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Flashing anomalous color contrast

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Abstract

A new visual phenomenon that we call *flashing anomalous color contrast* is described. This phenomenon arises from the interaction between a gray central disk and a chromatic annulus surrounded by black radial lines. In an array of such figures, the central gray disk no longer appears gray, but assumes a color complementary to that of the surrounding annulus. The induced color appears: (1) vivid and saturated; (2) self-luminous, not a surface property; (3) flashing with eye or stimulus movement; (4) floating out of its confines; and (5) stronger in extrafoveal than in foveal vision. The strength of the effect depends on the number, length, width, and luminance contrast of the radial lines. The results suggest that the chromatic ring bounding the inner tips of the black radial lines induces simultaneous color contrast, whereas the radial lines elicit, in conjunction with the gray disk and the ring, the flashing, vividness, and high saturation of the effect. The stimulus properties inducing the illusion suggest that flashing anomalous color contrast may be based on asynchronous interactions among multiple visual pathways.

Keywords: Simultaneous color contrast, Ehrenstein illusion, Brightness induction, Scintillating luster, Parvo-pathway, Magno-pathway, Konio-pathway

Introduction

Converging radial lines arranged around a central gap give rise to a number of illusory phenomena. The best known is the classical Ehrenstein illusion (shown in Fig. 1 top), where the white gap appears brighter than the surrounding background although it has the same luminance. The bright area appears to be delineated by a sharp border. When this illusory contour is covered by a thin black ring, the illusion is diminished (Ehrenstein, 1941). Surprisingly, a somewhat wider chromatic ring (e.g. light blue) has an entirely different effect, as shown in Fig. 1 (middle). Instead of cancelling the illusion, the chromatic annulus induces the perception of a self-luminous, paste-like white disk that is even brighter than the illusory patch in the regular Ehrenstein figure. Because perceived self-luminosity and apparent surface color do not ordinarily appear together (Heggelund, 1992), we call this phenomenon *anomalous brightness induction* (Pinna et al., 2003). When a gray disk is inserted into the central gap of an Ehrenstein figure, as shown in Fig. 1 (bottom), still another phenomenon emerges: the otherwise matte gray has a scintillating luster (Pinna et al., 2000). The strength of each of these effects depends on eye or stimulus movement.

Here we consider what happens when we combine brightness enhancement due to the radial lines (Ehrenstein figure) with the distinguishing stimulus features giving rise to anomalous brightness (a chromatic ring) and luster (a gray disk in the center) as shown in Fig. 2. We ask whether the resulting phenomenon is simply a combined effect of the other three or whether it has emergent properties resulting in still another effect. One could expect to see simultaneous color contrast in which the induced color is complementary to that of the surround (Hering, 1920). In classical simultaneous color contrast the induced color appears static and coplanar, and it is strongest with foveal viewing. Furthermore, color in simultaneous contrast becomes a property of the surface on which it is induced; for example, a gray disk no longer appears gray, but a desaturated green, red, or other color.

What is observed in Fig. 2 involves more than just simultaneous color contrast. Whereas in foveal vision, one perceives a mixture of gray and induced color, as in classical simultaneous contrast, in extrafoveal vision, the induced complementary color (here yellowish-green) is vivid, appears self-luminous and lustrous, and the induced color is not co-planar with the gray. In addition, this complementary color appears to produce flashing throughout the stimulus array, giving it the appearance of "colored lights." With a slow pendular movement, these flashes appear to float out of their confines (disks) not unlike Helmholtz's (1867) fluttering hearts, an effect arising under entirely different stimulus conditions. Because of these differences compared to simultaneous color contrast, we call this phenomenon *flashing anomalous color contrast*.

When the hue of the annuli is changed, other complementary colors emerge, as illustrated in Fig. 3. Here, redness is induced by

