A linkage of chromatic and achromatic cues in neon color effect

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Neon color effect consists of two phenomenal aspects of brightness/darkness enhancement and color bleeding. The spectral properties of these two aspects were determined by threshold measurements, using the Ehrenstein pattern configuration made up of elements of different colors. The results indicate that the Ehrenstein brightness illusion is mediated by the achromatic system and the neon bleeding effect by the opponent-color system, and that both have to be present for the neon color effect to occur. It is suggested that the contribution of the chromatic system to shape analysis is contingent upon the presence of luminance cues, implying strong linkage between luminance and color processing in form perception.

Key words: neon color effect, achromatic system, chromatic system, spectral sensitivity.
processing. It is widely accepted that there are multiple representations of the visual field in different cortical areas, which, to some degree, manifest parallel analyses of the retinal image. Correlation between the visual sensitivities of neurons and anatomical divisions of the striate cortex gives some support for the existence of distinct “form” and “color” pathways in V1 (Livingstone & Hubel, 1984, 1987; Tootell, Silverman, Hamilton, DeValois, & Switkes, 1988; Ts’o & Gilbert, 1988), although the distinction is not a sharp one (Tootell et al., 1988; Lennie, Trevarthen, Van Essen, & Wässle, 1990).

The achromatic pathway is widely assumed to be responsible for acute spatial vision, since its resolving power is higher than that of the chromatic or opponent-color system. In the cortex, form analysis may be a part of the specialized luminance analysis, just as seeing colors is a part of the specialized color analysis. Related psychophysical studies have demonstrated possible specific roles of the achromatic and chromatic pathways in form analysis (Livingstone & Hubel, 1987). Given the broad consensus about the parallel organization of the visual system, however, little is known about how perceptual tasks ought to be decomposed: are there really distinctive processes for color and form (luminance) in perceptual tasks? Are they as simple as has been often assumed?

In the present study we attempt to clarify the roles of the achromatic and chromatic systems in form perception, by utilizing the illusory-filling phenomenon called “the neon color effect”. There is a group of illusion that is generated by filling in an empty field, as shown in Figures 1 (a) and (b). When four lines or stripes are radially arranged so as to stop a certain distance from the point of intersection, brightness enhancement is observed in the central gap between the ends of lines. The brightness effect also occurs with dark areas when one uses white lines on a black field: here the darker area is induced by the white lines. This effect of illusory filling is called the Ehrenstein brightness illusion (Ehrenstein, 1941). If a colored cross is added so as to connect the line segments across the central gap, the cross can take on the aspect of colored film. A circular veil of color in the illusory area is called neon color and has the same hue as the inducing cross (van Tuijl, 1975). The boundary between the colored and the white lines creates an illusory border and the spread of color out of the fine line within the illusory border is called neon bleeding. The neon color effect is known to be very sensitive to slight changes in configuration. Van Tuijl and Leeuwenberg (1979) have demonstrated that the occurrence of the neon effect, as well as its strength, critically depends on the structural organization of an inducing pattern. Redies and Spillmann (1981) and Redies, Spillmann, and Kunz (1984) studied the effect of spatial variables on the neon color effect and found that its strength, form and extent strongly depended on the length of the colored connecting line, the length of achromatic adjoining lines, and the angular tilt between the colored connecting line and the achromatic adjoining lines. On this line of evidence, a valid explanation for the neon color effect may be given within a framework of interdependency of form and color, i.e., a process which can incorporate both hue and luminance discontinuities and interactions between them.

In this study, using a threshold procedure, we determined the limits and relative effects of stimulus parameters such as color and luminance, on the neon color effect. We focused on two aspects of the illusory-filling induced by the Ehrenstein pattern. One is the brightness effect which is called the Ehrenstein brightness illusion (Ehrenstein, 1941)(Figure 1 (a)). The other aspect is the color spreading induced by a colored cross embedded in the gap (Figure 1 (b)). Threshold
measurements were carried out to characterize the spectral properties of the Ehrenstein brightness effect and of the color bleeding. The results are expected to provide a cue to assess how hue may interact with luminance information in form-color processing.

