Published in final edited form as:

Perception. 2003 ; 32(11): 1289–1305.

Anomalous induction of brightness and surface qualities: A new illusion due to radial lines and chromatic rings

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Abstract

When a chromatic (eg light-blue) annulus surrounds the central gap of an Ehrenstein figure so as to connect the inner ends of the radial lines, a striking new lightness effect emerges: the central white disk has both a self-luminous quality (brighter than in the regular Ehrenstein figure) and a surface quality (dense, paste-like). Self-luminous and surface qualities do not ordinarily appear co-extensively: hence, the brightness induction is called *anomalous*. In experiment 1, subjects separately scaled self-luminous and surface properties, and in experiment 2, brightness was nulled by physically darkening the central gap. Experiments 3 and 4 were designed to evaluate the importance of chromatic versus achromatic properties of the annulus; other aspects of the annulus (width or the inclusion of a thin black ring inside or outside the chromatic annulus) were tested in experiments 5-7. In experiments 8-12, subjects rated the brightness of modified Ehrenstein figures varying the radial lines (number, length, width, contrast, arrangement). Variation of these parameters generally affected brightness enhancement in the Ehrenstein figure and anomalous brightness induction in a similar manner, but was stronger for the latter effect. On the basis of these results, anomalous brightness induction is attributed to a surface induction process triggered by an interaction between illusory brightness enhancement (due to the radial lines) and border ownership (due to the blue annulus).

1 Introduction

In the Ehrenstein illusion shown in plate 1, a bright circular patch conspicuously fills the central gap between the radial lines although there is no luminance increment relative to the surround. Likewise, the crisp circular border delineating this patch has no physical correlate in the stimulus. Ehrenstein (1941) demonstrated that the illusion is eliminated or reduced when a thin black ring is superimposed on the subjective contour.

In plate 2 we show that inserting a chromatic annulus instead of a thin black ring, does not cancel or reduce the illusion, but produces a striking new effect. The white disk within the blue annulus not only appears much brighter (self-luminous) than the illusory patch in the regular Ehrenstein figure, but also has a dense surface appearance comparable to a white paste added to the surface of the paper. This property is unique, as to our knowledge no other illusory effect exhibits a surface colour quite comparable to it, while also appearing quasi-luminous as if emitting light. Self-luminous and surface qualities do not ordinarily appear together, and have

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even been considered opponent, or mutually exclusive, modes of appearance (Heggelund 1992). We therefore call this phenomenon *anomalous brightness induction*.

Early attempts to explain the Ehrenstein illusion and similar illusions such as the Kanizsa triangle (Kanizsa 1955, 1974) or the ‘Sun effect’ (Kennedy 1976, 1978) have focused on whether there is a need for completeness of the pattern or for amodal completion (for review, see Spillmann and Dresch 1995). In the anomalous brightness induction reported here, the presence of the chromatic annulus would be expected to eliminate the need for figural completion because there are no terminators as the line ends are bounded by the annulus. As a consequence, illusory brightness enhancement should be absent (as in the case of a thin black ring surrounding the subjective contour of the Ehrenstein illusion). However, the opposite is the case.

There have been many attempts to demonstrate that illusory brightness also occurs without amodal completion of the inducing elements. Purghé (1991, figure 5) arranged four black polygons so that the inner illusory polygon appears linked to the other four. The Y-junctions necessary to create the linkage represent a limiting case of amodal completion. Some authors (Kennedy and Lee 1976; Ware and Kennedy 1977, 1978; Shipley and Kellman 1990; Kellman and Shipley 1991) demonstrate other interesting cases of illusory figures generating brightness induction with real contours or with solid objects. In all of these cases, self-luminous and surface qualities are separated, but this is not what is perceived in anomalous brightness induction.

In addition to the aforementioned factors, classical simultaneous contrast, due to the surrounding ring, might be thought to contribute to the anomalous brightness effect, but the light-blue annuli presented in isolation produce a rather weak effect and they do not impart the dense appearance (paste-like quality) to the central area. However, simultaneous contrast resulting from the combination of the blue annulus and the black radial lines may contribute, at least in part, to the anomalous brightness effect.

The experiments presented in this paper were designed to identify stimulus conditions giving rise to the anomalous brightness effect. Here we ask specifically: Must the annulus be chromatic? What is the role of simultaneous contrast? What is the role of the radial lines? These parametric variations are intended to set the stage for a theoretical understanding of the neural mechanisms underlying anomalous brightness induction. The first experiment was conducted to quantify the dissociation of self-luminous and surface colour properties in the illusion. In addition, we determined the degree to which brightness enhancements in the Ehrenstein illusion and anomalous brightness induction behave similarly when the inducing stimulus is varied along certain parameters. To this end, we varied annulus and line properties. The results demonstrate that anomalous brightness requires both black radial lines and a chromatic ring and that the interaction between separate mechanisms may be responsible for the appearance of self-luminous and surface qualities.