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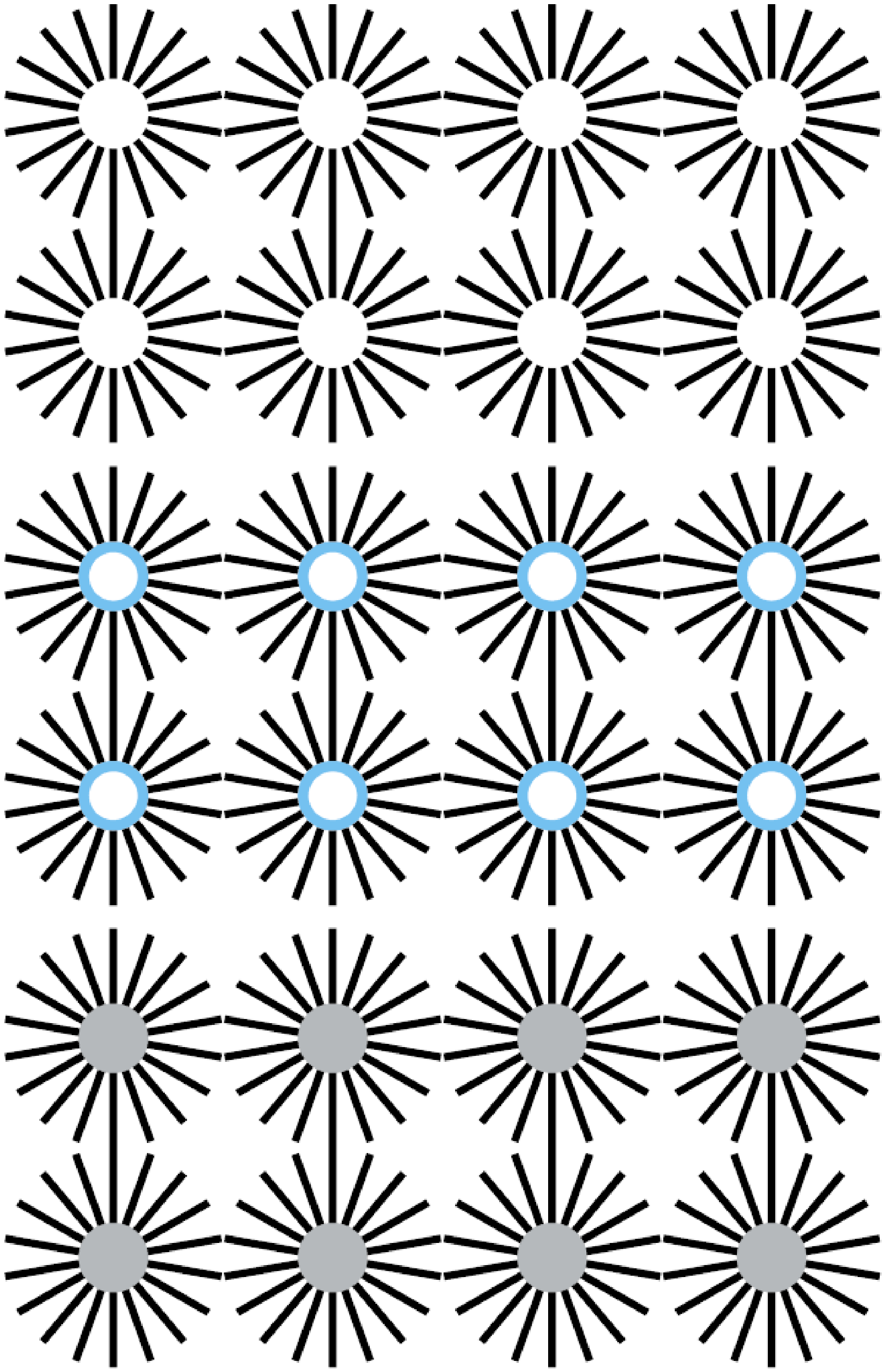

Fig. 1. Three phenomena arising from radial lines: Ehrenstein illusion (top), anomalous brightness (middle), and scintillating luster (bottom). Depending on the size of the figures, it may be necessary to vary the viewing distance to optimize the effects described in the text.

green annuli. The flashing color contrast effect is, however, readily perceived for a wide range of annulus chromaticities.

In a previous study (Pinna et al., 2003), we reported that without the radial lines, classical simultaneous contrast was weak for chromatic annuli on a white background (Fig. 1, middle). It was somewhat stronger with a gray disk (Fig. 1, bottom) as might be expected from Kirschmann's (1891) third law stating that simultaneous contrast is maximal when brightness contrast is minimal. The radial lines are clearly required to distinguish flashing anomalous color contrast from classical color contrast, but in preliminary experiments we found that a range of chromaticities of the radial lines (hues appearing purple, blue, green, yellow, orange,

