) arise at a higher level in

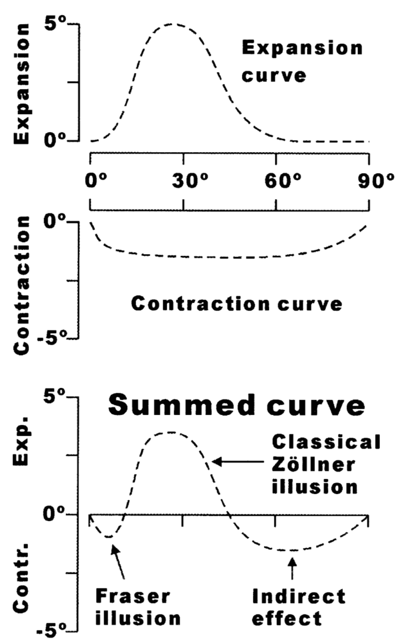

Figure 4. A model speculating the contraction mechanism underlying the Zöllner illusion behind the expansion mechanism. In this model, the summation of the expansion and contraction mechanisms explains not only the indirect effect but also the Fraser illusion.

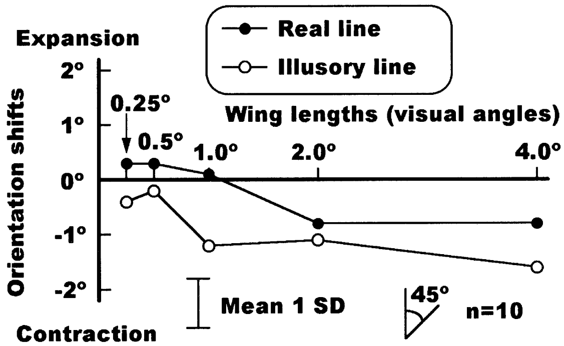

Figure 5. The results of Experiment 2. When the length of inducing lines was reduced, the contraction diminished. The contraction was greater for the illusory-line figures than for the real-line figures.

the visual system, where receptive fields are larger and more global processing occurs."

Finally, the contraction was greater for the illusory-line figures than for the real-line figures [$F(1,9) = 12.49$, $p < .01$]. This characteristic was the same as that of Experiment 1. However, this issue was not pursued any more in this study.

EXPERIMENT 3

It has so far been reported that the expansion is given by the inducing lines in the vicinity of the induced line, within the visual angle of 1° from the induced line (Oyama, 1975; Wallace, 1969). This implies that the expansion arises at a low level in the visual system. To examine whether or not the contraction, which is thought to arise at a higher level, is hidden by the expansion at the small angles where the expansion is predominant, we systematically separated the inducing lines from the induced line. The intersecting angle was 27°; this angle normally gives rise to the acute-angle expansion (see Figures 1a and 1c).

Method

Subjects. The subjects were the same as those who participated in Experiment 1.

Test figures. The intersecting angle was fixed at 27°, and a gap was made to conceal part of the inducing lines in the vicinity of the induced line (Figure 6a). The gap widths were 2, 1, 0.5, and 0 cm (no gap). Only the real-line induced lines were examined. The figure with no gap was the same as the 27° figure in Experiment 1.

Procedure. The procedure was the same as that in Experiment 1.

Results and Discussion

We found that the acute-angle expansion was replaced with the acute-angle contraction when a gap was added [$F(3,27) = 12.87, p < .01$] (Figure 6b). This result can be explained as follows: The effect of the acute-angle expansion is lost by the separation, and the hidden effect of the contraction appears. That is, this result reveals that the contraction energy exists at the small angles where the expansion is predominant, and this also confirms the suggestion that the contraction is rendered by broader regions than is the expansion.

EXPERIMENT 4

As described in the introduction, the standard Zöllner figure includes more than two induced lines, each intersected by inducing lines of different orientations symmetrical to each other. This global configuration has not been systematically examined so far. To examine the effect of the symmetrical configuration, we compared the illusion magnitude between the symmetrical configuration and each of the elemental figures.