2 General methods

2.1 Subjects

Separate groups of fourteen undergraduate students (19-26 years old; a ratio of about 1:3 between males and females) participated as observers in each experiment (independent groups for each experiment). They were naïve as to the purpose of the experiments. All had normal or corrected-to-normal vision.

2.2 Stimuli

Stimuli typically consisted of 4×4 arrays of regular as well as modified Ehrenstein figures, as shown in plates 1 and 2. The 4×4 array was used because pilot experiments showed that it was more effective than a single stimulus. This result is in agreement with other effects such as the Hermann grid (Wolfe 1984), and scintillating Hermann grid (Heidler et al 2000). The Ehrenstein figures were modified by bounding the tips of the black radial lines and the central gap with a chromatic (eg blue), grey, or black ring. The stimuli were presented at right angles to the line of sight at an observation distance of 50 cm and viewed binocularly under Osram Daylight fluorescent light (250 lux). The position of the observer was maintained by a chin-rest.

Stimuli, illustrated in plates 1-3, were printed with an Epson Stylus Printer (Photo 700) at 1400 dpi on Epson Photo-Quality Ink Jet Paper. The luminance of the white paper was 82.31 cd m^{-2} under the conditions of our experiments. Luminance contrasts for stimulus components (L_x) were defined by $(L_{\text{white background}} - L_x)/L_{\text{white background}}$. Black lines and rings had a luminance contrast of 0.98. Unless otherwise stated, there were 18 equally spaced radial lines per figure, the line length was 14 mm (1.6 deg), the width 1 mm (6.9 min of arc), the diameter of the central gaps 12.5 mm (1.43 deg), and the width of the annuli 2 mm (13.8 min of arc). The light-blue annulus had a luminance contrast of 0.67 and its CIE x, y chromaticity coordinates were 0.201, 0.277.

2.3 Procedure

Subjects were first familiarised with examples of brightness induction using stimuli eliciting the Kanizsa triangle, Ehrenstein illusion, and anomalous brightness induction that were different from those presented in the experiments. In experiments 3-12, subjects rated the strength of brightness in the central disks of each test pattern using magnitude estimation. An eight-point scale (0-7) was chosen for these experiments with '7' defining the upper modulus and '0' the lower modulus. The upper modulus, '7', was defined by the brightness observed in modified Ehrenstein figures with light-blue annuli surrounding the central areas (see section 2.2), while the lower modulus, '0', was defined by the brightness of a blank sheet of the white paper on which the stimuli were printed. Subjects were allowed to exceed the upper and lower moduli as needed because the appropriate range was not known beforehand and we did not wish to introduce ceiling or floor effects. Each stimulus was presented once, with a different random order for each observer. Each subject rated the brightness verbally and the experimenter recorded the value. The duration of the experiment ranged from 15 to 30 min.

3 Appearance qualities

3.1 Experiment 1. Self-luminous and surface-appearance qualities

The purpose of this experiment was to quantify self-luminous and surface qualities of anomalous brightness induction and to determine whether they can be dissociated, or whether they change in the same way with changes in the luminance of the blue annulus. Eight luminance contrasts of the blue annuli were used, ranging from 0.24 to 0.85 with respect to the white test region. Examples are shown in plates 2 and 3.

Separate groups of subjects were asked to rank either the self-luminous or the surface colour qualities of the same eight stimuli. Self-luminosity was defined as the appearance of emitted light. Surface colour was defined as the quality characteristic of an opaque surface. The stimuli were placed in two rows arranged randomly on a black background in front of the subject. The strength of self-luminous or surface qualities was ranked in either an ascending or descending order based on a random assignment of ranking direction to subjects.

Figure 1 presents self-luminous and surface rankings (converted to proportions) plotted as a function of the luminance contrast of the blue annuli (with the axis of abscissas spaced logarithmically). The two curves are essentially the inverse of one another. As the luminance contrast of the annulus is increased, the self-luminous ranking decreases, while the surface quality increases. They cross when the blue annulus has a contrast of 0.59. A χ^2 test revealed an overall effect of variation of both properties as a function of the contrast of the blue annuli (self-luminous property: $\chi^2 = 48.36, p < 0.001$; surface colour property: $\chi^2 = 36.55, p < 0.001$).