Method

Stimulus

Figure 1 shows the stimulus configurations employed in this study. Figure 1 (a) shows the stimulus used for the measurement of the illusory brightness effect evoked by the Ehrenstein figure. The stimulus consisted of six Ehrenstein figures in a $3 \times 2$ array. Each line subtended a visual angle of $41.2'$ in length and $1.6'$ in width with distance between the ends of the lines subtending a visual angle of $20.6'$. The overall size of the pattern was $3.78^\circ \times 2.75^\circ$. The pattern was presented on a uniform white background subtending $10^\circ$ in diameter. The Ehrenstein figure was composed of colored lines, and was seen as a 2 s increment superimposed on the steadily presented background. The retinal illuminance of the background was either 20 or 200 td. In the Ehrenstein figure's gap an illusory patch which appeared to be darker than the surround background could be seen. This patch was delineated by an illusory border which, to most observers, looked circular. During an experimental session, the radiant intensity of the colored inducing lines required to produce the just-perceptible illusory patch as a function of the wavelength of the colored inducing lines was determined.

For the measurement of neon color bleeding, crosses were added to the Ehrenstein figure as shown in Figure 1 (b). The stimulus consisted of six Ehrenstein figures in a $3 \times 2$ array with center crosses embedded in the gaps. Each line in the Ehrenstein pattern subtended $41.2'$ in length and $1.6'$ in width, and each of the crosses' lines subtended $20.6'$ in length and $1.6'$ in width. The whole pattern was presented on a white background subtending $10^\circ$ in diameter. The retinal illuminance of the white background was 20 td. Six conditions were used for the Ehrenstein figure: it could be composed of either white, black, or colored lines whose wavelength was either 460, 500, 580 or 640 nm. For each condition, the center crosses were composed of a monochromatic light presented for 2 s within the steadily presented Ehrenstein figure. During an experimental session, the retinal illuminance of the Ehrenstein pattern was fixed at 200 td for the white and monochromatic patterns and at 0 td for the...
black pattern. The radiant intensity of the colored crosses required to produce the just-perceptible neon color bleeding was determined as a function of the wavelength of the colored crosses.

**Apparatus**

Stimuli were presented by four-channel Maxwellian view optical system. Two channels provided white lights: one for a white background field and the other for a white pattern. The light source for the white beams was a 500 W xenon arc lamp run under constant current. The color temperature of the white beams was raised to 8700 K by a color-correction filter (Toshiba, LB-B11). The other two channels provided beams for the monochromatic patterns. Both beams were derived from a light source which was a halogen-tungsten filament lamp, and were rendered monochromatic by a diffraction grating monochromator (Jobin-Yvon, H-20). The half-bandwidth of the monochromators was set to 4 nm. Patterned images were produced by field stops. Stimuli were presented in Maxwellian view through a 2-mm-diameter artificial pupil. All lenses were achromatic doublets and mirrors were front surfaced. The observer’s head position was fixed by a dental bite mounted on a X-Y-Z manipulator. Test patterns appeared sharp and well registered.

The retinal illuminance of the white light was adjusted by using neutral density filters. The intensity of each monochromatic light was controlled by neutral density filters in conjunction with the voltage supplied to the lamps with the aid of a microcomputer that stored the programmed data in advance.

**Calibration**

The retinal illumination of the white light was determined by a photoelectric illuminometer (International Light, IL1700 ), and the retinal illuminance level was estimated by the method described by Westheimer (1966). The radiant fluxes of the monochromatic light beams were measured at the Maxwellian image plane by using a radiometer (International Light, PM271EG AAS ).

The monochromator was calibrated by a mercury lamp. The neutral density and blocking filters were calibrated for spectral transmission using a spectrophotometer. The field stops by which test patterns were produced were made from high contrast film. Light transmittance of these stops was negligible (<0.1%), and the spectral transmission was also calibrated.

**Observers**

One of the authors and one observer served as subjects. Both observers were within the limits of normal trichromatic color vision as tested by color mixing (the Rayleigh match) with a Nagel anomaloscope, the Ishihara pseudoisochromatic plates, and the Farnsworth-Munsell 100 hue test.