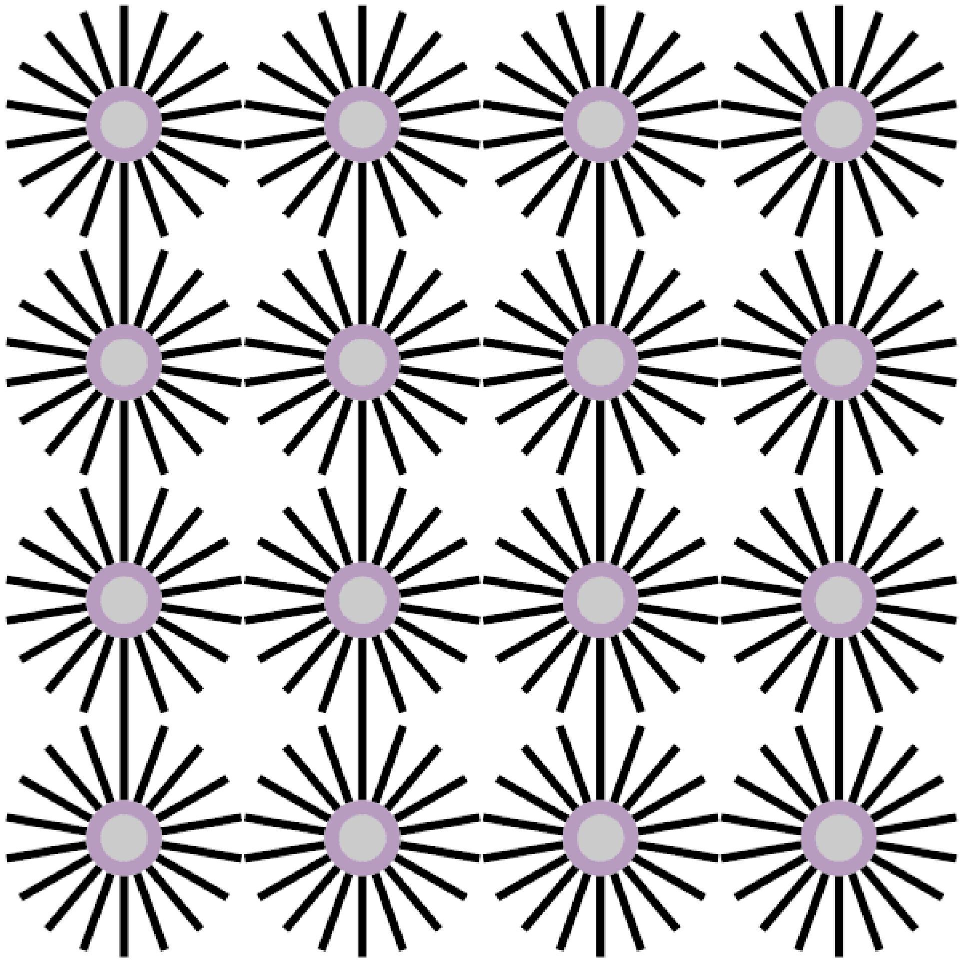

Fig. 2. Flashing anomalous color contrast. The induced yellowish-green color is vivid, flashes with eye movements, floats out of its confines with stimulus movement, and is stronger in peripheral than in foveal vision.

or red) produced the same effect as achromatic lines (all equated in brightness). Because none of the effects illustrated in Fig. 1 occur without the radial lines, this paper focuses on their role in flashing anomalous color contrast. Specifically we ask: Does parametric variation of the radial lines affect the flashing anomalous color contrast in the same way as the other three phenomena described above (Fig. 1)? To compare the effects of such variation, we determined, in separate experiments, the perceptual strength of the four phenomena as a function of the number, length, width, and luminance contrast of the radial lines. If the effects are comparable, we may infer that similar processes contribute to these different phenomena.

Materials and methods

Subjects

Independent groups of 14 undergraduate students participated as observers in all experiments. They were naive as to the purpose of these experiments and all had normal or corrected-to-normal vision.

Stimuli

The stimuli consisted of 4 × 4 arrays of figures containing one of the four stimuli eliciting the following:

1. *Ehrenstein illusion:* Black radial lines on a white background, *no annuli*. Subjects evaluated the brightness enhancement in the central area.
2. *Anomalous brightness induction:* Black radial lines bounded by a chromatic (light blue) annulus on a white background. The subjects evaluated the brightness enhancement of the inner disk.
3. *Scintillating luster effect:* Black radial lines as in the Ehrenstein illusion with the central gap replaced by a *gray disk* (no ring) on a white background. The subjects evaluated the strength of the scintillation within the gray area.
4. *Flashing anomalous color contrast:* Black radial lines with a central gray disk bounded by a chromatic annulus on a white background. Observers evaluated the vividness of the complementary color and the strength of the flashing.

