The Ehrenstein illusion: Effects of contrast polarity, gap size, and line orientation

JIRO HAMADA¹

Faculty of Integrated Arts and Sciences, University of Tokushima, Minami-Josanjima, Tokushima 770

The illusory strength of Ehrenstein figures with positive (black lines on gray background) or negative (white lines on gray background) contrasts, and gap sizes, and line orientations was investigated. Irrespective of contrast polarity, the gray between the lines was judged to be darker than the same gray in a figure without lines. The effect of gap size depended on contrast polarity: With positive contrast the illusion was strongest for the small gap and decreased with increasing gap size; with negative contrast the illusion was weakest for the small gap and increased with gap size. With mixed-contrast patterns (alternating light and dark radial lines) the perceived lightness laid between that of the positive and negative contrast figures. Horizontal and vertical lines had more influence than oblique lines in mixed-contrast: When they were negative, the results more nearly resembled those of pure negative contrast; when they were positive, the results resembled those of positive contrast. The results might be interpreted within the context of a compound model of contrast perception with local antagonistic and global nonantagonistic inhibition.

Key words: Ehrenstein illusion, overall darkening effect, local antagonistic inhibition, global nonantagonistic inhibition.

The phenomenon of contours that appear in the absence of physical gradients was called "amodal contour," "subjective contour" or "illusory contour," etc. These contours have no physical basis over most of their length, and the virtual lines are only phenomenally present (Kanizsa, 1976, 1979). The virtual lines usually accompany subjective surfaces, which appear to be superimposed on the other figures, and appear to be lighter or darker than the background, even though the two regions are physically identical in lightness² and color. The lightness

and/or the darkness of the subjective surface is determined by contrast polarity between the figures and the homogeneous background. With negative contrast (figures are darker than the background) the subjective surface is lighter than the background, with positive contrast (figures are lighter than the background) the subjective surface is darker than the background. In the present study, we would like to give attention to the contrast enhancement between the subjective surfaces. Specifically, effects of contrast polarity upon Ehrenstein's lightness illusion will be investigated with a few additional variables.

In Ehrenstein's lightness illusion, a light patch is perceived between the ends of dark radial lines on a light background (negative contrast) and a dark patch is perceived between the ends of light radial lines on a

¹ The support of this study by a Grant-in-Aid for Scientific Research, Ministry of Education, Science and Culture, No. 07610080, and by the German Academic Exchange: DAAD is gratefully acknowledged. The author would like to thank Mr. I. Izeki for his assistance with data collection. Furthermore, the author is grateful to Prof. C. R. Cavonius and Dr. W. H. Ehrenstein, Dortmund, and M. Hogeboom and L. Frie, Amsterdam for their invaluable comments and improvements of the manuscript.

² In the present study, the term "lightness" is mainly used to denote perceived reflectance, whereas the term "brightness" is used to denote the perceived brightness of luminance.

dark background (positive contrast) (Ehrenstein, 1941/1987). Hamada (1987) measured the lightness of the central gap area and the area outside the center for Ehrenstein figures of both contrast polarities and found that the lightnesses of both the illusory patch and the illusory background were darker than that of a uniform control field. The results were explained by a three-stage model as follows: (1) The illusory light and dark patches are not due to the summation of activities within the antagonistic receptive-field surround region, but are due to the angle-dependent lateral spreading of activities at the central field; (2) the circular subjective contour is the result of a boundary produced by the angle-dependent lateral spreading; and (3) the overall lightness decrease in the Ehrenstein illusion of both contrast polarities may be due to additional spreading of nonantagonistic inhibition.