The results of figure 1 are consistent with separate mechanisms mediating the perception of self-luminous and surface qualities experienced in anomalous brightness induction. Under these conditions, the two phenomena may oppose each other as they change in opposite directions with variations in annulus contrast, but they are not mutually exclusive (see Heggelund 1992). The following experiments further evaluate stimulus conditions influencing this anomalous brightness effect.

3.2 Experiment 2. Brightness cancellation

Anomalous brightness induction was rated for stimuli varying in the luminance contrast of the central gap. By substituting a grey disk (luminance decrement) for the normal white disk, illusory brightness could be nulled. The amount of physical darkening of the central gap required for cancellation of brightness was used as a measure of brightness induction. The purpose of this experiment was to compare the strength of anomalous brightness with brightness enhancement in the Ehrenstein illusion (radial lines only).

Ten luminance contrasts of the central gap ranging from 0 to 0.4 were tested. There were five stimulus conditions (illustrated in plate 3):

- i. Ehrenstein illusion. Black radial lines on a white background, no annuli.
- ii. Anomalous brightness induction. Black radial lines bounded by a light-blue annulus on a white background.
- iii. Achromatic control for anomalous brightness induction. Black radial lines bounded by a grey annulus on a white background. The luminance contrast (0.65) of the grey annulus was chosen on the basis of the results of the next experiment showing that this value elicits the strongest brightness induction (for an achromatic annulus) over the range of 0.21 to 0.98.
- iv. Simultaneous contrast. Black radial lines bounded by a black annulus on a white background. This was a control stimulus to test for any contribution from simultaneous contrast to anomalous brightness induction.
- v. Annuli only. Light-blue rings only on a white background, no radial lines. This was another control stimulus to evaluate the role of the radial lines in anomalous brightness induction.

Mean brightness ratings for each condition are plotted in figure 2 as a function of the luminance contrast of the disk area. For all five experimental conditions, there are parallel brightness decreases with increasing luminance contrast of the central area up to a value of approximately 0.23 and then the curves converge as they continue to decrease to the maximum value tested.

For decrements of 0-0.23, the five curves in figure 2 are vertically separated in accordance with the differences in induced brightness for the various stimulus conditions used. Figures producing anomalous brightness induction (black radial lines, blue annuli) yield the highest ratings. This condition is followed by the ratings for the unmodified Ehrenstein figure, then by the ratings for black-radial-line figures bounded by grey annuli (achromatic control) or black

annuli (simultaneous contrast), and finally for blue annuli only (no radial lines). There is no evidence of brightness induction for this last condition.

Cancellation contrast is given by the projection from the zero crossing of each curve onto the abscissa. The corresponding contrast values in ascending order are: 0.05 extrapolated for blue annuli only [condition (v)], 0.22 for black radial lines with black annuli [condition (iv)], 0.225 for black radial lines with grey annuli [condition (iii)], 0.23 for black radial lines without annuli [condition (i)], and 0.24 for black radial lines with blue annuli [condition (ii)]. Thereafter, rated brightness becomes negative, ie the gaps appear darker than the background.

A one-way ANOVA reveals an overall effect of variation in luminance of the central area (for all five conditions: $F_{9,130} > 110$, $p < 0.0001$). A two-way ANOVA shows that the percentage of black added to the disk area differs significantly with the size of the decrement contrast ($F_{9,650} = 154.8$, $p < 0.001$) as well as the five conditions ($F_{4,650} = 112.6$, $p < 0.001$). The interaction between these two factors is also significant ($F_{36,650} = 98.8$, $p < 0.001$). In a Fisher PLSD a posteriori analysis, all differences between the five test conditions are significant ($p < 0.0001$).

The results confirm that black radial lines and blue annuli [condition (ii)] were the most effective combination of those tested for inducing anomalous brightness induction. With equally wide grey or black rings [conditions (iii) and (iv)], the induced brightness effect is less and it is also less than for the black radial lines of the Ehrenstein figure alone [condition (i)]. Conditions (iii) and (iv) produced notably weaker brightness effects than conditions (i) and (ii), but do not entirely rule out a contribution from simultaneous contrast.

4 Annulus properties

4.1 Experiment 3. Achromatic and chromatic annuli

The previous experiment demonstrated that the light-blue annulus was more effective than the achromatic annuli in enhancing brightness in the central area. The purpose of experiment 3 was to determine whether this result is attributable to the chromatic properties of the annulus or the particular luminance contrast of the ring tested. This was accomplished by testing the effectiveness of grey and blue annuli over a series of luminance contrasts. If the chromatic annulus is more effective than the achromatic one over a range of luminance contrasts, it can be inferred that chromatic properties of the annulus contribute to anomalous brightness induction.