**Procedure**

Threshold was estimated by the double random staircase method (Cornsweet, 1962). After an initial 5 min of dark adaptation, the observer adapted to a given background illuminance for 5 min. Then, the observer set the starting points of two staircases, by adjusting the intensity of a monochromatic light. The criteria were the intensities giving just visible and just invisible illusory effects (darkness enhancement or color bleeding). These values which bracketed the region containing a threshold intensity were then used as the initial intensity values in each staircase. A pair of staircases was run to determine the threshold. On each trial, the observer was forced to make a binary decision whether the illusory effect was seen or not. Each staircase independently followed the same rule for step size: a “see” response was followed by a constant decrement in the intensity of the light and a “do not see” response was followed by a constant increment. In each staircase, an initial step size was set to 1/10 of the difference between the
two starting intensity values, and after the first reversal, the step size was set to half of the initial step size. Each staircase was terminated after three reversals were made. The six reversal points from each pair of staircases were averaged to give a mean. More than four mean values were then averaged to give an overall mean for each condition.

Results

In Figures 2 (a) and (b), the relative sensitivities for the perception of the brightness illusion induced by the Ehrenstein figure are plotted against the wavelength of the Ehrenstein pattern: (a) shows the result for observer YE and (b) shows the result for observer KI. Open symbols represent the sensitivities measured for the 200 td white background and solid symbols represent the data for the 20 td white background. In each panel, the ordinate denotes the relative sensitivity expressed as log reciprocal radiant intensity at the threshold for the perception of the brightness illusion (darkness enhancement in the gap). The abscissa denotes the wavelength of the lines of the Ehrenstein figure. The vertical bars denote ±1 SE. Results for both observers are similar: the spectral sensitivity curves are broad-band functions with a single peak near 550 nm, for both the 200-td and the 20-td background illuminance levels. Such sensitivity curves are typical of the spectral sensitivity of the achromatic system. The continuous lines shown in Figures 2 (a) and (b) are the modified luminosity function \( V' \) of Judd (Wyszecki & Stiles, 1982), each of which is shifted to match the datum at 560 nm. When comparing the data with the luminosity function, the following factors, contributing to the variability of the luminosity function, should be noted. First, there are individual differences in ocular transmittance and, secondary the difficulty of calibration in the short wavelength end of the visible spectrum. These factors may contribute to the variation in the sensitivities to short wavelength lights (below 490 nm). Secondary, in the longer-wavelength region of the spectrum, the relative number of L and
M cones in the retina vary among observers. Taking these factors into account, one can say that the sensitivity functions for the illusory brightness effect are in good, though not exact, correspondence with the luminosity function.

The present result indicates that the illusory filling such as the darkness enhancement induced by the radially arranged lines of the Ehrenstein figure may be exclusively mediated by the achromatic or luminance system. Even if a colored pattern is used, the chromatic system might have little contribution to the brightness illusion.

In Figures 3 (a) and (b), the relative sensitivities for the perception of the neon color bleeding are plotted against the wavelength of the crosses which are embedded in the gap of the white Ehrenstein figure (open symbols) and of the black Ehrenstein figure (solid symbols): (a) shows the result for observer YE and (b) shows the result for observer KI. In each panel, the ordinate denotes the relative sensitivity expressed as log reciprocal radiant intensity at the threshold for the perception of the neon color bleeding, and the abscissa denotes the wavelength of the lines of the crosses. The vertical bars denote ±1 SE. For the black Ehrenstein figure, the spectral sensitivity curve for the perception of the neon color bleeding shows two notches near 480 and 570 nm, for both the observers. The emergence of the notches near 570 and 480 nm is usually ascribed to the contribution of the opponent color system (Sperling & Harwerth, 1971; King-Smith & Carden, 1976; Takahashi & Ejima, 1986). For the white Ehrenstein figure, the shape of the sensitivity curve differs between the two observers. The sensitivity curve for observer YE shows three peaks near 460, 540 and 600 nm with deep notches at 480 and 570 nm.

![Figure 3](image-url)
On the other hand, in the sensitivity curve for observer K1, only one notch near 470 nm emerges and the notch near 570 nm is not clearly observed. However, comparing this sensitivity curve with the luminosity function, the sensitivity curve is broad-band and a dip is observed near 570 nm. This is an indication of the contribution of the opponent-color system. Thus, the above result clearly demonstrates that color bleeding may occur through the opponent-color system.