Ehrenstein (1941/1987) already demonstrated that the strength of the lightness illusion is dependent on the length of the radial lines, fixing the gap size (Ehrenstein, 1987, Figure 3.6) and on gap size, fixing the length of the radial lines (Ehrenstein, 1987, Figure 3.7). Spillmann, Fuld, and Gerrits (1976) reported that the Ehrenstein illusion was stronger with positive contrast than with negative contrast. Fuld and O'Donnell (1984) varied gap size between 9 and 34 min of arc.

in an Ehrenstein figure with negative contrast. They found an increase in illusory lightness enhancement with gap size. Prazdny (1983) demonstrated that dark and light bars on a gray background produce the lightness illusion comparable to the Ehrenstein illusions induced by dark or light bars. Therefore he concluded that the illusory lightness enhancement within the region bounded by the subjective contour does not participate in the causal link leading to the perception of the illusory contour. On the other hand, it has been shown that lightness enhancement and subjective contours are both similarly sensitive to spatial orientation, i.e., they are both stronger with orthogonal than with diagonal lines, this indicates a common mechanism for illusory contrast enhancements and illusory contour.

Figure 1. Schematic representation of the experimental apparatus (after Hamada, 1987).

Figure 2. Examples of Ehrenstein figures with (a) negative, (b) positive, (c) negative/positive and (d) positive/negative contrast; a uniform field (e) was used as control.

The present study investigates how the strength of the Ehrenstein illusion depends on (1) contrast polarity, (2) gap size, and (3) line orientation.

Method

Apparatus and stimuli. The apparatus used was basically same as described by Hamada (1987), see Figure 1. Eight quartz-iodine lamps (6 V, 20 W) illuminated a test field, a comparison field and its black surrounding area (Munsell N 2.5 corresponding to 6.2 cd/m², 38 deg both in width and height). The test field was exposed for 3 s by a shutter in front of the subject's eyes, whereas the comparison field was exposed during the whole session. Twelve different Ehrenstein figures were used. As shown in Figure 2, there were four stimuli, consisting of a gray background and either eight dark lines (negative contrast) (a), eight light lines (positive contrast) (b), four dark orthogonal lines and four light oblique lines (mixed-contrast : negative/positive) (c), or four light orthogonal lines and four dark oblique lines (mixed-contrast : positive/negative) (d). The lines were placed at 45 deg intervals and were 0.5 mm in width. Lines of 52.5 mm, 44.5 mm, or 36.5 mm, respectively formed three gap diameters of 16 mm, 32 mm, and 48 mm, subtending 0.78, 1.57, and 2.37 deg, respectively. The diameter of the gray background was 121 mm (6 deg). The reflectances of the dark and light lines were 2% and 73% respectively, that of the background was 39% (Munsell value N 6.7). The difference in reflectance between the gray background and the dark and the light lines was almost equal. A uniform field with the same reflectance and the same diameter as the background of the Ehrenstein figures served as a control field. To measure the perceived lightnesses of the central gap and the background of the Ehrenstein figure, and of

the control field, 33 Munsell patches of various shades of gray were used as comparison stimuli. They were presented in a comparison window (30' wide and 105' high), located 5.72 deg above the test figure. The gray values ranged from Munsell N 1.5 to N 9.5 in steps of N 0.25. The distance between the subject and the stimulus field was 116 cm. The head was stabilized by a head and chin rest.

Subjects. Four male and three female undergraduate students as well the author participated in the experiment. The students were about 22 years old, had normal or corrected-to-normal vision, and were all naive.

Figure 3. Matched lightness (Munsell values) at the center and in the background of the Ehrenstein figure with varying gap diameter. The difference between the solid line (judged lightness of the background) and the curves obtained for the central gap of Ehrenstein figures of different contrast polarity expresses the illusory strength. The difference between the dashed line (lightness of the uniform control field) and the solid line (background) indicates the paradoxical decrease of lightness in the Ehrenstein figure. Data are from 8 subjects; vertical bars indicate 1 SD.

