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Tilt illusions after Oyama (1960): A review[1]

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Abstract: This article reviews the study of tilt illusions by focusing on new illusions or new demonstrations reported by Japanese researchers after the review of Oyama (1960). Steady progress was observed in a variety of illusions. In particular, the development of the study of the Café Wall illusion and its related illusions during the past decade was remarkable. The study of the spiral illusion has also progressed dramatically.

Key words: tilt illusion, orientation, Zöllner illusion, Fraser illusion, Café Wall illusion, spiral illusion.

Visual illusion refers to the phenomenon that some properties of the percept of an object are different from those as they "really" are. Visual illusion includes the illusion of shape, lightness, color, motion, etc. (see Kitaoka, 2005a). The illusion of shape, traditionally called "geometrical" illusion, includes the illusion of orientation, size, and position (Robinson, 1972). This article focuses on the illusion of orientation, that is, tilt illusion.

Tilt illusion refers to apparent tilt of a line, bar or an edge. For example, parallel lines do not appear to be parallel, a straight line appears to curve, or the angle formed by two lines appears to be larger or smaller than it really is. The aim of this article is to review the study of tilt illusions reported by Japanese researchers after the review of Oyama (1960), with a focus on new illusions or new demonstrations.

Zöllner illusion

Zöllner illusion

The Zöllner illusion is the apparent expansion of the acute angle formed by two crossing lines. Figure 1 shows an example in which a horizontal line appears to tilt clockwise because it is crossed by oblique lines that tilt counterclockwise from the horizontal.

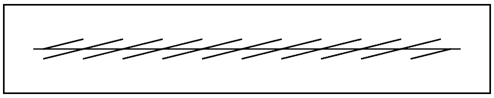

Figure 1. The Zöllner illusion. The horizontal line appears to tilt clockwise.

The Zöllner illusion is observed when the acute angle is between 0° and 90° (Morinaga, 1933; Parlangeli & Roncato, 1995; Wallace & Crampin, 1969), but the maximum magnitude is obtained when the acute angle is between 10° and 30° (Maheux, Townsend, & Gresock, 1960; Morinaga, 1933; Oyama, 1975; Wallace & Crampin, 1969). The Zöllner illusion is stronger when induced lines are rotated 45° from the vertical or horizontal than when they are vertical or horizontal, respectively (see Oyama, 1960).

Oyama (1975, 1977) revealed that, in the Zöllner illusion, interactions between two lines are limited to narrow visual fields and he

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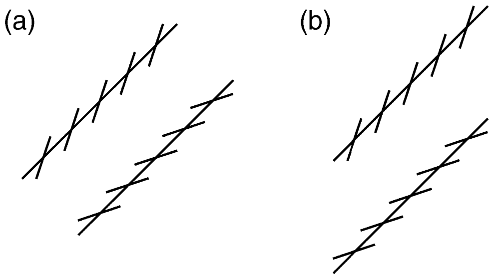

Figure 2. The P effect. When the (a) (standard) rectangular configuration of the induced lines is replaced with a (b) parallelogram configuration, the magnitude of the Zöllner illusion increases. Reproduced from Imai (1970), with permission.

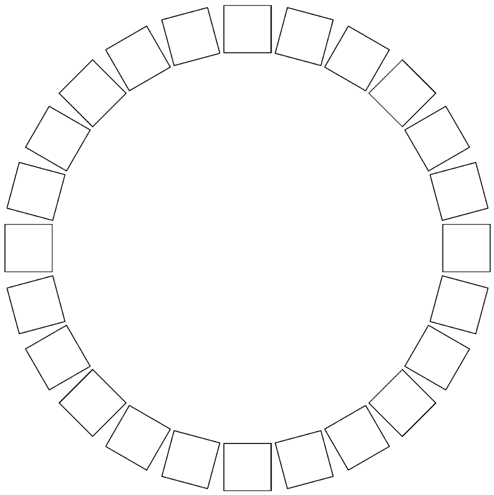

Figure 3. The squares-ring illusion. Each square appears to be a trapezoid, in which the inner side appears to be longer than the outer one. Reproduced from Imai (1973), with permission.

conjectured that this illusion originates from the activity of V1 neurons, which have relatively small receptive fields. Recently, Sakai and Hirai (2002) proposed a neural network model of V1 to explain the Zöllner illusion.

Imai (1970) proposed a new effect in the Zöllner illusion and called it the "P" effect (Figure 2). This effect enhances the Zöllner illusion when induced lines form a parallelogram configuration (Figure 2b) compared with the standard rectangular one (Figure 2a). Moreover, Imai (1973, 1976) pointed out shape distortion in a familiar image known as the color ring or hue circle and called it the "squares-ring" illusion (Figure 3), which he regarded as a variant of the Zöllner illusion.

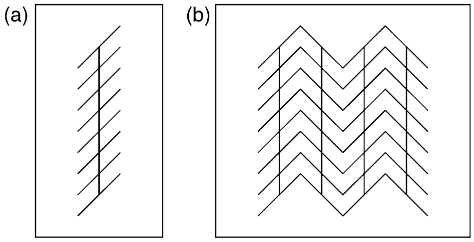

Figure 4. Symmetry effect. The Zöllner illusion or acute-angle expansion is stronger in (b) than in (a).

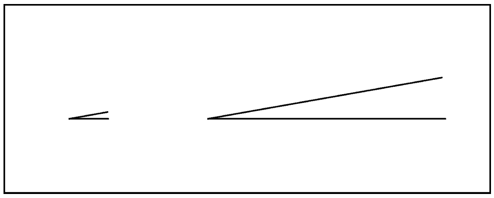

Figure 5. The Wada-Tanaka illusion (acute angle type). The longer the two converging lines, the larger the apparent angle. Adapted from Tanaka (1982), with permission.

Kitaoka and Ishihara (2000) revealed a new effect, which enhances the Zöllner illusion. When inducing lines intersect a single induced line at a large angle (e.g., 45°), the Zöllner illusion is weak (Figure 4a). Yet symmetrical arrangement of two or four induced lines (V or W shape) creates larger illusion magnitudes in the Zöllner illusion (Figure 4b).