For each of these conditions, the radial lines were varied in number (6, 10, 14, 18, and 24), length (0.37, 0.6, 1.08, and 1.6 deg), width (0.06–0.09, 0.12, and 0.20 deg), and luminance contrast (0.24, 0.57, 0.7, 0.84, and 0.98). Luminance contrast for any stimulus component (L_x) was defined by the ratio $(L_{\text{white background}} - L_x)/L_{\text{white background}}$.

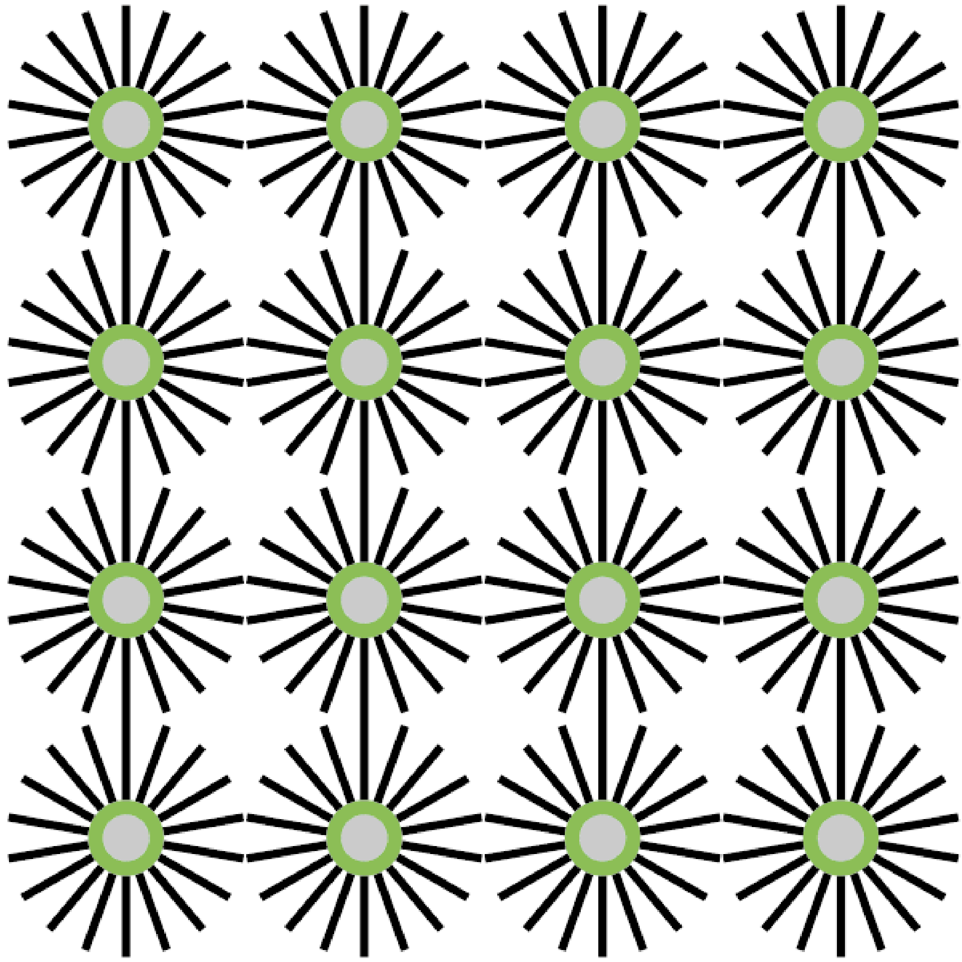

Fig. 3. Flashing anomalous color contrast. Gray disks surrounded by green annuli are perceived as reddish flashing lights.

Stimuli, for all experimental conditions, were viewed binocularly and presented in a frontoparallel plane at a distance of 50 cm away from the observer. The head position of the observer was stabilized by a chin rest.

The stimuli were printed at 1400 dpi on A4 Epson Photo Quality Ink Jet Paper. The luminance of the white (background) paper under our test conditions was 82.3 cd/m^2. Black lines and rings had a luminance contrast of 0.98. Unless otherwise stated, there were 18 equally spaced radial lines per figure, each 1.6 deg long, 0.12 deg wide, separated by a central gap of 1.43 deg, and bounded by an annulus of 13.8 min of arc. The luminance contrast of the light blue annulus relative to the white background was 0.67. The CIE chromaticity coordinates of the ring were $x,y = 0.20, 0.28$. The luminance contrast of the central gray disks was 0.60.

Procedure

In each experiment, independent groups of subjects were instructed to first describe the phenomena and then to rate the central disks in terms of (1) brightness in the Ehrenstein illusion, (2) brightness in anomalous brightness induction, and (3) strength of the scintillating luster effect. In addition, two other groups of subjects rated (4) the vividness (salience) of the complementary color and (5) the strength of the flashing effect in anomalous color contrast.