Twenty luminance contrasts of the inner grey annuli were tested, ranging from 0.21 to 0.98 (see example in plate 3). Brightness was rated as described in section 2.

Mean brightness ratings are plotted in figure 3 as a function of the contrast of blue and grey annuli. For both types of annulus, scaled brightness increases with contrast to a peak at about 0.6, and then decreases again. Over most of the range, brightness is higher for chromatic than for achromatic annuli. A two-way ANOVA revealed an overall effect of variation in luminance contrast ($F_{19,520} > 23.7$, $p < 0.001$) and between the two conditions ($F_{1,520} > 13.5$, $p < 0.001$). The interaction between the two factors is also significant ($F_{19,520} = 13.8$, $p < 0.001$).

To obtain maximal anomalous brightness induction, the luminance contrast of the annulus should be about 0.55-0.65 relative to the inner white disk for both chromatic and achromatic annuli. Over most of the range, however, the chromatic annulus was significantly more effective than achromatic annuli of the same luminance contrast. The difference in the magnitude of induced brightness between chromatic and achromatic annuli was similar to that obtained in experiment 2. These results confirm the superiority of the chromatic annulus in

inducing anomalous brightness over most of the range. This includes the range over which the subsequent experiments were conducted. The superiority of the chromatic over the achromatic annuli is not found, however, at the high luminance contrast values as shown in the graph and indicated by the significant interaction of the ANOVA.

The results of this experiment are inconsistent with an interpretation of the effect in terms of simultaneous contrast, which would predict a monotonic increase in brightness with contrast. At first glance, the results in figure 3 may also appear inconsistent with the results obtained in experiment 1 (figure 1). In both experiments similar conditions were used relative to the blue annulus, but different curves emerge. These differences can be understood if one considers that the data in figure 1 show surface colour and self-luminous qualities scaled separately, while figure 3 represents a global brightness scaling as also used in all of the subsequent experiments.

4.2 Experiment 4. Chromatic annuli

Previous research has demonstrated strong chromatic contributions to brightness (Guth et al 1969; Wagner and Boynton 1972; Bauer and Röhler 1977) and experiment 3 suggests that the chromatic properties of the annulus contribute to the strength of anomalous brightness induction. The purpose of this experiment was to determine whether other chromatic annuli are equally effective. The procedure was the same as in experiment 3, but the colours of the annuli were purple, blue (same as in the upper modulus), green, yellow, orange, and red (see example in plate 3). The brightness of the annuli was equated by each of the fourteen subjects using the method of limits. This was accomplished with a 2 cm × 2 cm blue square as the standard and finding a brightness match against ten different coloured squares having the same size, but varying in luminance. The CIE x , y chromaticity coordinates for the stimuli were: purple (0.51, 0.31), blue (0.201, 0.277), green (0.3, 0.5), yellow (0.46, 0.42), orange (0.48, 0.43), and red (0.54, 0.33).

Figure 4 shows the mean brightness ratings for the different chromatic annuli. Although the rated brightness was highest with blue annuli, the ratings for the other colours were not significantly different when tested with a within-subjects ANOVA. The results suggest that anomalous brightness induction is not specific to a light-blue annulus, but may occur with a wide range of chromatic stimuli.

4.3 Experiment 5. Width of annulus

It is known that the Ehrenstein illusion is weakened or even abolished by surrounding the central white gap with a thin black ring [Ehrenstein 1941, see also experiment 2, condition (iv)]. Why then do we see anomalous brightness, when a wider chromatic annulus is used instead? To find out, we varied the width of the annulus using the same procedure and conditions as in experiment 3. The width of the annuli was varied in five steps, 0.057, 0.11, 0.23, 0.46, and 0.51 deg (one example is shown in plate 3). The Ehrenstein figure [condition (i) in experiment 2] was not tested, since it was considered a limiting case. This stimulus variation may tell us not only about the role of the annulus as it changes in width, but also about how T-junctions (a radial line abutted by a thin ring) and wide annuli (area contrast) act in combination. In doing so, it may hold a clue as to the origin of surface induction associated with anomalous brightness induction.

Mean brightness ratings for each condition are plotted in figure 5 as a function of annulus width. For both experimental conditions, rated brightness first increases sharply with increasing annulus width, peaks at a width of 0.23 deg, and then decreases slightly. The curve for anomalous brightness induction (chromatic annuli) reaches a higher level than the curve obtained for black radial lines bounded by grey annuli. A two-way ANOVA revealed an overall effect of variation in width of the annulus ($F_{4,130} > 67.3$, $p < 0.001$) and in the two conditions

($F_{1,130} > 45.1$, $p < 0.001$). The interaction between the two factors is also significant ($F_{4,130} = 6.2$, $p < 0.001$). In a Fisher PLSD a posteriori analysis, the differences between the two test conditions are significant ($p < 0.0001$).