Nihei (1973, 1975) demonstrated that the path of motion of an object is affected by oblique lines in the direction of acute-angle expansion in a configuration of the Poggendorff illusion. This observation was later confirmed in a configuration of the Zöllner illusion by Swanston (1984).

Wada-Tanaka illusion

Tanaka (1982) reported a pair of new effects. One is that when the angle is acute, the longer the two converging lines are, the larger the apparent angle (Figure 5). The other is that when the angle

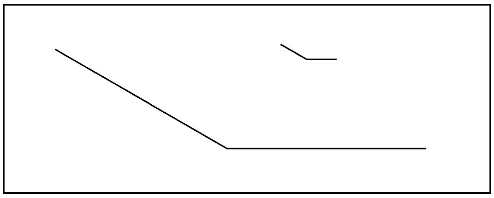

Figure 6. The Wada-Tanaka illusion (obtuse angle type). The longer the two converging lines, the smaller the apparent angle. Adapted from Tanaka (1982), with permission.

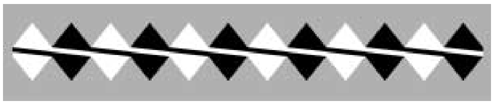

Figure 7. The Fraser illusion. The horizontal row made up of clockwise-tilted line segments (twisted cords) appears to tilt clockwise.

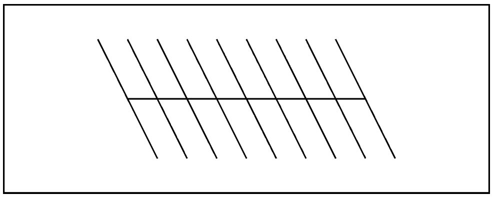

Figure 8. The indirect effect. The horizontal line appears to tilt clockwise, although the illusion magnitude is relatively small.

is obtuse, the longer the two converging lines are, the smaller the apparent angle (Figure 6). These illusions are called the Wada-Tanaka illusion (Kitaoka, 2005c). Although the apparent tilts are of the same orientation as those of the Zöllner illusion, the Wada-Tanaka illusion might be different from the Zöllner illusion because the illusion magnitude of the latter does not increase when the lengths of the inducing lines exceeds approximately 1° (Oyama, 1975).

Fraser illusion

Fraser illusion

There are two illusions that show the reversal of the Zöllner illusion, that is, acute-angle contraction. One is the Fraser illusion (Fraser, 1908) (Figure 7) and the other is the indirect effect (Gibson & Radner, 1937) (Figure 8).

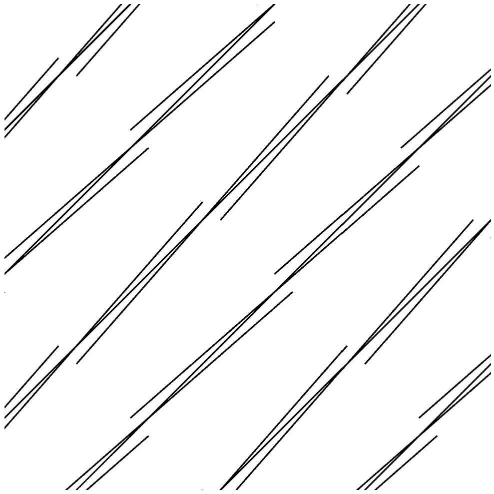

Figure 9. Imai's (1962) angle-contraction illusion. Each of the oblique, parallel lines appears to tilt toward the orientation of the crossing lines. Reproduced from Imai (1962), with permission.

There is an argument about the necessary condition for the Fraser illusion to occur. The accepted idea is that the Fraser illusion occurs when the acute angle is smaller than the angles that produce the Zöllner illusion. Imai (1962) reported that the reversal of the Zöllner illusion occurs when the acute angle is 3° (Figure 9). Oyama (1975) reported that the reversal occurs at 10° (Figure 10). Kitaoka (2005b) reported that angle 14° generates the Fraser illusion (Figure 11). Moreover, it has been reported that even larger angles can also produce it under a special condition (Dakin, Williams, & Hess, 1999; Morgan & Baldassi, 1997; Skillen, Whitaker, Popple, & McGraw, 2002) (Figure 12).

Indirect effect

The "indirect" effect occurs when the acute angle is relatively large (>50°) (Gibson & Radner, 1937; O'Toole, 1979; O'Toole & Wenderoth, 1977; Wenderoth & Johnstone, 1988) (Figure 8). Kitaoka and Ishihara (2000) revealed that this illusion can occur even when the angle is smaller than 45°, if the induced line is single and the inducing lines are long enough.

Kitaoka (1997) proposed the spider-web curvature illusion (Figure 13) and the illusion of

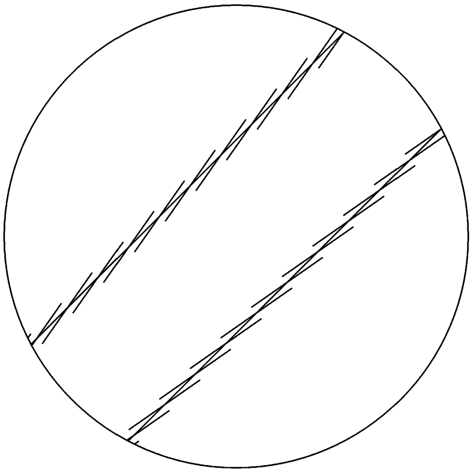

Figure 10. Oyama's (1975) angle-contraction illusion. Each of the two oblique, parallel lines appears to tilt toward the orientation of the crossing lines. Produced on the basis of his data.

