



Chromatic induction in neon colour spreading

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Received 7 December 2001; received in revised form 21 October 2002

Abstract

Neon colour spreading occurs when sections of a lattice are replaced by segments of a different colour. This colour appears to diffuse out of the segments, and produce a slightly tinted transparent surface floating above the lattice. In two of the four experiments reported here, observers varied the colour of an area in a test display, until it matched the neon colour perceived in a corresponding (illusory) area in a comparison display. We found that the neon colour is an additive mixture of the colour of the segments and the colour complementary to the lattice, as suggested by Bressan (Vision Research 35 (1995) 375). In the other two experiments, we separately manipulated the presence and alignment of lattice and segments, to test whether the neon effect is fully predicted by a combination of colour diffusion and simultaneous colour contrast. We found that the colour induced in a neon figure is more saturated than the colour induced in a comparable non-neon figure. We discuss the implications of these results on our current understanding of the mechanisms of neon colour spreading.

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Keywords: Neon colour spreading; Chromatic induction; Complementary colours; Colour vision

1. Introduction

If sections of the lines in a black lattice are replaced by coloured segments, the colour appears to flow out of the segments, producing the impression of a delicately tinted transparent veil hovering above the pattern. This visual illusion was first reported by Varin (1971) and independently rediscovered by van Tuijl (1975), who named it neon-like colour spreading (see Bressan, Mingolla, Spillmann, & Watanabe, 1997, for a review).

Neon colour spreading played a substantial role in the development of Grossberg and Mingolla's (1985) model of form perception. In extremely simplified terms, the model maintains that the perception of objects is based on the computations carried out within two parallel systems. The boundary contour system (BCS) generates invisible boundaries, while the feature contour system (FCS) fills the space limited by these boundaries with colour and brightness, thereby creating visible objects. Within the BCS, contour-extracting cells sensitive to orientation suppress the activity of nearby cells sensitive to similar orientations, and enhance the activity of

nearby cells sensitive to perpendicular orientations (see Fig. 1). At the junctions between lattice lines and segments, then, signals coming from the lattice lines *inhibit* those for the aligned segments, making their boundaries permeable. At the same time, they *amplify* signals for perpendicular boundaries; these amplified signals are then grouped to form illusory contours. Within the FCS, the lattice lines induce complementary (chromatic or achromatic) colour into the segments; but their weakened boundaries let the colour flow out and spread around. This diffusion is contained by the illusory contours, resulting in the neon effect.

Extending the logic of this approach, Bressan (1995) has proposed that the spreading colour is a mixture between the colour of the inhibited segments and the colour complementary to the lattice lines. If this is the case, the visibility of the illusory colour (hence, the strength of the neon effect) should depend on this mixture's saturation, which in turn depends on the specific colours of its components. This prediction is consistent with at least a set of empirical data: when lattice and segments are both chromatic, neon colour spreading is most vivid if the two hues are complementary to each other, weaker or even absent if they are similar (Ejima, Redies, Takahashi, & Akita, 1984). According to Bressan's proposal, this happens because if, say, blue segments are embedded in a

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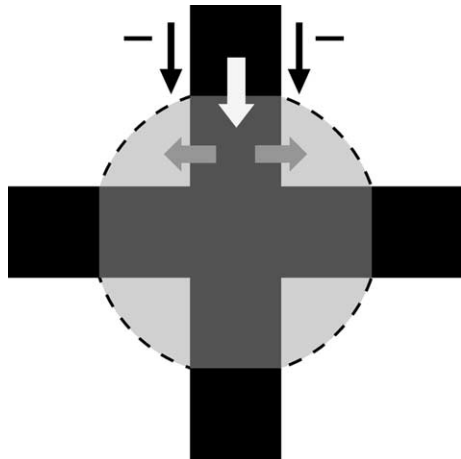


Fig. 1. A simplified representation of how neon spreading may occur from the standpoint of Grossberg and Mingolla's (1985) model. In the case depicted here, the segments-in-lattice pattern consists in a grey cross with black arms. In the FCS, the black arms induce (white arrow) complementary colour in the cross. In the BCS, the arms amplify signals for perpendicular boundaries at the junctions with the cross, creating illusory contours (dashed circumference) which delimit a circular area (in light grey). At the same time, the arms inhibit (thin arrows with the minus sign) the contiguous like-oriented contours of the cross, making them permeable. The colour of the cross can then flow out (grey arrows) through the permeable boundaries, and spread until it reaches the illusory contours (redrawn after Bressan, 1995).

