Effects of luminance contrast on color spreading and illusory contour in the neon color spreading effect

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The present study examined whether color spreading and illusory contours in the neon color spreading effect of Ehrenstein figures are governed by different mechanisms. In the experiment, Ehrenstein figures with colored crosses inserted in the central gaps were used. There were three luminance conditions: the luminance of the Ehrenstein figures was lower than, the same as, or higher than the luminance of the background. In each condition, 16 trials (2 sets of instructions $\times$ 8 repetitions) were conducted in a random order. Subjects were required to adjust the luminance of the colored crosses according to one of the two sets of instruction given before each trial. One was to adjust the upper and lower thresholds in the luminance of the colored crosses such that their color was seen to spread out of the crosses. The other was to adjust the thresholds such that circular illusory contours were visible. It was found that illusory contours disappeared and the color spreading remained when the crosses and the Ehrenstein figures were in or nearly in isoluminance or when the Ehrenstein figures and the background were in isoluminance. These results suggest that color spreading and illusory contours are governed by different mechanisms.

Redies and Spillmann (1981) showed that van Tuijl's (1975) neon color spreading effect occurred in the Ehrenstein figures (Ehrenstein, 1941) by inserting a colored cross (an inner segment) in the central gap to adjoin the radial lines (outer segments). The neon color spreading effect in the Ehrenstein illusion has two distinguishable phenomenal aspects: (1) The color of the inserted cross spreads outside its containing contours. We call this phenomenon the *spreading of inner color*. (2) This spreading forms a circular area surrounded by an illusory contour. We call this phenomenon the *formation of the illusory contour*.

The question then arises as to whether different mechanisms govern the spreading of the inner color and the formation of the illusory contour. Grossberg and Mingolla (Grossberg, 1987; Grossberg & Mingolla, 1985a, 1985b) have, in fact, constructed a model in which the mechanism for the color spreading is different from that for the illusory contour formation.

If we are able, experimentally, to separate the spreading of inner color from the formation of the illusory contour, we can suggest that different mechanisms govern these two phenomena. One possibility is to systematically

vary the luminance of the inner segment, the outer segments, and the background. Several studies have shown what effect this has on neon color spreading. Van Tuijl and de Weert (1979) found that the luminance of the inner segments must be between the luminance of the outer segments and that of the background for observers to perceive the neon color spreading effect. As for the effect of relative luminance between the inner segments and outer segments, Redies and Spillmann (1981), using the modified Ehrenstein matrix consisting only of interwoven red and green crosses, found that the neon color spreading effect disappeared when red and green crosses approached each other in hue, whereas it persisted when they approached each other in luminance. Ware (1980) also showed that when Kanizsa's (1955) illusory triangle was modified by inserting the inner, colored segments that completed disks and outline triangles (Varin, 1971), the neon color effect was observed when the inner segment and the outer segments were approximately the same in luminance.

These studies did not, however, distinguish the two phenomena in question. If either the spreading of the inner color or the illusory contour disappears when the inner segment and the outer segments are in isoluminance, that would suggest that the mechanisms underlying these phenomena are different.

As for the relative luminance between the outer segments and the background, Frisby and Clatworthy (1975) found that the illusory contour disappeared or at least was

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weakened when inducing figures, such as three incomplete disks and an incomplete triangle in Kanizsa's (1955) illusory triangle, and the background were in isoluminance. In addition, the neon color spreading effect usually occurred when inner segments were inserted in the figures, such as Kanizsa's illusory triangle and Ehrenstein's figure, to induce illusory contours. Therefore, it might be expected that the illusory contour will disappear when the outer segments and the background in the figures inducing the neon color spreading effect are in isoluminance.

If neon color spreading persists and the illusory contour disappears when the outer segments and the background are in isoluminance, it would suggest that the spreading of inner color and the formation of the illusory contour are caused by different mechanisms. In this experiment, we observed whether both the color spreading and the illusory contour persist or whether one of them persists and the other disappears when the inner segment and the outer segments, or the outer segments and the background, are in isoluminance.

METHOD

Subjects

Two males and 1 female, ranging between 25 and 29 years of age, participated as subjects. All of them had normal color vision and normal or corrected-to-normal visual acuity.

Apparatus and Stimuli

A computer (Mascomp) with a high-resolution cathode ray tube ($1,152 \times 910$) was used. The viewing distance was 69 cm. Subjects sat in a chair equipped with a chinrest.