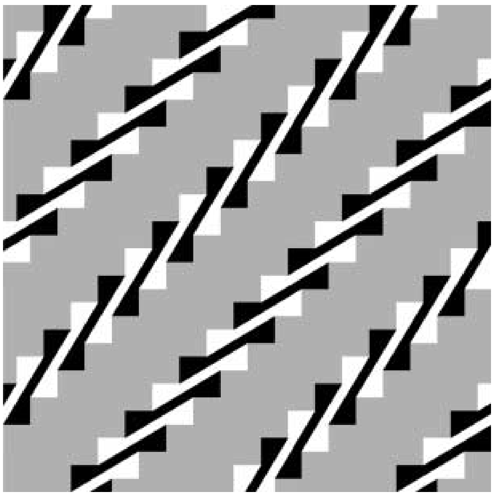

Figure 11. Fraser illusion with 14° angles. Each of the oblique, parallel rows appears to tilt toward the orientation of twisted cords.

shifted rows (Figure 14), which are characterized by apparent angle contraction. These illusions might depend on the same mechanism as the indirect effect because they show the maximum effect at large angles (e.g., 60°). Moreover, the illusion of shifted rows was also shown in Dakin et al. (1999) in a different image (Figure 15).

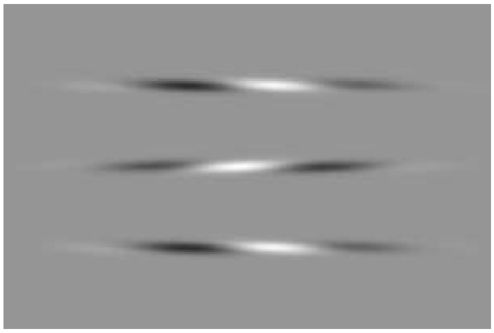

Figure 12. The Fraser illusion demonstrated in a contrast-modulation image, where inducers are carriers (black-and-white gratings) and induced lines are horizontally elongated envelope windows (the fields in which carriers are seen). In this image, the carriers tilt at 20° from the horizontal. Each envelope appears to tilt in the same orientation as that of the carrier. Modified from Figure 1a of Skillen, J., Whitaker, D., Popple, A., & McGraw, P. V. (2002) "The importance of spatial scale in determining illusions of orientation." *Vision Research,* **42,** 2447–2455, with permission from Elsevier.

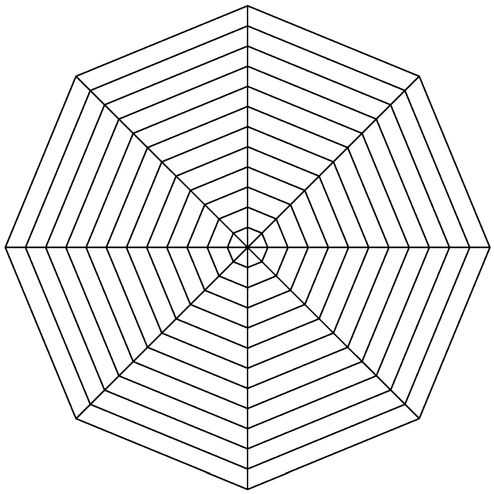

Figure 13. The spider-web curvature illusion. The threads that run crosswise appear to curve toward the center. Concentric squares also work.

Café Wall illusion

Café Wall illusion and Münsterberg illusion

The Café Wall illusion refers to the apparent tilt of a gray line (frequently called the "mortar"

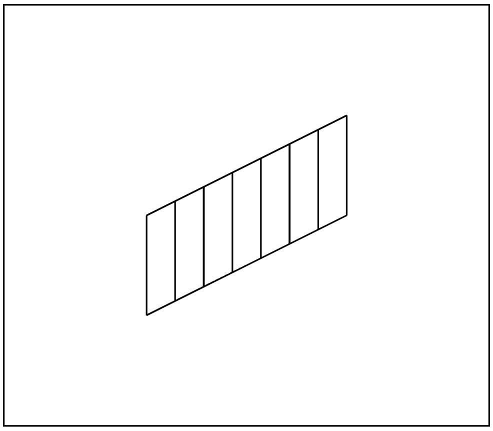

Figure 14. The illusion of shifted rows. The eight verticals appear to tilt clockwise.

Figure 15. Dakin et al.'s (1999) version of the illusion of shifted rows. The carrier or the luminance grating appears to tilt clockwise, although it is vertical. Modified from Figure 5f of Dakin, S. C., Williams, C. B., & Hess, R. F. (1999) "The interaction of first- and second-order cues to orientation." *Vision Research,* **39,** 2867–2884, with permission from Elsevier.

line) placed on the border between two shifted rows of black and white squares (Figure 16). This illusion was first demonstrated by Fraser (1908) and named so by Gregory and Heard (1979). When the induced line is black, the illusion is called the Münsterberg illusion (Münsterberg, 1897) (Figure 17), which is thought to be a special case of the Café Wall illusion.

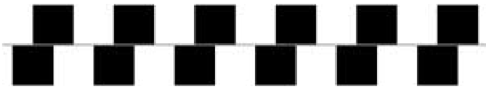

Figure 16. The Café Wall illusion. The gray horizontal line (mortar line) appears to tilt clockwise.

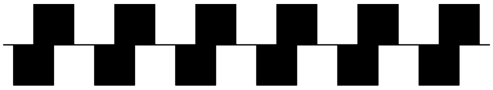

Figure 17. The Münsterberg illusion. The black horizontal line appears to tilt clockwise.

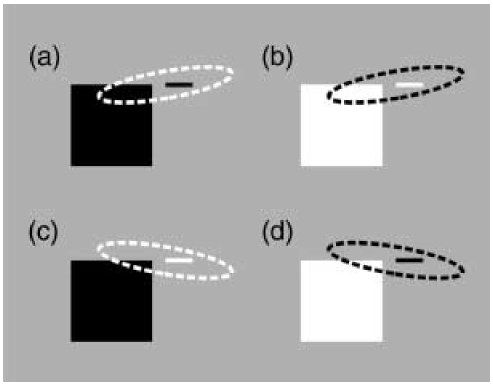

Figure 18. The phenomenal model of the Café Wall illusion. Combinations between squares and line segments determine the orientations of apparent tilts depending on contrast polarity, as indicated with elongated ellipses. In this model, the Café Wall illusion depends on only the elemental illusions (a) and (b).