Figure 4 shows the relative spectral sensitivity curves for the perception of the neon color bleeding for the monochromatic Ehrenstein figures: (a) shows the result for observer YE and (b) shows the result for observer KI. In each panel, four curves represent the data for four wavelengths of the Ehrenstein figure: 460, 500, 580, and 640 nm. The ordinate denotes the log relative sensitivity for the perception of the neon color bleeding, and the abscissa denotes the wavelength of the crosses. Each set of the data is vertically displaced 1.0 log unit for clarity. When the color of the Ehrenstein figure is similar to that of the crosses, sensitivity is reduced. However, within the spectral region where the colors of the Ehrenstein figure and the crosses are different, the curves still show opponent-color properties: a notch...
or an inflection near 480 nm is observed for the 500-nm, the 580-nm and the 640-nm Ehrenstein figures; a notch near 580 nm is not prominent except for the 580-nm Ehrenstein pattern for observer YE but the inflection is observed in the longer-wavelength region of the spectrum.

Although the results of Figures 3 and 4 clearly show the contribution of the opponent-color system to the perception of neon color bleeding, the pattern of the results reveals a significant variation in the shape of the sensitivity curves for different colors of the pattern elements. Several factors may be contributing to the variation. First, the shape of the sensitivity curves is quite similar between the white and the 580-nm Ehrenstein patterns. This suggests that spectral saturation may affect the formation of the neon color effect. Since spectral saturation is formally expressed in terms of a differential activity between the opponent-color and the luminance systems, this feature of the result indicates an interaction between the achromatic and chromatic systems. Second, there is a significant difference in the shape of the sensitivity curve between the white and the black Ehrenstein figures, although both are neutral for the opponent-color system. This indicates that the amount of luminance contrast and the direction of luminance contrast (darker or brighter), influences the generation of neon color effect. The third factor is that when the cross and the figure have similar hues the spatial discontinuity between the two is much reduced. These three factors seem to be related to the processes which are important for separating the figure from the background (saturation and luminance contrast), and to the spatial discontinuity between elements of different colors. The fourth factor to be considered is chromatic induction. The observers reported that when the monochromatic Ehrenstein figure was presented, the field was uniformly tinged with a complementary hue, and that this chromatic induction made it difficult to see the spreading of the color of the crosses particularly when the crosses and the figure had similar hues. Takahashi and Ejima (1983) measured chromatic effects induced by monochromatic, isoluminant stimuli, and found that the induced chromatic response functions showed the characteristics of the opponent-color process. It is likely that the color induced by the colored Ehrenstein figure may counteract or cancel the hue of the neon bleeding. For example, a red Ehrenstein figure induces green hue into the background field. This green induced hue may selectively cancel the red response in the field, resulting in the sensitivity reduction for the reddish neon colors, while it may not cancel the green or other (blue and yellow) responses in the field.

Note that the sensitivity reduction observed for the monochromatic Ehrenstein figures is selective for the color of the Ehrenstein figure but that the reduction takes place within a rather wide range of the spectral region. Such a reduction cannot be simply explained by color discriminability. The above consideration of the factors affecting the spectral sensitivity for the perception of the neon color effect suggests that the occurrence of the neon bleeding cannot be understood in terms of a simple framework of the opponent-color processing, indicating the involvement of multiple processes which may be based separately on the chromatic and achromatic systems.

**Discussion**

**Two Systems Contributing to the Generation of the Neon Color Effect**

The present results demonstrate that the two aspects of the illusory filling occurring in a line gap, i.e., the darkness enhancement and the neon color bleeding, are mediated by two
separate systems. The darkness enhancement induced by the Ehrenstein figure is mediated by the achromatic system and color bleeding is mediated by the opponent-color system. It should be emphasized here that both systems have to be present for the neon color effect to occur.

Some observations have clearly indicated that luminance factors such as luminance relations between the different line elements in the pattern and between these line elements and their background are critical for the occurrence of the neon color effect as well as its strength (van Tuijl & de Weert, 1979; Ejima, Redies, Takahashi, & Akita, 1984). In order for the neon color effect to occur, luminances of the different line elements have to be above or below the luminance of the background (van Tuijl & de Weert, 1979). The strength of a neon color effect is independent of the illuminance level of the crosses if the illuminance ratio to the Ehrenstein pattern is maintained (Ejima et al., 1984). On this line of evidence, the contribution of the achromatic or luminance system to the neon color effect seems to be indispensable.

It has been argued that the bleeding of color in the neon color effect may occur through the chromatic system when the fine pattern can be resolved only by the achromatic system (Day, 1983; Livingstone & Hubel, 1987). It has been well accepted that the chromatic system has lower acuity than the achromatic system. This lower resolution of the chromatic system implies that if an image is too fine for the chromatic system to resolve, its fine shape cannot be discriminated. Thus, there is a relatively narrow range of pattern sizes over which one can discriminate a pattern but still perceive color bleeding. As a consequence, colors become assimilated (blend or bleed) when the pattern exceeds the resolution of the chromatic system.