The presented stimulus consisted of 169 (13×13) Ehrenstein-like figures whose radially arranged arms (the outer segments) were connected to each other, and a cross (the inner segment) was inserted in the gap between the four arms in each Ehrenstein figure. As shown in Figure 1, each arm (the outer segments) and each of the two lines constituting each cross (the inner segment) subtended a visual angle of 39° and 52° of arc, respectively. The lines' width subtended $2.6'$ of arc. The luminance of the background was a constant 29.3 cd/m^2 . The color of the background was light blue ($x = .21$, $y = .36$, in chromaticity). The luminance of the outer segments was varied with three luminance conditions: 43.5 , 29.3 , or 12.7 cd/m^2 . The color of the outer segments was white ($x = .29$, $y = .36$, in chromaticity). The luminance of the inner segment could be varied by subjects over the range from $.66$ to 51.9 cd/m^2 with 256 steps. The color of the inner segment was yellow (approximately $x = .38$, $y = .52$, in chromaticity).

Procedure

The experiment had three luminance conditions. In Condition 1, the luminance of the outer segments was 12.7 cd/m^2 . The luminance contrast between the outer segments and the background was $-.4$ when defined as $(L_{OS} - L_{BG}) / (L_{OS} + L_{BG})$, where L_{OS} and L_{BG} refer to the luminance of the outer segments and of the background, respectively. In Condition 2, the luminance of the outer segments was 29.3 cd/m^2 , and the luminance contrast between the outer segments and the background was zero. In Condition 3, the luminance of the outer segments was 43.5 cd/m^2 , and the luminance contrast between the outer segments and the background was $.2$. The order in which the three luminance conditions occurred was randomly determined for each of the 3 subjects.

The method of adjustment was used. The subjects had to adjust the luminance of the inner segment by pushing two buttons (the

Figure 1. The Ehrenstein figure with the cross (the inner segment) inserted in the gaps between the four arms (the outer segments). The arms of the Ehrenstein figure with the cross were connected to the arms of the other Ehrenstein figures with the crosses (13×13) and constituted the presented stimulus.

left was for increasing luminance of the inner segment, and the right was for decreasing luminance of the inner segment) according to instructions given before each trial. The two buttons on the small box were connected to the computer. By pushing the right (or left) button for less than 1 sec, the luminance of the inner segment would increase (or decrease) by one step. If subjects continued pushing the right (or left) button for more than 1 sec, the luminance of the inner segment would continuously increase (or decrease).

There were two sets of instructions. Instruction A was to adjust the upper and lower thresholds of the luminance of the inner segment such that the color of the inner segment (yellow) was seen to spread out of the inner segment. Instruction B was to adjust the upper and lower thresholds of the luminance of the inner segment such that the spreading formed a circular area.

Eight trials were conducted under each of the two instructions. Four of the eight trials were for the increment sequence, and the other four for the decrement sequence. In one luminance condition, 16 trials (2 sets of instructions $\times$ 8 trials) were conducted in a random order. Thus, there were 48 trials (2 sets of instructions $\times$ 3 luminance conditions $\times$ 8 repetitions) in an experimental session for each subject.

During the intertrial interval (about 20 sec), the subjects were asked to turn to the gray screen behind them in order not to adapt to the presented colors. The experiment was conducted in a dark room after a 10-min dark adaptation.

RESULTS AND DISCUSSION

The adjusted luminance of the inner segment is shown in Figure 2 as a function of luminance contrast between

Figure 2. The mean and the individual data representing the adjusted luminance of the inner segment under each of the two sets of instructions as a function of luminance contrast between the outer segments and the background. In each of the four graphs, the upper and lower lines bounding the shaded area represent the upper and lower luminance thresholds, respectively, under Instruction A. Vertical bipolar arrows represent the range between the upper and lower thresholds at which an illusory contour was perceived under Instruction B. A dotted line represents the luminance of the outer segments as a function of the luminance contrast defined as $(L_{OS} - L_{BG}) / (L_{OS} + L_{BG})$, in which L_{OS} and L_{BG} refer to the luminance of the outer segments and the background, respectively.

the outer segments and the background, for each subject and the mean of the subjects. The upper and lower lines that bound the shaded area represent the upper and lower thresholds obtained under Instruction A. Therefore, the shaded area represents the range of luminance in the inner segment over which the inner color (yellow) spread out of the border of the inner segment. Vertical arrows indicate the range between the upper and lower thresholds at which the illusory contour was perceived under Instruction B. No arrow is shown when the luminance contrast between the outer segments and the background is zero, because no illusory contour was seen by any subject. A dotted line represents the luminance of the outer segments

as a function of luminance contrast between the outer segments and the background.