Kitaoka-Pinna-Brelstaff's phenomenal model

Kitaoka, Pinna, and Brelstaff (2004) proposed a phenomenal model to explain the Café Wall illusion, which stressed the importance of contrast polarities of a solid square and its adjacent line segment. When a dark/light square is accompanied by a dark/light line segment, the apparent tilt is the direction of contraction of the square angle (Figure 18a,b). In contrast, when a dark/light square is accompanied by a light/dark line segment, the apparent tilt is the

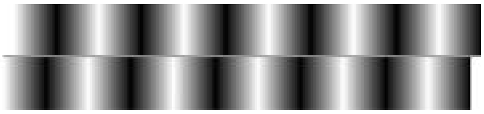

Figure 19. The illusion of shifted gradations. The gray horizontal line appears to tilt clockwise.

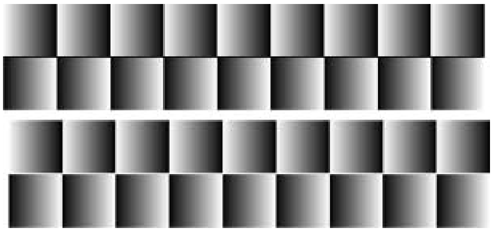

Figure 20. The Montalvo illusion or the Lavatory Wall illusion. The black line in the upper image appears to tilt counterclockwise while the white line in the lower image appears to tilt clockwise, although the inducing gradation patterns are the same between the upper and lower images. The upper illusion depends on an ensemble of Figure 18a and 18d, while the lower one is based upon that of Figure 18b and 18c. For a clearer portrayal of how the Montalvo illusion can be explained using the phenomenal model, see Figure 7a–c of Kitaoka et al. (2004).

direction of expansion of the square angle (Figure 18c,d).

This model satisfactorily explained most tilt illusions that resemble the Café Wall illusion, such as the illusion of shifted gradations (Kitaoka, 1998) (Figure 19) and the Montalvo illusion (Lavatory Wall illusion) (Sakane, 1980; Woodhouse & Taylor, 1987) (Figure 20). Moreover, the model produced "new" illusions, such as the reverse Café Wall illusion (Figure 21) and the Café Wall illusion of black and white squares (Figure 22).

Recently, Takeuchi (2005) proposed an energy-based model to explain the Café Wall illusion, although he did not mention the phenomenal model. Arai (2005) applied wavelet filters to give a new computational model of a variety of visual illusions including the Café Wall illusion. He cited Kitaoka et al. (2004) but did not examine illusions based upon the two elemental illusions of Figure 18(c,d).

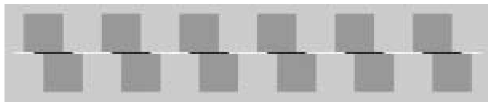

Figure 21. The reverse Café Wall illusion. The black-and-white horizontal line appears to tilt clockwise. This illusion depends on the elemental illusions of Figure 18c and d.

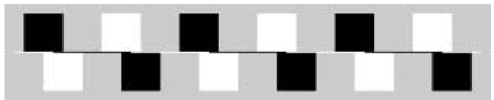

Figure 22. The Café Wall illusion of black and white squares. The black-and-white horizontal line appears to tilt clockwise. This illusion depends on the four elemental illusions of Figure 18.

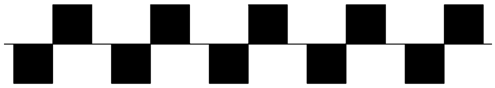

Figure 23. The checkered illusion. The black horizontal line appears to tilt clockwise.

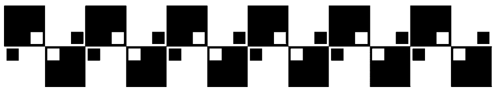

Figure 24. The enhanced checkered illusion. This image consists only of squares. The horizontal border between the upper and lower rows appears to tilt clockwise.

Checkered illusion

Kitaoka (1998) devised the checkered illusion (Figure 23), although Kitaoka (2005b) later noticed that this illusion had already been proposed by Lipps (1897). This illusion was fully explained with the phenomenal model (Figure 18).

Moreover, Kitaoka (2001) proposed an enhanced version of the checkered illusion, as shown in Figure 24. This variation gives a much stronger illusion than the originals of Lipps (1897) and Kitaoka (1998).

It should be noted that the configuration of Figure 24 includes another novel tilt illusion,

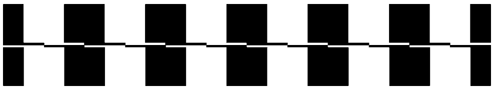

Figure 25. The illusion of shifted lines. The black or white shifted line segments, each of which is horizontal, are aligned horizontally. In this image, the row appears to tilt clockwise.

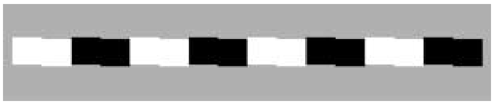

Figure 26. The illusion of shifted edges. The black or white blocks with vertically shifted edges, each of which is horizontal, are aligned horizontally. In this image, the row appears to tilt clockwise.

which is characterized by a shift between two adjacent line segments (Figure 25). The present article tentatively calls this the "illusion of shifted lines." This novel tilt illusion resembles the Fraser illusion (Figure 7), although the latter is characterized by oblique lines.

Other tilt illusions

Illusion of shifted edges

Kitaoka, Pinna, and Brelstaff (2001, 2004) proposed a new illusion called the illusion of shifted edges (Figure 26). Slight shifts between two edges of the same contrast polarity cause this illusion, whereas shifts between two edges of different contrast polarity do not. Although the original version of the illusion of shifted edges is characterized by abrupt shifts, smooth shifts also work (Figure 27).

Moreover, oblique edges give a similar illusion (Figure 28). This novel illusion, or the illusion of "oblique edges," can be regarded as the counterpart in edge-drawn images of the Fraser illusion because the Fraser illusion is characterized by oblique lines as inducers or is based upon line-drawing images (Figure 7). Actually, the illusion of oblique edges has been shown previously in Popple and Sagi's (2000) figure 6 as "traditional Fraser illusion figures."