The present results reveal that neon color bleeding may be mediated by two mechanisms based separately on the chromatic and achromatic systems. Given the evidence for an important contribution of luminance factors to neon color effect, one can conclude that the neon color effect can not be due simply to the reduced resolution or contrast inherent in a representation of an image by the chromatic system. There are two reasons why assimilation is not a viable explanation for the neon color effect. First, neon bleeding is evoked by the embedded colored line, even though that line can be seen in isolation in sharp focus and on the other hand no color bleeding is perceived when the isolated line is presented on a uniform field. The second difficulty with the assimilation explanation is that it can’t account for the fact that the effect is very sensitive to tiny changes in configuration.

Note that the difference between the phenomena of assimilation and neon color bleeding seems to be quite similar to the difference observed between the brightness illusion seen in the Hermann grid and in the Ehrenstein figure (Spillmann, 1975): a most prominent difference is the maximum diameter of the illusory area across which uniform brightness changes occur; with central vision, it ranges a little over 5° of arc in the Hermann grid, whereas the area of brightness enhancement in the Ehrenstein figure may subtend up to 1° (Spillmann, 1975). These sizes of illusory areas vary with retinal eccentricity (Redies & Spillmann, 1981; Spillmann, 1975). A comparable difference is observed in the illusory area of color bleeding between the assimilation and the neon color effect. It is reasonable to assume that the neon color effect may primarily reflect cortical visual processing, while assimilation may reflect spatial summation within the center-surround receptive fields of the color-opponent cells in the retina and LGN.
**Distinctive Roles of the Achromatic and the Chromatic Systems in Form Perception**

We have shown that the manner of the contributions of the achromatic and chromatic systems quite differ between the detection and the illusory perception. It has been well established that in the detection of color stimuli, with a suitable selection of spatial and temporal test conditions and photopic adaptation level, two different increment thresholds, each of which is dominated by either the achromatic system or the opponent-color system, can be isolated (Sperling & Harwerth, 1971; King-Smith & Carden, 1976; Takahashi & Ejima, 1986; Mullen, 1987). The transformation of the dominant system (from the achromatic system to the chromatic system or vice versa) is stimulus dependent, and the notion that the most sensitive pathways are responsible for detection seems reasonable for near threshold performance. On the other hand, in the present illusory-filling phenomenon, the concurrent processing of the achromatic and the chromatic systems is likely to be responsible for the percept. These systems seem to be separate and are likely to serve different perceptual functions in the formation of the neon color effect: detection of an illusory patch in the Ehrenstein figure is mediated by the achromatic system and detection of illusory colors by the color-opponent system. The contribution of the achromatic system may be responsible for the effect taking place at line-terminations, while the contribution of the chromatic system may be responsible for the color spreading.

Present results do not support the hypothesis that the color information is proceeded independently from many luminance-based tasks (Livingstone & Hubel, 1987), but support the hypothesis that there is a substantial facilitatory interaction between the chromatic and achromatic systems (Gur & Akri, 1992). It is evident that each of the luminance and color pathways is inherently capable of representing two-dimensional shape (form analysis). Since the color pathway is provided with a rich set of shape primitives involving chromatic contrast, the shape information available in the color pathway is sufficient for performing shape analysis based on color information. However, the phenomenon of the neon color effect shows that colors bleed in particular configurations formed by a series of terminations (e.g. line ends). Present findings reveal that this bleeding of color results from the concurrent processing by the luminance and opponent-color systems: thresholds for an illusory color phenomenon seem to be controlled by the achromatic system. This suggests that there may be some images which appear to depend on a particular process or shape code available only in the luminance pathway. Similar results are found for real targets. There are indications that luminance information plays some privileged role in images involving implicit contours, namely, line-based illusory contours (Takahashi, Kiihara, Takemoto, Ido, & Ejima, 1992) and shadows (Cavanagh & Leclerc, 1989). The present results also suggest that luminance cues are necessary for color to elicit a sharp image. This suggests that while color can code shape, its contribution is contingent upon the presence of luminance cues. Such a contingency implies strong links between luminance and color processing in human vision: the color spreading (filling-in) process may be shaped by a luminance signal.

**References**


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