Procedure. The subjects' task was to compare the perceived lightnesses of the central gap, the background of the Ehrenstein figure, and the uniform field, with those of the Munsell gray patches shown in the comparison window. The psychophysical method of limits with three categories was used. The three categories were "darker," "lighter," and "equal." Upper limits and lower ones were defined by a transition of the three categories. Point of subjective equalities were the means of two upper limits and two lower ones, which were measured by both an ascending series and a descending series in an experimental session. The Ehrenstein figures and the uniform field were presented in random sequence for each subject. The sequences for the central gap and the background were counterbalanced within subject. Free fixation between the test figure and comparison field was allowed. After a practice session, subjects participated in six experimental sessions, each on a different day.

Results

Overall lightness decrease. The mean of the Munsell values matched for the background of the twelve Ehrenstein figures was 5.90 (solid horizontal line in Figure 3). A two-way analysis of variance on the backgrounds (12) and subjects (8) revealed a significant main effect for subjects ($F(7, 480)=148.8, p<0.01$), indicating interindividual differences, whereas the main effect for backgrounds and the interaction between subjects and backgrounds was not significant ($F(11, 480)=0.68$ and $F(77, 480)=0.93, p>0.05$ for each). Thus, there were no significant differences among the matched Munsell values for the same gray backgrounds of the 12 different Ehrenstein figures.

The mean of Munsell values matched for the twelve backgrounds (5.90: solid line in Figure 3) was clearly less than that for the

uniform field (6.29: dashed horizontal line in Figure 3). This indicates a general darkening for the background of the Ehrenstein figures for all contrasts compared to a uniform field with equal reflectance. Furthermore, as shown in Figure 3, the matched Munsell value for the center of the Ehrenstein figure of negative contrast with the largest gap diameter was clearly lower than that for the uniform field. Thus an overall lightness decrease was found in the Ehrenstein figures under all conditions.

Illusory strength. The matched Munsell values for the central gap in the Ehrenstein figure as a function of the gap diameter are shown in Figure 3. In order to investigate the illusory strength in each figure, twelve two-

Figure 4. Information flow in a compound model of antagonistic and nonantagonistic mechanisms (after Hamada, 1991). Nonantagonistic inhibition is linked to previous edge detection; in the absence of an edge brightness information is processed as depicted by the dotted line on the left.

way analyses of variance were carried out with location (2: central gap, background) and subjects (8). A significant main effect was found for subject ($F(7, 80) > 16.1, p < 0.01$ for each), and a significant main effect for location was found in eight cases ($F(2, 80) > 4.17, p < 0.05$ in two cases, and $p < 0.01$ in six cases) whereas the main effect was non-significant in four cases ($F(2, 80) < .54, p > 0.05$; cases indicated by "ns" in Figure 3). Interactions were small ($F(7, 80) > 4.32, p < 0.01$ in three cases, $p < 0.05$ in four cases, and $p > 0.05$ in five cases). With negative contrast the illusory strength increases as gap diameter increases, whereas it decreases for positive contrast (i.e., it becomes more like the background). The illusory strength of the mixed-contrast figures fall between these two cases. In other words, when the gap diameters increase, all of the lightness-values at the center approach that of the uniform control field.

Discussion

Irrespective of contrast polarity and gap diameter, the overall lightness of the backgrounds in all Ehrenstein figures was judged to be lower than that of the control uniform gray field. The amount of lightness decrease was constant for all backgrounds of different Ehrenstein figures. This supports the paradoxical lightness decrease obtained by Hamada (1984a) who showed that with low-contrast gratings, the lightness of the high-reflectance phase is less than that of a uniform field of equal reflectance. Since the matched lightness of the light and the dark phases showed a symmetrical relationship, he assumed that the overall darkening effect in the gratings was constant for any reflectance difference condition. A similar overall darkening effect with a simultaneous brightness contrast was obtained by Hamada, Ehrenstein, Müller, and Cavonius (1992). We

may thus conclude that under these conditions the overall darkening effect is independent of contrast polarity³.