Furthermore, I here propose a new illusion called the reverse checkered illusion (Figure 29),

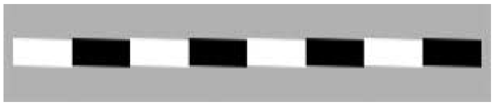

Figure 27. The illusion of smoothly shifted edges. The black or white blocks with smoothly graded edges are aligned horizontally. In this image, the row appears to tilt clockwise.

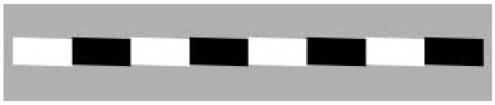

Figure 28. The illusion of oblique edges. The black or white blocks with oblique edges are aligned horizontally. In this image, the row appears to tilt clockwise.

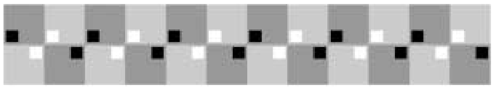

Figure 29. The reverse checkered illusion. This image consists only of squares. The horizontal border between the upper and lower rows appears to tilt clockwise.

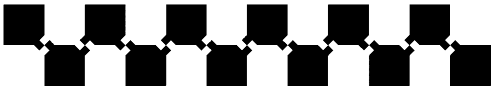

Figure 30. The illusion of fringed edges. This image consists of squares and diamonds. The horizontal border between the upper and lower rows appears to tilt clockwise.

an apparent reversal of the enhanced checkered illusion. This illusion might be able to be attributed to the illusion of shifted edges (see Roncato, 2006).

Illusion of fringed edges

Kitaoka et al. (2001) proposed a new illusion called the illusion of fringed edges (Figure 30). This illusion occurs when a diamond block made up of two smaller black diamonds and two smaller white ones is placed at the corners of squares of a black-and-white checkered pattern.

This illusion can be regarded as a special case of more general illusions. One is shown in

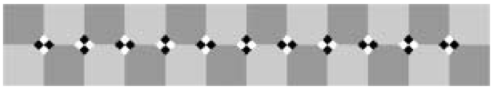

Figure 31. The illusion of fringed edges, in which squares are dark gray or light gray instead of black or white squares. The horizontal border between the upper and lower rows appears to tilt clockwise.

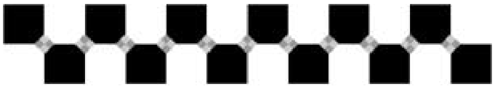

Figure 32. The illusion of fringed edges, in which diamonds are dark gray or light gray instead of black or white diamonds. The horizontal border between the upper and lower rows appears to tilt clockwise.

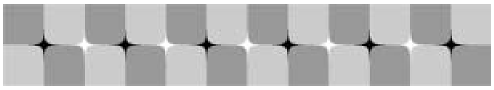

Figure 33. The illusion of Y-junctions. This image consists of squares and stars. The horizontal border between the upper and lower rows appears to tilt clockwise.

Figure 31, in which squares are dark gray or light gray. The other is shown in Figure 32, in which diamonds are dark gray or light gray.

This illusion was explained by the phenomenal model (Kitaoka et al., 2004) (Figure 18). In my present opinion, however, there remains a possibility that this illusion can also be attributed to the illusion of shifted edges (Figure 26).

Illusion of Y-junctions

Kitaoka et al. (2001) proposed a new illusion called the illusion of Y-junctions (Figure 33). This illusion occurs when stars are placed at the corners of the squares of a checker pattern. The orientation of an apparent tilt depends on the combination between the contrast polarity of a star and those of its surrounding squares. There are two other variations of this illusion as shown in Figures 34 and 35.

Illusion of striped cords

The illusion of Y-junctions resembles the illusion of striped cords, which was proposed by

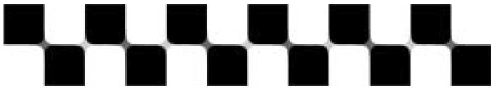

Figure 34. The illusion of Y-junctions, in which stars are dark gray or light gray while squares are black or white. The horizontal border between the upper and lower rows appears to tilt clockwise.

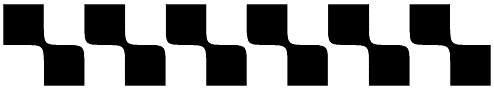

Figure 35. The illusion of Y-junctions, in which stars as well as squares are black or white. The horizontal border between the upper and lower rows appears to tilt clockwise.

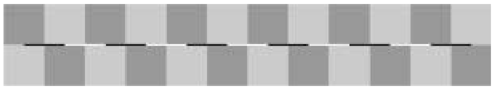

Figure 36. The illusion of striped cords. The horizontal line made up of black and white line segments drawn between the upper and lower rows appears to tilt clockwise.

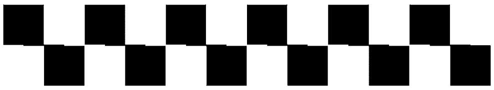

Figure 37. A variation of the illusion of striped cords. The horizontal border between the upper and lower rows appears to tilt clockwise.

Kitaoka (1998) (Figure 36). Later, it was claimed that this illusion can be fully explained by the phenomenal model (Figure 18).

However, I have to point out a flaw in this explanation. When the dark gray squares and the light gray ones are replaced with black squares and white ones, respectively, Figure 36 is changed to Figure 37, where the tilt illusion remains. This illusion, however, cannot be explained by the phenomenal model because there are no longer any line segments. Instead, the tilt illusion of Figure 37 should be attributed to the illusion of shifted edges (Figure 26).

Moreover, when the black line segments and the white ones are replaced with dark gray

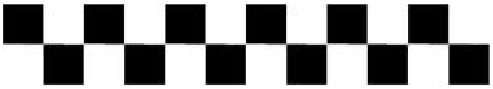

Figure 38. A variation of the illusion of striped cords. The horizontal border made up of dark gray and light gray line segments between the upper and lower rows appears to tilt clockwise.