yellow lattice, this blue additively combines with the blue colour induced in the segments by the yellow lattice, producing a maximally saturated, easily visible mixture: hence, a strong neon effect. If the same blue segments are embedded in a cyan lattice, however, the blue additively combines with the orange colour (roughly complementary to blue) induced in the segments by the cyan lattice. Complementarity implies that a mixture of the two colours in appropriate proportions appears achromatic. The mixture between blue and orange would thus give rise to a washed-out, barely perceptible colour: hence, a weak neon effect.

The idea that the neon tinge derives from the additive combination of two separate colours implies that the actual colours chosen for the segments and the lattice will not only affect the illusory colour's strength, but determine its hue as well. As of today, however, no empirical data have been systematically collected on the perceived hue of neon colour spreading. When the display consists of chromatic segments within an achromatic lattice, as in the classic illustrations of the effect, there is no doubt that the illusory neon colour has the same hue as the segments. The reversed case (achromatic segments in a chromatic lattice), however, has elicited contradictory reports. In his original paper, van Tuijl (1975) claimed, without presenting experimental findings, that such a pattern generates "complementary colours"; but in the only study that has (peripherally) addressed this point, Redies and Spillmann (1981) re-

ported that black segments embedded in a coloured lattice appeared to be "surrounded by 'blackish' neon", and "no complementary colour induction" (p. 672) was observed. Hence, although it was crucial in the elaboration of Grossberg and Mingolla's (1985) model, the notion that in these displays the neon colour is complementary to the lattice colour has not been empirically tested. The work we report in this paper addresses this issue in Experiment 1.

The idea that, when lattice and segments are both chromatic, the neon hue should correspond to an additive mixture of the two colours has never been tested either. Ejima et al.'s (1984) study is mute on this point. We dealt with it in Experiment 2.

Two further experiments (Experiments 3 and 4) were designed to address the issue of whether, in its chromatic-inducer version, neon colour spreading is simply a manifestation of classical simultaneous colour contrast.

2. Experiment 1: achromatic segments in a chromatic lattice

Experiment 1 was performed to test the hypothesis that, when the segments are achromatic and the lattice is chromatic, the perceived neon colour is complementary to the colour of the lattice.

2.1. Observers

Three observers participated in the experiment. All had normal or corrected acuity, and normal colour vision. Author ODP, a 57-year-old male, is a well-practised psychophysical observer and has experience making colour judgements in chromatic displays. KP (a 25-year-old female) and GS (a 23-year-old male) were inexperienced observers, and naive regarding the purpose of the experiment.

2.2. Apparatus, calibrations and stimuli

Stimuli were generated on a PC-compatible computer (Pentium II). Images were presented on a 1024×768 pixels monitor display (15" Panasonic Multisync SL70i). Luminance was measured by a UDT 350 photometer and chromaticity by a LMT 1200 colorimeter (Montag & Berns, 1999). Since colour variations due to area size and specific location on the monitor were found to be negligible, the actual measurements were taken at the centre of the monitor; the size of the area to be measured was enlarged so as to fill the detector surface. For each colour combination used in the experiment, all photometric and colorimetric measures were taken just after the observations.

In the first part of the experiment, each stimulus consisted of two rectangles placed side by side on a

black background; the size of each rectangle was 104×132 mm, about 3° in width and 3.8° in height for a viewer at 2 m. The rectangles were white (118 cd/m^2 , approximately $x = 0.304$ and $y = 0.317$ CIE 1931) and covered by a grid of lines (0.3 mm thickness, 5×5 mm inter-line distance). In one of the rectangles (the comparison stimulus, shown on the left in Fig. 2), the chromaticity and luminance of the grid segments corresponding to a central virtual ring (60 mm, 1.7° inner diameter; 90 mm, 2.6° outer diameter) were different from the rest of the lattice. From a viewing distance of 2 m, the surface of the virtual ring appeared filled by neon colour. In the other rectangle (the test stimulus, shown on the right in Fig. 2), the lattice was always achromatic, and had the same luminance of the ring segments in the comparison stimulus. A central ring of adjustable chromaticity and luminance (15 mm in thickness, subtending $25'$), invisible at the beginning of each trial, became perceptible as soon as the adjustment process began.