Subjects were first familiarized with examples (different from those in the experiments) of the specific effects to be tested. Each subject described the properties of the effect under consideration and evaluated only one of the five sets of stimuli previously described, using magnitude estimation. An upper modulus "7" was defined in all experiments by a reference figure specific to the effect under consideration, and a lower modulus "0" was defined by the brightness perceived on a blank sheet of white paper as used for printing the stimuli. For the scintillating luster effect and the flashing anomalous color contrast illusion, the lower modulus "0" was defined by the gray disk alone (i.e. no radial lines). Because the scaling range required by the subjects was not known in advance of the experiments, they were allowed to exceed the upper and lower moduli as needed. Each stimulus was presented once, in a different random order for each observer. Because different groups of subjects rated different attributes, the results provide relative rather than absolute ratings of the influence of the various parameters.

Results

Number of radial lines

Mean ratings plotted in Fig. 4 for conditions 1–3 (left panel) increased with the number of radial lines up to 18, whereupon they

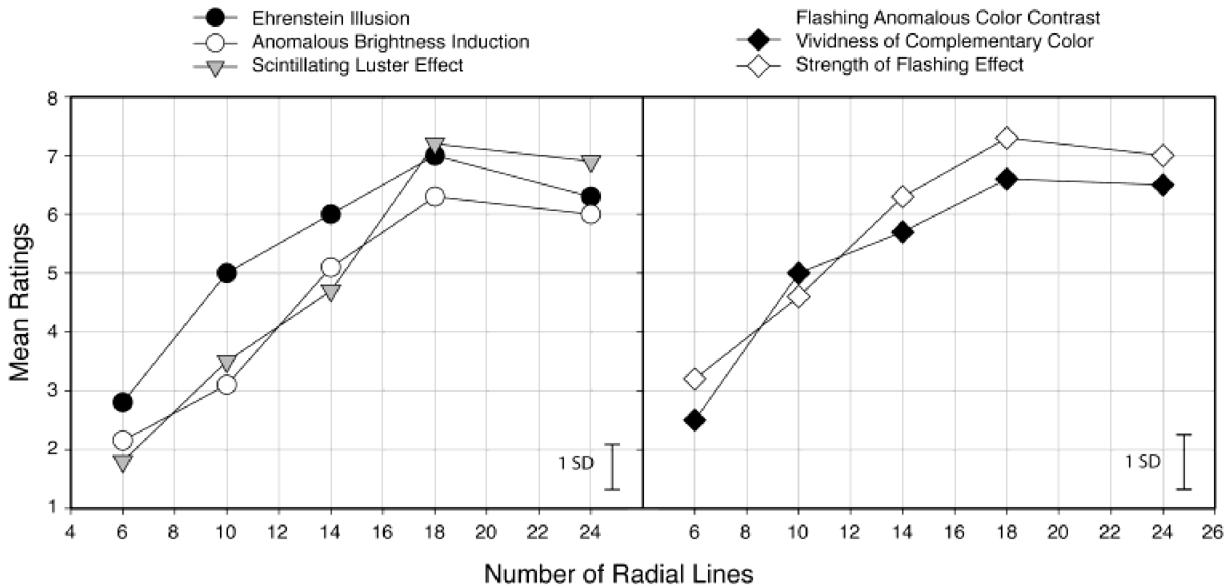

Fig. 4. Mean ratings plotted as a function of the number of radial lines. Here and in the following figures the calibration line denotes the mean standard deviation.

slightly decreased. The vividness of the complementary color and the strength of the flashes in the anomalous color contrast illusion (condition 4) behaved similarly with an increasing number of radial lines (Fig. 4, right panel). A one-way within-subjects ANOVA revealed an overall effect of variation in the number of radial lines ($P < 0.001$). Of importance here is that each curve follows a similar course. A statistical comparison between curves was not performed in this and the subsequent experiments because the ratings refer to different perceptual qualities.

Length of radial lines

Mean ratings for each condition are plotted as a function of the length of the radial lines, in Fig. 5 (left) for the Ehrenstein illusion, anomalous brightness induction, and the scintillating luster effect, and in Fig. 5 (right) for the two properties of the flashing anomalous color contrast illusion. In all five conditions, the percept under consideration increased with line length, but did not reach a plateau. A one-way within-subjects ANOVA revealed an overall effect of variation in the length of radial lines ($P < 0.001$).