The overall lightness decrease leading to an asymmetry in lightness/darkness was also obtained in the Craik-O'Brien-Cornsweet illusion (Hamada, 1984a, 1985) supporting a compound model of antagonistic and nonantagonistic mechanisms (see Hamada, 1991 for review). In this model the antagonistic excitation/inhibition is related to border contrast, whereas the nonantagonistic inhibition is related to area contrast. The information flow of the model is shown in Figure 4.

Compound processes of local antagonistic and global nonantagonistic mechanism. The hypothetical neural activities of the compound process for the Ehrenstein figure of medium gap diameter with negative and positive contrasts are shown in Figure 5. The local antagonistic mechanism corresponds to Békésy's (1960) neural units or to ON-center and OFF-center in terms of line-induced lateral interaction in hypercomplex receptive fields (Fuld & O'Donnell, 1984; Spillmann Fuld, & Gerrits, 1984). The hypothetical neural activities organized in the mechanisms are shown in Figure 5-A and 5-a. Dark lines reduce excitation at the center and inhibition in the surrounding area, whereas light lines induce excitation at the center and inhibition in the surrounding area. This local antagonis-

³ In order to explain the perception of overlay and depth in illusory contour figures, von der Heydt and Peterhans (1989) theorize that there are "foreground-background cells" which have asymmetric grouping input without preference for contrast polarity. These cells differ from "brightness cells" which have symmetric, but contrast selective grouping input. Similarly, de Weert (1991) and du Buf (1992) state that brightness assimilation and brightness contrast can occur at the same time suggesting that the visual system contains independent band pass and low-pass channels or mechanisms.

tic excitation/inhibition is assumed to depend upon the absolute level of luminance.

The neural profile of the output from the antagonistic mechanism should have contour lines with an abrupt change at the edge of each line. At the edge detection stage, contour lines with abrupt change in the two-dimensional outputs of the antagonistic mechanisms are detected as edges, as indicated thick dotted lines in Figure 5-B and 5-b (Hamada, 1976, 1984b). The edges corre-

spond to the zero-crossings, which were proposed by Marr and Hildreth (1980).

The antagonistic mechanisms successfully predict Mach bands, however, they do not predict the paradoxical darkening effect ("Hamada brightness paradox" according to Cohen & Grossberg, 1984). In order to explain the paradoxical lightness decrease, global nonantagonistic inhibition is assumed to be strong at the line ends, and to be diffused widely over a large area of the figures, as shown by concentric circles in Figure 5-B and 5-b. It is further assumed that the nonantagonistic mechanism depends upon the relative luminance difference, i.e., it requires a linking to the previous edge detection stage.

Finally the outputs of the antagonistic and nonantagonistic mechanisms reach a lateral spreading stage. As indicated by the arrows in Figure 5-B and 5-b, it is assumed here that neural activities outside the contour line (i.e., edge) should be homogenized to spread to the right angle against the dark/light lines (Hamada, 1984b, 1987). The angle-dependent lateral spreading could lead to the illusory light or dark patches perceived in the Ehrenstein figure, since the background receives lateral spreading from each line, whereas the center gap does not. The neural activities at the center gap will be homogenized within the center. The lateral spreading may correspond to a filling-in process of Gerrits and Vendrik (1970)⁴. The resulting neural activities are schematically shown in

Figure 5. Hypothetical neural activities of the compound process of the antagonistic and nonantagonistic mechanisms for the Ehrenstein figures with negative contrast (left) and with positive contrast (right). At the local stage of processing (above) antagonistic excitation/inhibition of the receptive fields of line detectors takes place that fulfill the function of edge detection. At the stage of processing (middle) edge detection, global inhibition and lateral spreading are assumed as illustrated by thick dotted lines, concentric circles and arrows. The final perceptual outcome of the model are shown below.