Figure 39. "Three-field" positional illusions. In each square, the upper and lower sides are the positions where the illusion occurs. (a) The left dark gray square appears to be higher than the right one, even though they are aligned horizontally. (b) The left black square appears to be higher than the right one, even though they are aligned horizontally.

ones and light gray ones, respectively, Figure 37 is changed to Figure 38, where the tilt illusion remains as well. This illusion also cannot be explained using the phenomenal model. Instead, the tilt illusion of Figure 38 also should be attributed to the illusion of shifted edges (Figures 26–29).

Can positional illusions explain tilt illusions?

One may prefer solving the problem described above by introducing a hypothesis that these tilt illusions are explained with positional illusions (Fermüller & Malm, 2004; Roncato, 2000, 2006; Roncato & Casco, 2003). In the images of these tilt illusions, positional illusions appear in the configuration made up of three fields of different luminances, one being thin and the other two being thick, with the latter flanking the former (Gregory & Heard, 1983; Kitaoka, 2006; Morgan, Mather, Moulden, & Watt, 1984). Moreover, the line type (Figure 39a) is distinguished from the edge type (Figure 38b). The latter was named the "gray edge" or "fuzzy edge" by Roncato (2000).

In the line-type positional illusion, the darker flank appears to shift toward the darker line while the lighter flank appears to shift toward the lighter line (Gregory & Heard, 1983) (Figure 39a). In the edge-type position illusion, the darker flank appears to shift toward the darker edge line while the lighter flank appears to shift toward the lighter edge line (Kitaoka, 2006; Morgan et al., 1984) (Figure 39b).

This hypothesis appears to solve the problem of the illusion of striped cords because the apparent tilt in Figure 36 can be explained by the apparent positional shift of Figure 39a, while the apparent tilt in Figure 38 can be explained by the apparent positional shift of Figure 39b.

However, the tilt illusion of Figure 37 as well as the illusion of shifted edges (Figure 26) cannot be explained by this hypothesis without some additional assumptions. Moreover, this hypothesis cannot be applied to how the Café Wall (Figure 16) or Münsterberg illusions (Figure 17) occur because their images cannot be resolved into the configurations of the positional illusions.

It is therefore suggested that these positional illusions might play some part in generating some of the tilt illusions, but that the former are not the only determinants of the latter.

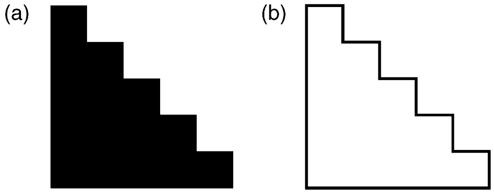

Figure 40. Corner effect. (a) The right angles appear to be acute. (b) The lines also appear to generate an effect similar to the corner effect.

Corner effect

The corner effect refers to the apparent contraction of an edge angle (Kitaoka, 1998; Moulden & Renshaw, 1979). For example, each of the angles of the "staircase" shown in Figure 40a is at right angles, but they appear to be more acute. Kitaoka (1998) applied this illusion to explain the Café Wall illusion or the checkered illusion, but the explanation was later withdrawn by Kitaoka et al. (2004) who instead proposed the phenomenal model (Figure 18).

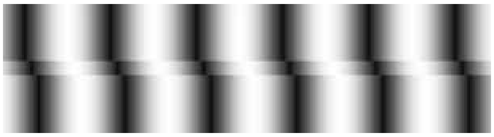

Figure 41. The Haig illusion. The middle grating appears to tilt clockwise, although it is horizontally displayed.

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Figure 42. Letter-row tilt illusion. The upper row, made up of four Japanese katakana letters, appears to tilt counterclockwise although it is horizontally aligned. This row is adapted from Kohara (2005), with permission. The lower row, made up of four Chinese characters, appears to tilt clockwise although it is horizontally aligned. The word used in this row means "grant-in-aid for scientific research awarded."

Here I point out a finding that edges are not absolutely necessary because lines alone can also yield this distortion (Figure 40b), although the illusion magnitude appears to be smaller than that in edge-drawn images. This effect was first reported in Tanaka (1982).

The configuration of the corner effect resembles that of the Haig illusion (Haig, 1989) (Figure 41). However, the latter is not explained by the former because the orientation of apparent tilt is opposed to one another. That is, the Haig illusion is characterized by the apparent expansion of edge angles whereas the corner effect is apparent contraction.

Letter-row tilt illusion

In Japan, a new illusion has suddenly become popular on the Internet since the beginning of 2005. It is called the letter-row tilt illusion. Arai and Arai (2005a, 2005b) highlighted the critical role of horizontal line segments, which should be vertically shifted between two letters neighboring each other (Figure 42). Kohara (2005) proposed an idea that this illusion may be a variation of the phase-shift illusion or Popple illusion (Popple & Levi, 2000; Popple & Sagi, 2000) (Figure 43).

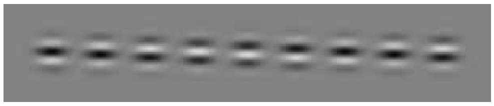

Figure 43. Popple illusion or phase-shift illusion. In this image, there are nine Gabor patches, in which the phase of the carrier of a patch is slightly (60°) shifted downward in its right patch. The row of the envelope windows appears to tilt clockwise, although it is horizontally aligned. This illusion looks similar to the Fraser illusion, but the inducers do not have oblique components. Modified from Figure 2 of Popple, A. V., & Sagi, D. (2000) "A Fraser illusion without local cues?" *Vision Research,* **40,** 873–878, with permission from Elsevier.

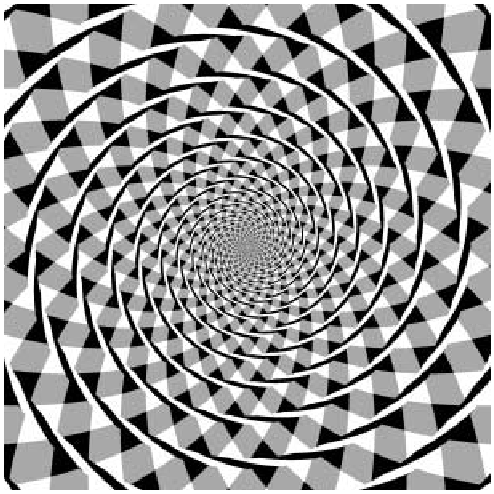

Figure 44. The spiral illusion of the Fraser illusion. In this image, observers perceive illusory spirals that rotate clockwise to approach the center, although the twisted cords are actually concentric circles.