Width of radial lines

Mean ratings for each condition are plotted as a function of the width of the radial lines in Fig. 6. For all five conditions, the curves have a similar shape demonstrating that the effect under consideration increased with increasing width of the radial lines up to 0.12 min of arc before it reached a plateau. A one-way within-

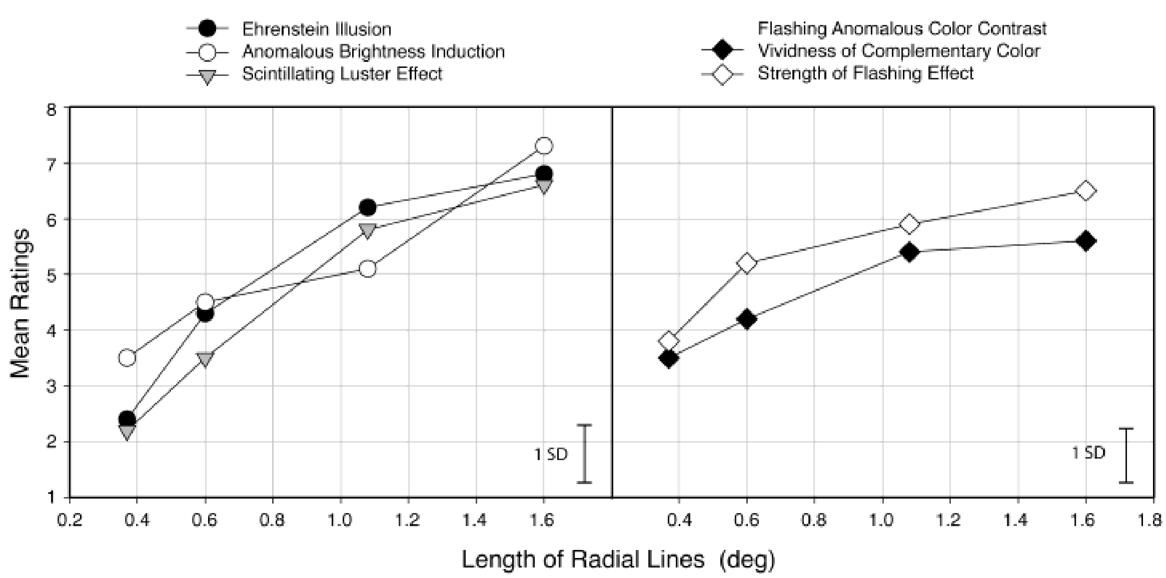

Fig. 5. Mean ratings plotted as a function of radial line length.

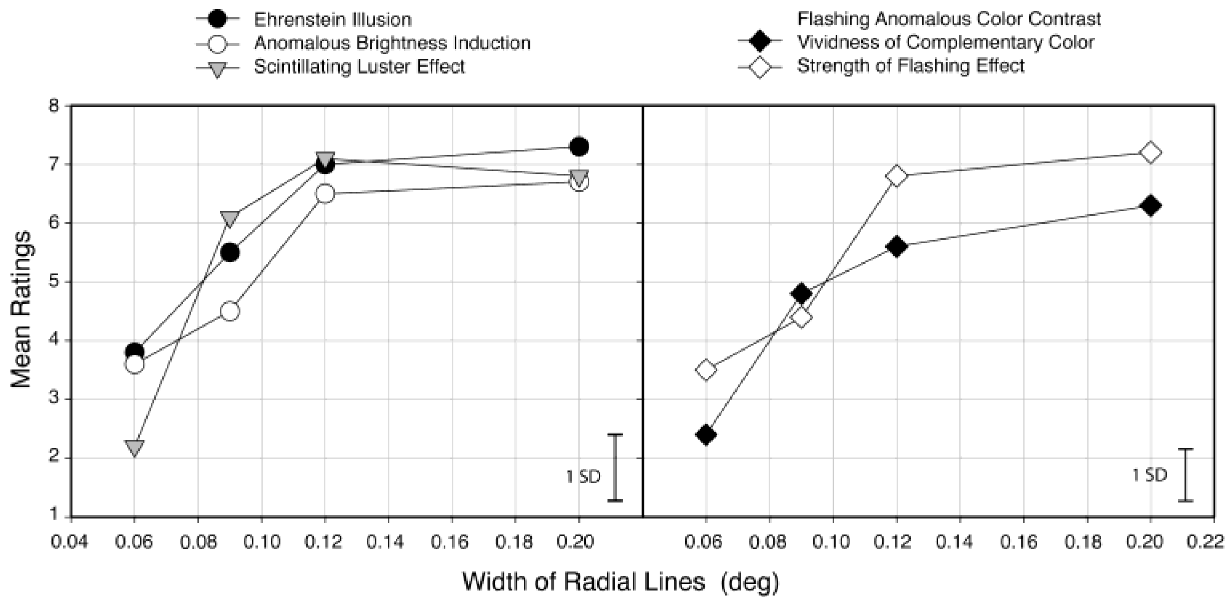

Fig. 6. Mean ratings plotted as a function of radial line width.

subjects ANOVA revealed an overall effect of variation in the width of the radial lines ($P < 0.001$).