⁴ More recently, Morgan and Hotopf (1989) specified that the mechanisms integrating brightness information over a large area are different than that of a small area (i.e., classical receptive field). They proposed the idea of "collector units" which, for a given polarity, sum the signals generated by local feature detectors. These signals may provide cooperative input that generates illusory brightness and contours in the Ehrenstein figure (Dresp, Spillman, & Bonnet, 1993).

Figure 5-C and 5-c, where the boundary of the angle-dependent lateral spreading in the Ehrenstein illusion is shown by a circular subjective contour.

The lightness enhancement with expansion of the gap diameter between the ends of black lines is consistent with the results obtained by Fuld and O'Donnel (1984). The illusory patches in both negative and positive contrasts become relatively lighter when the gap diameters are expanded. According to the model of compound processes, this may be due to a decrease of the nonantagonistic activity when the central gap increases. The darkening effect at the central gap in positive contrast was stronger than the lightening effect in negative contrast, when the gap diameter was smaller or medium. This finding is consistent with the findings of Spillmann et al. (1976) and possibly reflects an asymmetry between the D (darkness) and B (brightness) systems of Jung (1973).

With mixed-contrast figures the perceived lightness for all gap diameters lay between the positive and negative contrast values. This implies an additivity of the illusory effects, i.e., the illusory effect of positive contrast will add to that of negative contrast which is opposite in sign, and vice versa. The mutual weakening of both contrast polarities may be interpreted within the framework of the receptive field model of hypercomplex cells proposed by Spillmann et al. (1976), Spillman, Fuld, and Neumeyer (1984) and Fuld and O'Donnel (1984). The dark lines of the Ehrenstein figure maximally stimulate cells whose receptive fields are elongated inhibitory regions surrounded by excitatory areas. On the other hand, the light lines produce maximal firing in cells whose receptive fields are elongated excitatory regions surrounded by inhibitory areas. Consequently, in the area corresponding to the gap of the Ehrenstein figure with mixed-contrast, the excitatory and inhibitory activities inhibit one

another.

Confirming earlier findings (Spillmann, 1975; Purghe, 1989), the present results support the notion that neural activities for vertical/horizontal lines are stronger than those for diagonal ones. Accordingly, von der Heydt and Peterhaus (1989) propose an orientation-specific tuning in their neuronal model of Ehrenstein- and Zöllner-type illusion. They argue that end-stopped fields of a cooperative assembly must be predominantly orthogonal to the orientation represented by the target neuron because an occluding contour is more likely to intersect line elements in the background which are orthogonal to it than line elements of other orientations. Similarly, in the present study, orthogonal lines had more influence than oblique lines: When the horizontal and vertical were negative, the results more nearly resembled those with pure negative contrast; when they were positive, the results resembled those with positive contrast. The results confirm that the illusory strength is dependent upon the orientation of the radial lines, and that the contrast of vertical/horizontal lines is superior to diagonal lines.

References

- Békésy, G. von. 1960 Neural inhibitory units of the eye and skin. Quantitative description of contrast phenomena. *Journal of the Optical Society of America*, **50**, 1060-1070.
- Cohen, M. A., & Grossberg, S. 1984 Neural dynamics of brightness perception: Features, boundaries, diffusion, and resonance. *Perception and Psychophysics*, **36**, 428-456.
- Dresp, B., Spillmann, L., & Bonnet, C. 1993 Collector units and illusory form perception: evidence for cooperative mechanisms in the Ehrenstein illusion. *Perception*, **22**, suppl. A3b.
- de Weert, Ch. M. 1991 Assimilation versus contrast. In A. Valberg & B. B. Lee (Eds.), *From pigments to perception* New York: Plenum Press. Pp. 305-311.
- du Buf, J. M. H. 1992 Low-pass channels and White's effect. *Perception*, **21**, 80.