The difference between the curves confirms the brightness enhancement of a chromatic annulus. The intense whiteness and density of the anomalous effect may thus be a combined effect of the black radial lines and the chromatic annuli imparted onto the central area.

4.4 Experiment 6. Width of black intervening ring between blue annulus and white disk

If anomalous brightness induction arises because of an interaction between the radial lines and the chromatic annular surround, then spatially separating the two by inserting a (thin) black ring should weaken the induced brightness (see example in plate 3). The opposite would be expected if simultaneous contrast were at work. The question then is: what happens if one blocks the action of the chromatic annulus onto the enclosed white disk area by adding a black ring to the inside edge of the chromatic annulus? This was tested with stimuli consisting of black radial lines bounded by a blue annulus and a black ring separating the white central disk from the blue annulus. The widths of the black intervening ring were: 0 (no step), 0.03, 0.11, and 0.17 deg.

Mean brightness ratings are plotted in figure 6 as a function of the width of the black inner ring. Brightness ratings decrease monotonically with increasing width of the black ring. This was verified statistically by a significant main effect in an ANOVA ($F_{3,52} = 13.56$, $p < 0.0001$).

The results are consistent with the suggestion that anomalous brightness induction arises from a synergistic interaction between black radial lines and surrounding chromatic annuli (T-junctions). We interpret the effect of the black intervening ring as obstructing the combined action of the radial lines abutting the blue annulus onto the white disk. Finally, the negative slope of the curve is inconsistent with an interpretation of the data by simultaneous contrast.

4.5 Experiment 7. Width of black intervening ring between blue annulus and radial lines

The same rationale as in the previous experiment applies when the black ring is inserted between the tips of the radial lines and the blue annulus. The assumed interaction between the two is expected to be disrupted by the intervening black ring as illustrated by example in plate 3. Test conditions were the same as in the previous experiment, but with the black ring added to the outside edge of the blue annulus to test for anomalous brightness induction when the radial lines were not in direct contact with the annulus. The width of the black rings was varied in six steps: 0, 0.03, 0.11, 0.17, 0.21, and 0.25 deg.

Mean brightness ratings are plotted in figure 7 as a function of the width of the black ring. Brightness decreases monotonically with increasing width of the black ring. An ANOVA revealed an overall main effect ($F_{5,78} = 12.1$, $p < 0.001$). These results further strengthen our hypothesis that anomalous brightness induction is attributable to a synergistic interaction between the radial lines and the chromatic annulus enclosing the central white area, and that simultaneous contrast is not the primary factor underlying this effect. With a black intervening ring, there is no T-junction with the blue annulus and consequently the induced brightness decreases. In the next three experiments we evaluated properties of the black radial lines in contributing to anomalous brightness induction.

5 Line properties

5.1 Experiment 8. Number of radial lines

Previous research has demonstrated that the strength of brightness enhancement in the Ehrenstein illusion changes in an inverted U-shape manner with an increase in the number of the radial lines (Ehrenstein 1941; Spillmann 1975; Fuld and O'Donnell 1984). In this experiment, we asked whether anomalous brightness induction changes in the same manner. The number of lines was varied in five steps (6, 10, 14, 18, and 24; see example in plate 3), with lines spaced evenly around the central gap for each of the following conditions:

- i. Black radial lines on a white background, no annuli (Ehrenstein illusion).
- ii. Black radial lines bounded by a light-blue annulus on a white background (anomalous brightness induction).
- iii. Black radial lines bounded by a grey annulus on a white background (achromatic control).

Mean brightness ratings are plotted in figure 8 as a function of the number of radial lines. All curves begin low and then increase with the number of radial lines. The curve for anomalous brightness induction yields the highest ratings followed by the curve for the Ehrenstein figure. A two-way ANOVA revealed an overall effect of variation in the number of radial lines ($F_{4,195} > 88.1, p < 0.001$) and in the three conditions ($F_{2,195} > 44.3, p < 0.001$). The interaction between the two factors is also significant ($F_{8,195} = 6.8, p < 0.001$). In a Fisher PLSD a posteriori analysis, all differences between the three test conditions are significant ($p < 0.0001$).

These results indicate that the inner endpoints (terminators) of the radial lines play a role in inducing brightness in the central area because ratings increase as the number of lines increases and then level off or decrease as the tips of the radial lines merge into a quasi-continuous circle [conditions (i) and (ii)]. The importance of the radial lines was tested further in the next experiment by varying their length while the spatial separation between the lines was kept constant. The results in figure 8 again confirm the superiority of the chromatic blue over the achromatic grey annuli in anomalous brightness induction.