Luminance contrast of radial lines

Mean brightness ratings are plotted in Fig. 7 as a function of the luminance contrast between the radial lines and the background. Curves with positive acceleration were obtained for all five conditions showing that the effects under consideration increase with increasing luminance contrast between the radial lines and the background. As in the line number experiment (Fig. 4), the curve for the Ehrenstein illusion lies above those of the other effects at lower stimulus levels. A one-way within-subjects ANOVA revealed an overall effect of variation in the luminance contrast of radial lines ($P < 0.001$).

Discussion

Flashing anomalous color contrast is a new type of complementary color induction that is different from simultaneous color contrast. This new effect has a similar dependence on radial lines to that of the other effects illustrated in Fig. 1, but it also has unique phenomenal qualities of its own that seem to make it more than a mere combination of the other effects. The observers' descriptions

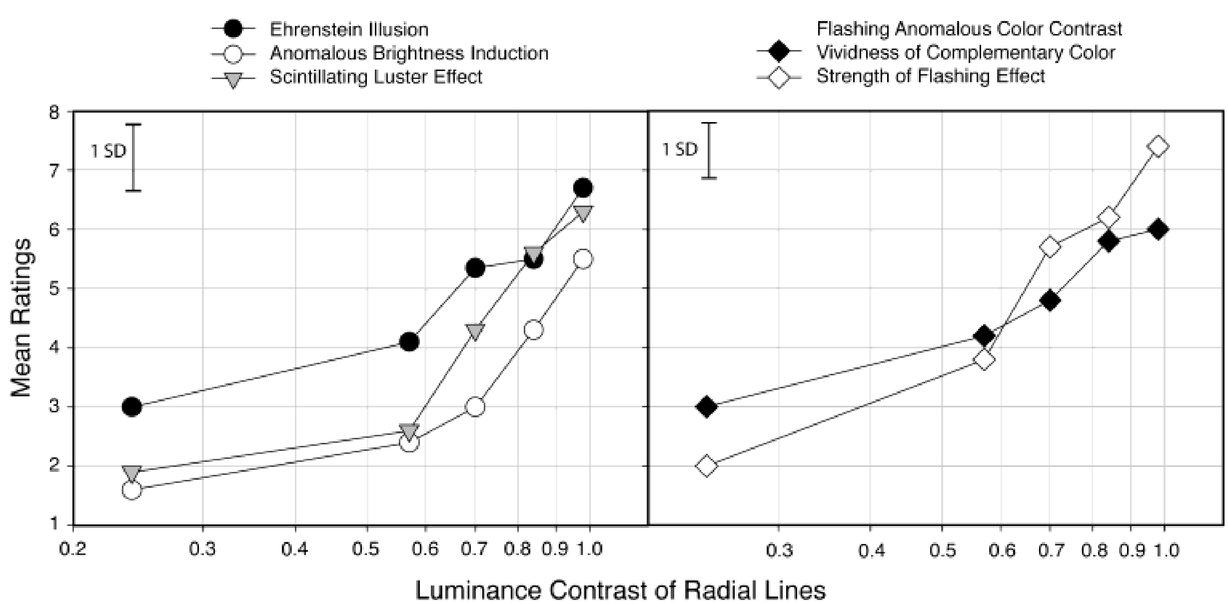

Fig. 7. Mean ratings plotted as a function of luminance contrast (log scale) between the radial lines and the background.

of the stimuli contained some but not all of the attributes of the comparison stimuli shown in Fig. 1. Of particular importance is that in flashing anomalous color contrast, the induced color appears self-luminous ("chromatic lights"), scintillating (flashes), not spatially tied to the central disks (floating), and phenomenally independent of the gray surface color of the disk. Rather than mixing, surface color and self-luminous color are distinct properties, one belonging to the gray disk and the other (chromatic lights) *emerging* from a combination of the characteristics of the three kinds of stimuli presented in Fig. 1. This phenomenal *scission* [Metzger's (1954) *Prinzip der gegabelten Wirkung*] is only present in anomalous color contrast, not in any of the other three effects. Flashing anomalous color contrast is a prime example demonstrating that a local change of stimulus pattern, such as adding a chromatic annulus and a gray disk to the central area of the Ehrenstein figure, may lead to a global change in perceived surface properties (see also Nakayama et al., 1989; Kamitani & Shimojo, 2004). What seems to be different in flashing anomalous color contrast from the perception of more typical visual stimuli is that the interactions among perceptual dimensions are not entirely cooperative and hence result in unstable percepts.