Method

Subjects. The subjects were the same as those who participated in Experiment 1.

Test figures. The intersecting angle was fixed at 45°, and the wing length was also fixed at 1 cm. First, we produced two types of elemental figures, the inducing lines of which sloped either down to the left or down to the right (Figure 7). Then, we produced two types of symmetrical figures by connecting the elemental figures to

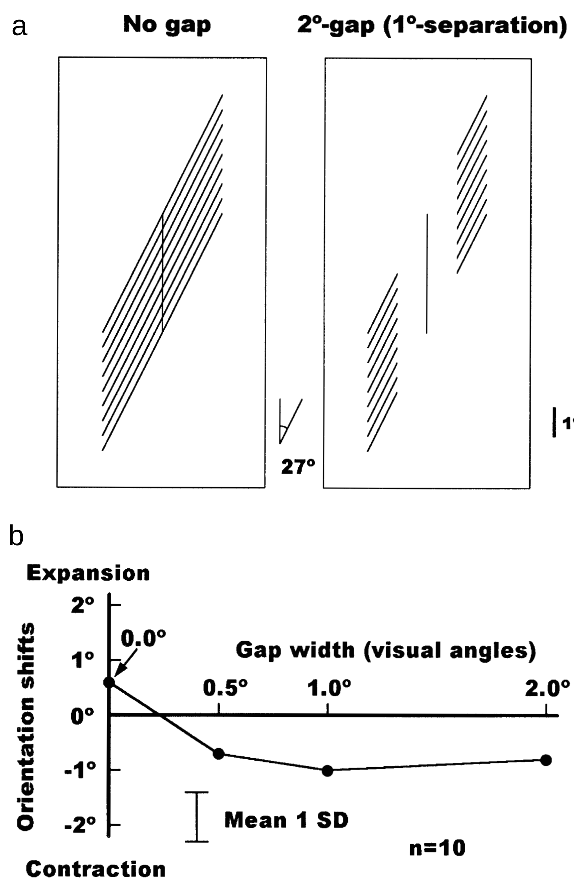

Figure 6. Experiment 3. (a) Examples of the test figures. (b) The results. When the inducing lines did not cross the induced line, the contraction appeared, though the intersecting angle was 27°.

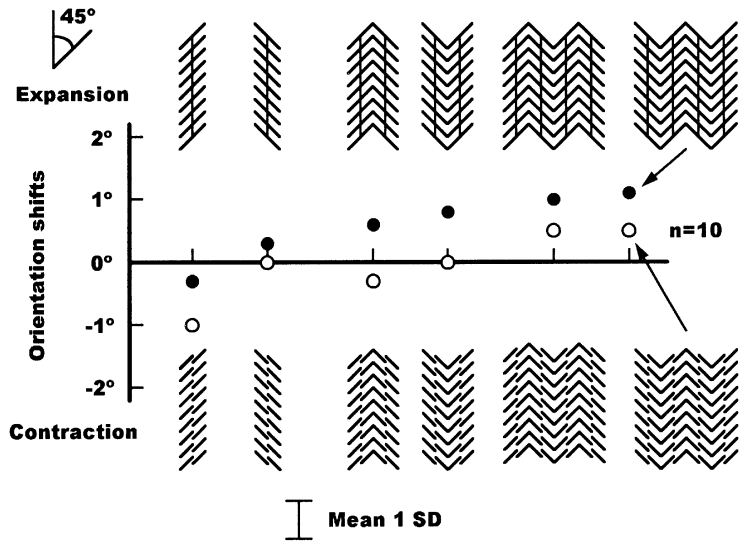

Figure 7. The results of Experiment 4. All test figures were superimposed. Although the elemental figures gave little illusion when the induced line was a real line (the left two of the upper row), the symmetrical figures and the double symmetrical ones composed of the elemental figures (the middle two and the right two of the upper row, respectively) rendered the acute-angle expansion. For the figures of an illusory line (the lower row), the tendency was similar, except that the expansion clearly appeared in only the double symmetrical figures (the right two of the lower row).