5.2 Experiment 9. Line length

The strength of brightness enhancement in the Ehrenstein illusion increases with increasing length of the radial inducing lines (Ehrenstein 1941; Spillmann 1975; Salvano-Pardieu 2000). Does the strength of anomalous brightness induction also increase with line length? This question was addressed by using the same experimental conditions and procedures as in the previous experiment, but with the length of the radial lines varied (see example in plate 3) in four steps: 0.37, 0.6, 1.08, and 1.6 deg.

Mean brightness ratings for each condition are plotted in figure 9 as a function of line length. Rated brightness for all three conditions increases with increasing line length and then gradually levels off at approximately 1 deg. However, the curve for anomalous brightness induction has a steeper initial slope and asymptotes at a higher level than the other two curves (Ehrenstein figure and black radial lines bounded by a grey annulus). A two-way ANOVA revealed an overall effect of variation in the length of radial lines ($F_{3,156} > 97.3, p < 0.001$) and in the three conditions ($F_{2,156} > 38.6, p < 0.001$). The interaction between the two factors is also significant ($F_{6,156} = 9.6, p < 0.001$), revealing nonparallel curves. In a Fisher PLSD a posteriori analysis, all differences between the three test conditions are significant ($p < 0.0001$). These results suggest a long-range effect of the black radial lines that extends to approximately 1 deg. Classical simultaneous contrast cannot explain these data.

5.3 Experiment 10. Line width

The strength of brightness enhancement in the Ehrenstein illusion follows an inverted U-shape function with increasing width of the radial lines (Ehrenstein 1941; Spillmann 1975; Petry et al 1983). In this experiment, we asked whether anomalous brightness induction changes similarly with the width of the radial inducing lines. This was tested by scaling brightness for varying line widths (0.06, 0.09, 0.12, and 0.2 deg; see plate 3).

Mean brightness ratings are plotted in figure 10 as a function of radial line width. Rated brightness for all three conditions starts at a common low value and then increases monotonically with increasing width up to the maximum width tested. Curves are highest for anomalous brightness induction and lowest for black radial line figures bounded by grey annuli; the curve for the Ehrenstein figure lies inbetween. A two-way ANOVA revealed an overall effect of variation in width of radial lines ($F_{3,156} > 67.6, p < 0.001$) and in the three conditions ($F_{2,156} > 46.5, p < 0.001$). The interaction between the two factors is also significant ($F_{6,156} = 13.5, p < 0.001$), revealing nonparallel curves. In a Fisher PLSD a posteriori analysis, all differences between the three test conditions are significant ($p < 0.0001$).

The results for anomalous brightness induction are different from those obtained with the Ehrenstein illusion in that no inverted U-shape function was obtained. We cannot, of course, rule out the possibility that anomalous brightness induction would decrease with still further increases in line width, as the widest radial lines did not yet touch at the tips. The trend of the curves suggested, particularly for the Ehrenstein figure, that an asymptote is being approached and may precede a decrease in brightness induction if the width of the radial lines is further increased. Note again that the superiority of the Ehrenstein figure over the achromatic annulus condition is contrary to expectations based on a strong contribution from simultaneous contrast mechanisms. Instead, the annulus, if chromatic, may play a role in defining border ownership (Rubin 1915; Nakayama and Shimojo 1990).

5.4 Experiment 11. Luminance contrast between radial lines and background

The strength of brightness enhancement in the Ehrenstein illusion increases with the luminance contrast between the radial lines and the background (Frisby and Clatworthy 1975; Spillmann et al 1976, 1984; Petry et al 1983). The purpose of this experiment was to determine whether the strength of anomalous brightness induction similarly depends on the contrast between the radial lines and the background. The conditions and procedures were the same as in experiment 8, but the luminance contrast of the radial lines was varied among six stimuli from 0.2 to 0.97. Plate 3 shows one example.

Mean brightness ratings are plotted in figure 11 as a function of the luminance contrast between the radial lines and the background. For all three conditions, brightness ratings increase monotonically with luminance contrast. The curve for anomalous brightness induction (blue annulus) is highest, the curve for the grey annulus is the lowest, and the results for the Ehrenstein illusion are inbetween. However, the differences between the curves are small. A two-way ANOVA revealed an overall effect of variation in contrast of radial lines ($F_{5,234} > 132.4, p < 0.001$) and in the three conditions ($F_{2,234} > 88.6, p < 0.001$). The interaction between the two factors is also significant ($F_{10,234} = 9.6, p < 0.001$). In a Fisher PLSD a posteriori analysis, all differences between the three test conditions are significant ($p < 0.0001$). These results demonstrate an effect of radial-line contrast on the induced brightness of the central area, irrespective of whether the annulus was blue, grey, or absent. However, a strong effect is only reached if the contrast is equal to or larger than 0.7.