The experiments demonstrate that the properties of the phenomena studied (Figs. 1 & 2) show a similar dependence on parametric variations of the radial lines. The change in the strength of the effects with line number, length, width, and contrast is similar to that previously reported with the Ehrenstein illusion (Ehrenstein, 1954; Frisby & Clatworthy, 1975; Spillmann, 1975; Spillmann et al., 1976; Petry et al., 1983). The similarity of the curves referring to the four kinds of phenomena, and the fact that they depend crucially on the presence of the black radial lines, strongly suggests that any explanation of these percepts must be based on an understanding of the role of these lines and their long-range influence on the central area across the chromatic annulus. Note that the ratings in Fig. 5 do not appear to have reached a plateau at the longest length tested. The need for radial lines may call for local end-stopped receptive fields as have been proposed for filling-in of gaps by illusory contours (von der Heydt et al., 1984; Redies et al., 1986; Heider et al., 2000), but this is not sufficient to account for the new phenomenological features characteristic of flashing anomalous color contrast. From these experiments, it is not clear whether the radial lines have a direct effect on color induction or whether the vividness of the color is derived from the scintillation caused by the radial lines.

To account for these observations, consider the relevant stimulus parameters and their perceptual effects in Fig. 1: (1) Black radial lines induce brightness enhancement in the Ehrenstein illusion (Fig. 1 top). (2) Chromatic annuli bounding the tips of the radial lines induce anomalous brightness having both surface color quality and self-luminosity (Fig. 1 middle). (3) Gray disks inserted in the central gaps of an Ehrenstein figure elicit scintillating luster (Fig. 1 bottom). All these effects contribute to the perception of the effect under study, not only by addition, but also by generating the new and unique percept of flashing anomalous color. This percept is characterized by a scission between the gray surface color of the disks and the self-luminous "colored lights" induced by the surround. How could one explain these properties in terms of neural circuitry?

Cortical cells with double-opponent receptive fields are generally regarded as the main candidates for mediating simultaneous contrast (Michael, 1978; Ts'o & Gilbert, 1988). An L-M double-opponent cell, for example, one that is conventionally labeled as +R-G/-R+G, would be expected to fire more strongly to a green annulus in its receptive-field surround than to an extended gray field. This activity should produce a pattern of responses consistent with the induction of a reddish center. While such cells may contribute to color contrast, they cannot easily account for all of the other properties of this new contrast effect: high chromatic salience, apparent flashing, and the phenomenal scission between the gray disk color and the chromatic "lights" described above. High chromatic salience may conceivably be mediated by the double-opponent cells (DeValois & Marrocco, 1973) in conjunction with neurons having end-stopped receptive fields. On the other hand, flashing may be produced by an asynchrony between the brightness (ON) and darkness (OFF) channels and with rapidly alternating incremental and decremental percepts in the central gray area of the figure. This asynchrony has been shown to produce luster by flickering physical increments and decrements (Anstis, 2000); it may also be present when line-induced brightness enhancement (*illusory* increment) interacts with a gray disk (Pinna et al., 2000).

The neuronal nature of scission is unclear, but may potentially be linked in flashing anomalous color contrast to an asynchrony between chromatic and achromatic pathways. Thus, flashing anomalous color contrast may depend upon the integration of luster and hue induction, combined with brightness induction dependent on the length of the radial lines. However, the complexity and the diversity of the observed effects suggest that they are not the result of a unitary process in the brain, but originate in multiple specialized pathways. These parallel processes are almost certain to involve different neural conduction speeds. Color induction is likely to be coded initially by parvo- and konio-pathways, whereas the effect of the radial lines does not vary with hue and thus may be attributable to achromatic pathways (parvo- and magno-pathways). The differences in signal speed between these pathways may result in phase differences that could cause the perceived floating in the anomalous color contrast illusion reminiscent of the fluttering hearts phenomenon described by Helmholtz (1909–1911; see also von Grünau, 1975). The enhancement of flashing anomalous color contrast by stimulus, eye, or head movement is consistent with this interpretation.

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