each other, the apexes of which pointed either upward or downward. Finally, we produced two types of double symmetrical figures by connecting the symmetrical figures to each other, the inducing lines of which formed either "M"-like or "W"-like shapes. Each of the figures was placed in the center of the frame. The comparison line was single for the elemental figures, double for the symmetrical figures, and quadruple for the double symmetrical figures. The tilts of the double or quadruple comparison lines covaried. Hence, the apparent tilt measured in the symmetrical figures and the double symmetrical figures equaled the half of the apparent angle formed by two adjacent induced lines. The induced lines that were real lines and illusory lines were both examined.

Procedure. The procedure was the same as that in Experiment 1.

Results and Discussion

Figure 7 shows that the elemental figures gave little illusion when the induced line was a real line, whereas the symmetrical figures and the double symmetrical ones composed of the elemental figures rendered the acute-angle expansion. For the figures of an illusory line, the tendency was similar, except that the expansion clearly appeared in only the double symmetrical figures. A two-way analysis of variance, with a 3 (number of induced lines) × 2 (real line vs. illusory line) factorial design, confirmed the tendency described above [$F(2,18) = 9.34$, $p < .01$] but showed no significant difference between the real-line figures and the illusory-line figures [$F(1,9) = 2.05$, n.s.].

This means that the symmetrical configuration gave the expansion of acute angles, though each elemental figure rendered little illusion. This paradoxical result shows that the symmetrical configuration drives another mechanism of the acute-angle expansion, different from and more global than the expansion that has been examined so far. We suggest that the energy of this novel expansion might contribute to the acute-angle expansion of the Zöllner illusion at the large angles between 50° and 90° (Morinaga, 1933) (Figure 1b) where the contraction is observed in the tilt illusion (Figure 1d).

EXPERIMENT 5

In Experiment 5, we examined the effect of the number of inducing lines, since it affects the illusion magnitude (Oyama, 1975; Wallace & Crampin, 1969). The number was reduced from 9 to 1.

Method

Subjects. The subjects were the same as those who participated in Experiment 1.

Test figures. The intersecting angle was fixed at 45°, and the numbers of inducing lines were 9, 5, 3, 2, and 1 (Figure 8). The interval of intersections was constant. Only the real-line induced line was examined. The figure with 9 inducing lines was the same as the 45° figure in Experiment 1, and the size of the other figures followed it.

Procedure. The procedure was the same as that in Experiment 1.

Results and Discussion

We found the contraction in every condition—that is, the effect of the number of inducing lines was small [$F(4,36) = 0.57$, n.s.] (Figure 8). This result is surprising since the observed contraction in the case of 1 inducing

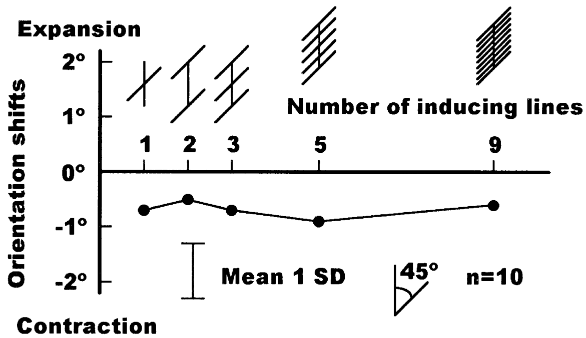

Figure 8. The results of Experiment 5. All test figures were superimposed. It was revealed that the number of inducing lines exerted little influence on the illusion, or the contraction was recorded throughout these conditions.

line indicates that the contraction appeared in the "standard" figure of the tilt illusion at the intersecting angle of 45°. This novel result might have been due to the fact that we used a considerably long inducing line (total length = about 7°), relative to that used in the previous experiments on the tilt illusion, normally up to 3°.