Spiral illusion

When Fraser's twisted cords are drawn along concentric circles, the spiral illusion occurs (Fraser, 1908) (Figure 44). Although it had long been accepted implicitly that only the Fraser illusion produces the spiral illusion,

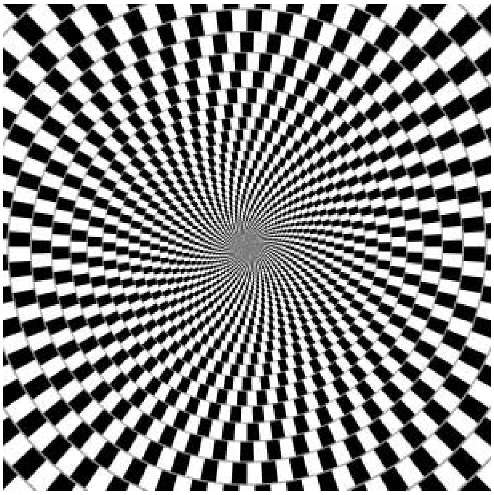

Figure 45. The spiral illusion of the Café Wall illusion. In this image, observers perceive illusory spirals that rotate clockwise to approach the center, although the mortar lines are actually concentric circles.

Kitaoka et al. (2001) revealed that any tilt illusion can yield the spiral illusion (Figure 45), and explained it with a neural model by assuming the detector of Bernoulli's spiral to play a part.

Conclusion

Steady progress was observed in a variety of tilt illusions in Japan after the review of Oyama (1960). Using these cumulative resources, further fruitful development is expected in the future.

References

Arai, H. (2005). A nonlinear model of visual information processing based on discrete maximal overlap wavelets. *Interdisciplinary Information Sciences*, **11**, 177–190.

Arai, H. & Arai, S. (2005a). Analysis on the letter-row tilt illusion. I: Wavelet analysis on an illusion produced by Japanese characters "KONIAGA" (Mojiretsu keisha sakushi no kaiseki I. "Koniaga" no ueibu retto ni yoru kaiseki). *Arai's Laboratory Technical Report*, April 8 (in Japanese). Available from URL: http://www4.ocn.ne.jp/~arai/mvel/e-repo.html.

Arai, H., & Arai, S. (2005b). Analysis on the letter-row tilt illusion. II: Creation of character-string tilt illusions by the use of wavelets (Mojiretsu keisha sakushi no kaiseki II. Ueibu retto kaiseki o mochiita mojiretsu keisha sakushi no sakusei). *Arai's Laboratory Technical Report*, April 14 (in Japanese). Avalailable from URL: http://www4.ocn.ne.jp/~arai/mvel/e-repo.html.

Dakin, S. C., Williams, C. B., & Hess, R. F. (1999). The interaction of first- and second-order cues to orientation. *Vision Research*, **39**, 2867–2884.

Fermüller, C., & Malm, H. (2004). Uncertainty in visual processes predicts geometrical optical illusions. *Vision Research*, **44**, 727–749.

Fraser, J. (1908). A new illusion of visual direction. *British Journal of Psychology*, **2**, 307–320.

Gibson, J. J., & Radner, M. (1937). Adaptation, after-effect, and contrast in the perception of tilted lines. I. Quantitative studies. *Journal of Experimental Psychology*, **20**, 453–469.

Gregory, R. L., & Heard, P. (1979). Border locking and the Café Wall illusion. *Perception*, **8**, 365–380.

Gregory, R. L., & Heard, P. F. (1983). Visual dissociations of movement, position, and stereo depth. *Quarterly Journal of Experimental Psychology*, **35A**, 217–237.

Haig, N. D. (1989). A new visual illusion, and its mechanism. *Perception*, **18**, 333–345.

Imai, S. (1962). An experiment of the reverse Zöllner illusion (Zöllner gyaku sakushi ni kansuru jikken). *Journal of Social Sciences and Humanities (Jimbun Gakuho), Tokyo Metropolitan University*, **30**, 31–43. (In Japanese.)

Imai, S. (1970). Positional and shape effects of parallel test lines in the Zöllner illusion (Zöllner irujon ni okeru heikoshusen no ichi oyobi keitai no koka). *Journal of Social Sciences and Humanities (Jimbun Gakuho)*, **77**, 8–16. Tokyo Metropolitan University. (In Japanese.)

Imai, S. (1973). New illusion of square distortion. *Journal of Social Sciences and Humanities (Jimbun Gakuho)*, **90**, 41–42. Tokyo Metropolitan University.

Imai, S. (1976). Experiments on the illusion of square distortion (Seihokei no katachi no sakushi ni kansuru jikken). *Journal of Social Sciences and Humanities (Jimbun Gakuho*, **111**, 85–97. Tokyo Metropolitan University. (In Japanese with English abstract.)

Kitaoka, A. (1997). An overview of illusion images (Sakushizukei no obabyu). *Vision (Journal of the Vision Society of Japan)*, **9**, 131–162. (In Japanese.)

Kitaoka, A. (1998). Apparent contraction of edge angles. *Perception*, **27**, 1209–1219.

Kitaoka, A. (2001). Illusion designs (3) Stereoscopic effects from checker patterns (Sakushi no dezaingaku (3) Ichimatsumoyo de egakidasu rittaikan). *Nikkei Science*, **31**, 22–23. (In Japanese.)

Kitaoka, A. (2005a). *Trick Eyes Graphics.* Tokyo: Kanzen.

Kitaoka, A. (2005b). The Zöllner illusion, the Fraser illusion, and the Café Wall illusion (Tseruna irujon, Fureza irujon, Kafeworu irujon). In T. Goto & H. Tanaka (Eds.), *Handbook of the Science of Illusion (Sakushi No Kagaku Handobukku)* (pp. 136–152). Tokyo: University of Tokyo Press. (In Japanese.)