Figure 2 shows the following: (1) When the luminance contrast between the outer segments and the background is -0.4 or 0.2 , and if the inner segment and the outer segments are roughly in isoluminance, the illusory contour disappears while the spreading of inner color remains. The range of luminance of the inner segment over which the spreading of inner color occurs is wider than, and includes, the range of luminance of the inner segment over which the illusory contour is seen. (2) When the luminance contrast between the outer segments and the background is zero (the outer segments and the background are in isoluminance), no illusory contour is seen, irrespective of the luminance of the inner segment, but the spreading of inner color remains. In short, when the inner segment and the outer segments are in or nearly in isoluminance, or when the outer segments and the background are in isoluminance, the illusory contour disappears while the spreading of inner color remains.

As for the subjective impression of the color spreading without an illusory contour, it is seen to diffuse from the center of the inner segment, has no clear boundary, and fades into its surroundings. The size of the spreading is about half of what it should be with the illusory contour. The color is less saturated than that of the inner segment, and it soon disappears when fixed. The spreading is hard to observe within the central visual field, but becomes distinctive in the periphery.

Recently, Redies and Spillmann (1981) found a reduced neon spreading effect that was "confined to a narrow, diffuse streak flanking the colored connecting lines" (Redies, Spillmann, & Kunz, 1984). They called this effect *neon flank*. This occurred, for example, when the gap size of the outer segments was too large for the neon color spreading to occur or when the orientations of the inner segment were different from those of the outer segments. The color spreading without illusory contour found in this study is seen at about the center of the inner cross (the inner segment) rather than "confined to the immediate vicinity on either side of the colored connecting lines," as indicated by Redies, Spillmann, and Kunz (1984). However, in other aspects, the color spreading without illusory contour found in our experiment is very similar to the neon flanks. Thus, it is quite plausible that they are equivalent phenomena.

Our results indicate that the illusory contour is induced by a difference in luminance between the outer segments and their surroundings (the inner segment plus the background), whereas color spreading is induced by a difference in color between the inner and outer segments. This result suggests that the mechanism for the spreading of inner color is separate from the mechanism for the formation of the illusory contour.

The question then arises as to how the illusory contour and color spreading are processed by different mechanisms. According to Grossberg and Mingolla (1985a), the feature contour system involves "the process whereby

brightness and colors spread until they either hit their first boundary contours or their spread is attenuated due to their spatial spread" (p. 176). The boundary contour system generates perceptual boundaries and "synthesizes boundaries sensitive to the global configuration" (p. 173) as a result of the interaction between scenic elements.

Our findings are in accordance with this model. The color spreading found in this experiment may be attributed to the feature contour system, and the formation of the circular shape surrounded by the illusory contour may be attributed to the boundary contour system. The reason why the spreading of the inner color occurs even when the outer and inner segments are roughly in isoluminance might be that the boundary contours of the outer and inner segments, which are made of the same luminance contrasts against the background but of different colors, inhibit and weaken one another.

Cavanagh (1987) and Livingstone and Hubel (1987b) indicated that the real contours of figures inducing illusory contours (e.g., PacMan figures) remained while the illusory contours disappeared when the inducing figure and its background were made of isoluminant but different colors. Cavanagh (1987) further showed that the difference between the inducing figures and the background in such features as luminance, color, texture, stereo, and motion can signal shape defined by the real contours, but that the illusory contours cannot be produced without any luminance contrast.¹ Several researchers have found that there are anatomically and physiologically separated pathways in which the color contrast and luminance contrast are processed independently (e.g., Hubel & Livingstone, 1987; Livingstone & Hubel, 1984, 1987a; Van Essen, 1985). In this vein, the achromatic process responding to the luminance contrast may be responsible for the illusory contour (Livingstone & Hubel, 1987b), whereas the chromatic process responding to the color contrast is responsible for the color spreading.

In summary, we found that an illusory contour disappeared, but the spreading of inner color remained, when the inner segment and the outer segments were in or nearly in isoluminance or when the outer segments and the background were in isoluminance. This suggests that the mechanism for the illusory contour is different from the mechanism for the spreading of inner color.

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NOTE

1. Even with the lower luminance contrast of the inducing figures against the background, the illusory contour is visible. Therefore, the loss of the illusory contour cannot be attributed simply to the lower contrast (Cavanagh, 1987; Watanabe & Oyama, 1988).

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