Furthermore, the small effect of the number of inducing lines might be explained by the idea that each inducing line exerted both the expansion and the contraction influences on the perception of the induced line and the contraction was greater than the expansion. But this idea fails to explain why there was no quantitative difference among the conditions.

GENERAL DISCUSSION

In summary, we have discovered the surprising evidence that at least three neural mechanisms are underlying the Zöllner illusion, two of them being the acute-angle expansion and one being the acute-angle contraction. Furthermore, we have found that one of the expansion mechanisms is restricted to narrow regions (or being "local"), whereas the other expansion mechanism and the contraction mechanism are affected by broad regions (or being "global").

We propose a model including the "local" expansion mechanism and the "global" contraction mechanism (Figure 4), in which the summation of both mechanisms explains not only the indirect effect but also the Fraser illusion. Furthermore, we presume that the global expansion mechanism works at large angles as well as at 45°. This might be the main reason why the Zöllner illusion showed the acute-angle expansion even at large angles (50°–90°) (Morinaga, 1933; Wallace & Crampin, 1969), whereas the tilt illusion did not (Gibson & Radner, 1937; O'Toole & Wenderoth, 1977; Over et al., 1972).

Previous models cannot integrate these findings. For example, Tyler and Nakayama's (1984) model, which assumes an interaction between orientation-specific neurons with small receptive fields and those with large receptive fields, does not explain the indirect effect. Morgan and Baldassi's (1997) model, which posits that second-order orientation units receive excitation from V1 units of similar orientation whereas they receive inhibition from V1 units of dissimilar orientation, also does not explain the indirect effect. These models are valid if the indirect effect and the Fraser illusion are of different origins.

In neurophysiological terms, what cortical areas might play an important role in the three mechanisms? The local angle-expansion illusion has so far been attributed to the behavior of V1 cells (Wallace, 1969, 1975; Wenderoth & Johnstone, 1988). A speculative idea is that the two global mechanisms (expansion and contraction) might exist in area V4 or even higher areas coding "form" such as TEO and TE, whereas the local mechanism (expansion) might be located in area V1 and V2 when the induced line is a real line and an illusory line, respectively. This speculation agrees with the average receptive field sizes of neurons in each cortical area—that is, they are large in V4 or higher areas (more than $4° \times 4°$ around fovea) and small in V1 or V2 (less than $2° \times 2°$ around fovea) (Desimone & Gross, 1979; Desimone & Schein, 1987; Dow, Snyder, Vautin, & Bauer, 1981; Gattass, Gross, & Sandell, 1981; Kobatake & Tanaka, 1994; Van Essen, Newsome, & Maunsell, 1984). Furthermore, this speculation about the local mechanism is quite consistent with previous reports that gave the neurophysiological evidence of the acute-angle expansion with real lines in area V1 (Gilbert & Wiesel, 1990) and with illusory lines in area V2 (Peterhans & von der Heydt, 1992; von der Heydt & Peterhans, 1989).

In the earliest cortical stage of visual systems or V1, orientations of small regions are detected. They are then integrated in higher cortical areas. In this context, we support the "collector-unit" model proposed by Morgan and Hotopf (1989; also see Morgan & Baldassi, 1997), who postulated second-order orientation-detecting "collector units" that combine inputs from first-order orientation-detecting units. In their model, global orientation detected by collector units shifts in the same direction as the direction in which local orientations detected by first-order units shift, if the first-order units are aligned along the preferred orientation of the collector units. We then suppose that the local expansion illusion is first generated in the first-order units or V1 neurons and that the global orientation detected by collector units (V4 neurons?) thereby shifts toward expansion. After that, the global orientation might be affected by the global contraction and/or the "global expansion" mechanisms. Their summation or interactions might determine the final orientation shift.

In conclusion, we have revealed three different sources of illusion in the Zöllner figure; this discovery might encourage us to clarify the tangled mechanisms of visual illusions and furthermore lead to understanding vision more deeply.

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