5.5 Experiment 12. Arrangements of the lines relative to the annulus

In this final experiment concerning the role of radial lines in inducing anomalous brightness we evaluated the arrangement of the lines relative to the annulus. It is known that an orthogonal orientation of the lines relative to the inner disk elicits the strongest brightness effect (Ehrenstein 1941). Here, we evaluated whether different orientations and arrangements of the lines relative to the blue annulus influence anomalous brightness induction. The lines were arranged relative to the annuli in the following ways: orthogonal, tilted by 45°, irregularly oriented (ie scrambled) and with the line-ends detached from the annuli (see example in plate 3). In addition, annuli without lines were presented as a control.

Mean brightness ratings are plotted in figure 12 as a function of the arrangement of the lines. It is clear that the orthogonal arrangement elicited the strongest brightness induction. Tilting the radial lines by 45° greatly reduced the brightness. The irregular arrangement elicited no effect as did the ‘annuli only’ condition. A one-way within-subjects ANOVA revealed an overall effect of conditions ($F_{3,52} = 122.99, p < 0.001$). In a Fisher PLSD a posteriori analysis, all differences of paired comparison between the four conditions are significant ($p < 0.0001$), except for the comparison between ‘annuli only’ and ‘irregular arrangement’.

These results buttress the finding that the radial lines play a fundamental role in inducing anomalous brightness. The results further suggest that anomalous brightness induction may be activated by a mechanism that is sensitive to orthogonal junctions (or T-junctions) and is separate from simultaneous contrast mechanisms.

6 Discussion

We have shown that inserting a chromatic (light-blue) annulus between the tips of the black radial lines and the central white area of an Ehrenstein figure elicits *anomalous brightness induction*, a striking white that has both surface and self-luminous qualities. The experimental data are contrary to predictions of brightness induction based on amodal completion (as in the Ehrenstein illusion; see section 1) and cannot be accounted for by simultaneous contrast.

Anomalous brightness induction is characterised by an unparalleled strength of illusory brightness that can be dissociated in self-luminous quality and apparent surface density of the illusory white disks inside the coloured rings (plate 2). Surface density is a property described by Katz (1911,1930) and others (Metzger 1954; Kanizsa 1994) as a material property (*Stoffeigenschaft*). The conditions under which perceived opacity of a surface is induced are little understood, except that they cannot be attributed to simple physical properties of the stimulus. A factor not yet addressed is the influence of the grain or texture of the paper on which the stimulus is presented. From our experiments, the optimal conditions for anomalous brightness induction are as follows: 18 radial lines of 1.6 deg length and 0.2 deg width, of high contrast (> 0.9) to the ground, bounded by a chromatic ring 0.23 deg in width and of intermediate contrast (~ 0.5). The blue ring and the enclosed white disk as well as the ring and the black radial lines should be spatially contiguous.

By using a cancellation technique, we have observed similar dependences for illusory brightness enhancement (Ehrenstein illusion) and anomalous brightness as radial lines and the chromatic annulus were varied. We therefore conclude that the anomalous brightness induction reported here may result from an interaction between the (black) radial lines on the one hand and the chromatic annuli on the other, as neither feature by itself is capable of inducing the dense surface whiteness observed in this study. To enable the interaction between the two, the radial lines need to be oriented orthogonally to the annuli; misaligned or scrambled lines have less or no effect (figure 12). Similarly, too many radial lines may (figure 8) reduce the strength

of the effect. We therefore suggest that line-end contrast (terminators) and end-stopping (T-junctions) play a role in anomalous brightness induction.

Simultaneous contrast is unlikely to account for anomalous brightness induction, as its strength varies inversely over a range of increasing contrast (figure 3) of the chromatic annuli surrounding the central white area. Furthermore, spatially separating (detaching) the chromatic annuli either from the white inner disk (figure 6) or the radial lines (figure 7) by a black annulus weakens brightness induction, presumably by interfering with the synergistic interaction between the two.