Kitaoka, A. (2005c). Geometrical illusions (Kikagakuteki sakushi). In T. Goto & H. Tanaka (Eds.), *Handbook of the Science of Illusion (Sakushi no Kagaku Handobukku)* (pp. 56–77). Tokyo: University of Tokyo Press. (In Japanese.)

Kitaoka, A. (2006). Configurational coincidence among six phenomena: a comment on van Lier and Csathó (2006). *Perception*, **35**, 799–806.

Kitaoka, A., & Ishihara, M. (2000). Three elemental illusions determine the Zöllner illusion. *Perception & Psychophysics*, **62**, 569–575.

Kitaoka, A., Pinna, B., & Brelstaff, G. (2001). New variations of spiral illusions. *Perception*, **30**, 637–646.

Kitaoka, A., Pinna, B., & Brelstaff, G. (2004). Contrast polarities determine the direction of Café Wall tilts. *Perception*, **33**, 11–20.

Kohara, M. (2005). The role of horizontal components in the tilt illusion of letter rows (Mojiretsu ga katamuite mieru sakushi ni okeru suiheiseibun no yakuwari). Graduation Thesis, Ritsumeikan University (in Japanese).

Lipps, T. (1897). *Raumästhetik und Geometrisch-Optische Täuschungen.* Leipzig: Barth.

Maheux, M., Townsend, J. C. & Gresock, C. J. (1960). Geometrical factors in illusions of direction. *American Journal of Psychology*, **73**, 535–543.

Morgan, M. J., & Baldassi, S. (1997). How the human visual system encodes the orientation of a texture, and why it makes mistakes. *Current Biology*, **7**, 999–1002.

Morgan, M. J., Mather, G., Moulden, B., & Watt, R. J. (1984). Intensity-response nonlinearities and the theory of edge localization. *Vision Research*, **24**, 713–719.

Morinaga, S. (1933). A study of the Zöllner illusion (Tseruneru shi sakushi no kenkyu). *Japanese Journal of Psychology*, **8**, 195–242 (in Japanese).

Moulden, B., & Renshaw, J. (1979). The Münsterberg illusion and "irradiation." *Perception*, **8**, 275–301.

Münsterberg, H. (1897). Die vershobene Schachbrettfigur. *Zeitschrift für Psychologie*, **15**, 184–188.

Nihei, Y. (1973). A preliminary study on the geometrical illusion of motion path: the kinetic illusion. *Tohoku Psychologica Folia*, **32**, 108–114.

Nihei, Y. (1975). The effect of direction of motion on the magnitude of the geometrical illusion of motion path: the kinetic illusion (II). *Tohoku Psychologica Folia*, **34**, 88–94.

O'Toole, B. I. (1979). The tilt illusion: length and luminance changes of induction line and third (disinhibiting) line. *Perception & Psychophysics*, **25**, 487–496.

O'Toole, B., & Wenderoth, P. (1977). The tilt illusion: repulsion and attraction effects in the oblique meridian. *Vision Research*, **17**, 367–374.

Oyama, T. (1960). Japanese studies on the so-called geometrical-optical illusions. *Psychologia*, **3**, 7–20.

Oyama, T. (1975). Determinants of the Zöllner illusion. *Psychological Research*, **37**, 261–280.

Oyama, T. (1977). Feature analysers, optical illusions, and figural aftereffects. *Perception*, **6**, 401–406.

Parlangeli, O., & Roncato, S. (1995). The global figural characteristics in the Zöllner illusion. *Perception*, **24**, 501–512.

Popple, A. V., & Levi, D. M. (2000). A new illusion demonstrates long-range processing. *Vision Research*, **40**, 2545–2549.

Popple, A. V., & Sagi, D. (2000). A Fraser illusion without local cues? *Vision Research*, **40**, 873–878.

Robinson, J. O. (1972). *The psychology of visual illusion*. Mineola, NY: Dover.

Roncato, S. (2000). The effect of luminance variation on the apparent position of an edge. *Perception & Psychophysics*, **62**, 762–785.

Roncato, S. (2006). Orientation misperceptions induced by contrast polarity: comment on Contrast polarities determine the direction of Café Wall tilts' by Akiyoshi Kitaoka, Baingio Pinna, and Gavin Brelstaff (2004). *Perception*, **35**, 401–409.

Roncato, S., & Casco, C. (2003). The influence of contrast and spatial factors in the perceived shape of boundaries. *Perception and Psychophysics*, **65**, 1252–1272.

Sakai, K. & Hirai, Y. (2002). Neural grouping and geometric effect in the determination of apparent orientation. *Journal of the Optical Society of America A*, **19**, 1049–1062.

Sakane, I. (1980). *Shin Asobino Hakubutsushi (A new museum of fun book) Part II.* Tokyo: Asahi-bunko (in Japanese).

Skillen, J., Whitaker, D., Popple, A., & McGraw, P. V. (2002). The importance of spatial scale in determining illusions of orientation. *Vision Research*, **42**, 2447–2455.

Swanston, M. T. (1984). Displacement of the path of perceived movement by intersection with static contours. *Perception & Psychophysics*, **36**, 324–328.

Takeuchi, T. (2005). The effect of eccentricity and the adapting level on the café wall illusion. *Perception & Psychophysics*, **67**, 1113–1127.

Tanaka, H. (1982). The influence of lengths of lines on apparent angle: a new demonstration (Kakudo no chikaku ni oyobosu senbun no nagasa no eikyo: Yoku shirareteinai kakudo no sakushi). *Journal of Social Sciences and Humanities (Jimbun Gakuho)*, **152**, 19–29. Tokyo Metropolitan University (in Japanese).

Wallace, G. K., & Crampin, D. J. (1969). The effect of background density on the Zöllner illusion. *Vision Research*, **9**, 167–177.

Wenderoth, P., & Johnstone, S. (1988). The different mechanisms of the direct and indirect tilt illusions. *Vision Research*, **28**, 301–312.

Woodhouse, J. M., & Taylor, S. P. (1987). Further studies of the Café Wall and Hollow Squares illusions. *Perception*, **16**, 467–471.

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