- Ehrenstein, W. 1941 Ueber Abwandlungen der L. Hermannschen Helligkeitsercheinung. *Zeitschrift für Psychologie*, **150**, 83-91.
- Ehrenstein, W. 1987 Modifications of the brightness phenomenon of L. Hermann (English Translation by Anne Hogg). In S. Petry & G. E. Meyer (Eds.), *The perception of illusory contours*. New York: Springer-Verlag. pp. 35-39.
- Fuld, K., & O'Donnell, K. 1984 Brightness matching and scaling of the Ehrenstein illusion. In L. Spillmann & B. R. Wooten (Eds.), *Sensory experience, adaptation, and perception*. Hillsdale, NJ: Lawrence Erlbaum Associates. Pp. 461-469.
- Gerrits, H. J. M., & Vendrik, A. J. H. 1970 Simultaneous contrast. Filling-in process and information processing in man's visual system. *Experimental Brain Research*, **11**, 411-430.
- Hamada, J. 1976 A mathematical model for brightness and contour perception. *Hokkaido Report of Psychology*, HRP-11-76-17.
- Hamada, J. 1984a Lightness decrease and increase insquare-wave gratings. *Perception and Psychophysics*, **35**, 16-21.
- Hamada, J. 1984b A multi-stage model for border contrast. *Biological Cybernetics*, **51**, 65-70.
- Hamada, J. 1985 Asymmetrical lightness cancellation in Craik-O'Brien patterns of negative and positive contrast. *Biological Cybernetics*, **52**, 117-122.
- Hamada, J. 1987 Overall brightness decrease observed in the Ehrenstein illusion induced for both contrast polarities. *Perception and Psychophysics*, **41**, 67-72.
- Hamada, J. 1991 Asymmetries in the perception of lightness and darkness. *Trends in Biological Cybernetics*, **2**, 93-105.
- Hamada, J., Ehrenstein, W. H., Müller, M., & Cavonius, C.R. 1992 Global loss of brightness accompanying simultaneous brightness contrast. *International Journal of Psychology*, **27**, 33-34.
- Jung, R. 1973 Visual perception and neurophysiology. In R. Jung (Ed.), *Handbook of sensory physiology*. Vol. VII/3A. Berlin: Springer. Pp. 54-58.
- Kanizsa, G. 1976 Subjective Contours. *Scientific American*, **234**, 48-52.
- Kanizsa, G. 1979 *Organization in vision: Essays on Gestalt perception*. New York: Praeger.
- Marr, D., & Hildreth, E. 1980 A theory of edge detection. *Proceedings of Royal Society of London*, **B207**, 187-217.
- Morgan, M. J., & Hotopf, W. H. N. 1989 Perceived diagonals in grids and lattices. *Vision Research*, **29**, 1005-1015.
- Prazdny, K. 1983 Illusory contours are not caused by simultaneous brightness contrast. *Perception and Psychophysics*, **34**, 403-404.
- Purghé, F. 1989 Privileged directions for subjective contours: horizontal and vertical versus tilted. *Perception*, **18**, 201-213.
- Spillmann, L. 1975 Perceptual modification of the Ehrenstein illusion. In S. Ertel, L. Kemmler & M. Stadler (Eds.), *Gestalt theorie in der modernen Psychologie*. Darmstadt: Steinkopff. Pp. 210-218.
- Spillmann, L., Fuld, K., & Gerrits, H. J. M. 1976 Brightness contrast in the Ehrenstein illusion. *Vision Research*, **16**, 713-719.
- Spillmann, L., Fuld, K., & Neumeyer, C. 1984 Brightness matching, brightness cancellation, and increment threshold in the Ehrenstein illusion. *Perception*, **13**, 513-520.
- von der Heydt, R., & Peterhans, E. 1989 Ehrenstein and Zöllner illusions in a neuronal theory of contour processing. In J.J. Kulikowski, C. M. Dickinson & I. J. Murray (Eds.), *Seeing contour and colour*. Oxford: Pergamon Press. Pp. 729-734.

(Received Nov.24, 1993; accepted Sept. 3, 1994)