Strong asymmetries in the interaction between chromatic and achromatic mechanisms have been observed in induction experiments with simple centre—surround configurations (Shinomori et al 1997). In anomalous brightness induction, a light-blue annulus proved superior to a grey annulus. Thus the question arises, why is the maximal effect dependent on the annulus being chromatic? Indeed, a thin black ring superimposed onto the illusory contour of the Ehrenstein illusion diminishes the brightness enhancement effect, whereas a wider chromatic annulus connecting the inner tips of the black radial lines enhances it. This difference suggests that radial lines ending on a wide blue circumference induce a surface appearance at the inside edge of the annulus. Because the coloured ring appears solid, it may impart its dense appearance to the enclosed disk in the interest of a homogeneous surface. Note that annuli presented in isolation hardly produce any effect (figure 2). Thus, the brightness induction in the central area would arise from the radial lines as in the Ehrenstein illusion, whereas the dense appearance of the white surface may be attributed to an induction process originating from the chromatic annulus. The increase in strength of the effect with increasing length of the radial lines (figure 9) attests to the long-range interaction (maximal 1 deg) that may be at work.

The neurophysiological mechanisms underlying these phenomena and the processes leading to them can be considered in the light of Grossberg's FACADE theory (Grossberg 1994, 1997). Within this theory, perceptual boundaries are created in the ventral stream through coherent patterns of inhibitory and excitatory signals across a network extending from the retina through the LGN and the V1 interblob and V2 interstripe areas (Gove et al 1995). Filling-in is suggested to occur in the surface processing stream and is considered to behave similarly to the diffusion of brightness across space starting from brightness buttons surrounding the line-ends. However, it is not clear how this theory can account for opposite properties belonging to the anomalous brightness induction (a self-luminous quality and a surface quality), that appear together and are not mutually exclusive.

A similar difficulty applies to Anderson's scission theory (Anderson 1997) based upon perceptual transparency and lightness for images that contain X-, T-, and I-junctions. This theory states that geometric shape and luminance relations among contour junctions induce phenomenal scission of a uniform surface area into different contributions creating illusory transparency and lightness differentiation. The term scission refers to Koffka's (1935) term that a single perceived property can be decomposed into multiple (usually two) properties (eg decomposition in different layers as in perceptual transparency). It is not clear how the suggested scission operates in the case of anomalous brightness induction. In fact, the contradictory co-presence of self-luminous and surface properties cannot be accounted for by any scission processes described previously. However, while in the Anderson scission model the co-presence of the two properties may be considered conflicting, in Grossberg's theory it is not.

Acknowledgments

Supported by the Alexander von Humboldt Foundation Research Fellowship (to BP), DFG grant SP 67/8-1 and Extended Freiburg—Padova Academic Exchange Program (to LS), and an Alexander von Humboldt Foundation

Senior Research Prize, NIA grant AG04058 and Research to Prevent Blindness (to JSW). We thank the Friedrich Miescher Foundation, Basel-Riehen, Switzerland, for generously supporting the reproduction of the chromatic stimuli. We also thank Cristiana Lenzerini, Monica Gaias, and Massimo Dasara for assistance in testing the subjects.

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Figure 1. Ranking of self-luminance and surface qualities converted to proportions and plotted as a function of the luminance contrast of the blue annuli relative to the white background.

Figure 2.

Mean brightness ratings plotted as a function of the luminance contrast of the central disks relative to the white background. A rating of '0' represents cancellation of the induced brightness; negative rating values correspond to central areas that appear darker than the white background. Five stimulus conditions were used, as defined in the figure key.

Figure 3. Mean brightness ratings for blue and achromatic annuli plotted as a function of luminance contrast relative to the white background. Error bars denote ± 1 SD.

Figure 4.
Mean brightness ratings plotted for different chromatic annuli. Error bars denote ± 1 SD.

Figure 5.
Mean brightness ratings for blue and achromatic annuli plotted as a function of annulus width. Error bars denote ± 1 SD.

Figure 6.

Mean brightness ratings plotted as a function of the width of an intervening black ring placed between the chromatic annulus and the enclosed central white area.

Figure 7. Mean brightness ratings plotted as a function of the width of an intervening black ring placed between the radial lines and the chromatic annulus. Error bars denote ± 1 SD.

Figure 8. Mean brightness ratings plotted as a function of the number of radial lines. Error bars denote ± 1 SD.

Plate 1.

Plate 2.

Plate 3.

Figure 9.
Mean brightness ratings plotted as a function of the length of radial lines. Error bars denote ± 1 SD.

Figure 10. Mean brightness ratings plotted as a function of the width of radial lines. Error bars denote ± 1 SD.

Figure 11.

Mean brightness ratings plotted as a function of the luminance contrast between the radial lines and the white background. Error bars denote ± 1 SD.

Figure 12. Mean brightness ratings as a function of the arrangement of the radial lines. Error bars denote ± 1 SD.