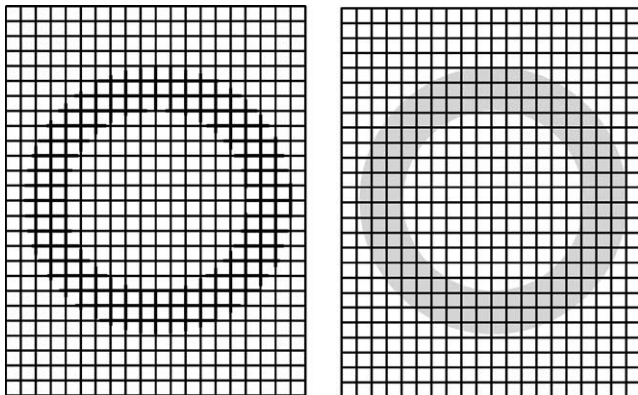


Fig. 2. Schematic of the stimuli used in Experiments 1 and 2. The comparison stimulus is displayed on the left. The thin lines represent the colour of the lattice (chromatic in both Experiments 1 and 2). The thick lines represent the colour of the ring segments (achromatic in Experiment 1, chromatic in Experiment 2). The test stimulus is displayed on the right. The thin lines represent the colour of the lattice (achromatic in both Experiments 1 and 2). The colour of the ring could be adjusted by observers until it matched the perceived neon colour of the comparison ring.

2.3. Procedure

Observations were performed in a semi-darkened room, whose walls and ceiling were white, lit by natural light coming through two windows almost completely obscured by Venetian blinds (an average of 60 lx on the walls). The monitor was placed in front of a dark grey background (1 cd/m^2) and observed from a distance of about 2 m.

Subjects used the method of adjustment: they varied the colour of the (real) ring in the test rectangle (right display in Fig. 2), until it matched the neon colour perceived in the corresponding (illusory) ring of the comparison rectangle (left display in Fig. 2). Adjustments were made by varying independently the intensities of the red, green and blue beams of the monitor.

2.4. First part of the experiment

In this experiment, the ring segments of the comparison rectangle were achromatic, and the lattice segments were chromatic. They could be Red, Green, Blue, Yellow, Orange, Magenta, Purple, or Cyan (see Table 1). The luminance of the achromatic segments was chosen (in a pilot experiment where the two authors served as observers), so as to maximize the neon effect in each condition, and therefore depended on the colour of the lattice (Table 1, bottom row). The lattice of the test rectangle was achromatic, and had the same luminance as the ring segments of the comparison rectangle.

2.4.1. Results

The solid circles in the CIE 1931 xy chromaticity diagram of Fig. 3 show the colours adjusted by observer KP in the test ring to match the perceived neon colours in the comparison ring (the solid square indicates the achromatic colour). For reasons of space, the data from observers ODP and GS are not shown; they were very similar to the data from observer KP, as will be seen in Table 2.

Since any additive mixture of two colours lies on the segment connecting them in an additive colour space

Table 1

Experiment 1: Colorimetric data (CIE 1931) for lattice and ring segments in the comparison rectangle; the entire lattice of the test rectangle had the same luminance as the comparison ring segments (bottom row)

| | | R | G | B | Y | O | M | P | C |
|--------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Comparison lattice | x | 0.5872 | 0.2931 | 0.1976 | 0.4553 | 0.5843 | 0.3420 | 0.2029 | 0.2438 |
| | y | 0.3040 | 0.5985 | 0.2364 | 0.4745 | 0.3745 | 0.1720 | 0.0979 | 0.4126 |
| | Y | 0.21 | 0.60 | 0.29 | 0.65 | 0.22 | 0.28 | 0.11 | 0.61 |
| | Purity | 0.58 | 0.73 | 0.45 | 0.81 | 0.84 | 0.62 | 0.65 | 0.21 |
| Ring segments | Y | 0.22 | 0.44 | 0.39 | 0.55 | 0.39 | 0.29 | 0.16 | 0.56 |

Y is a measure of relative luminance, being 1 for the white (118 cd/m^2). R = Red, G = Green, B = Blue, Y = Yellow, O = Orange, M = Magenta, P = Purple, C = Cyan.

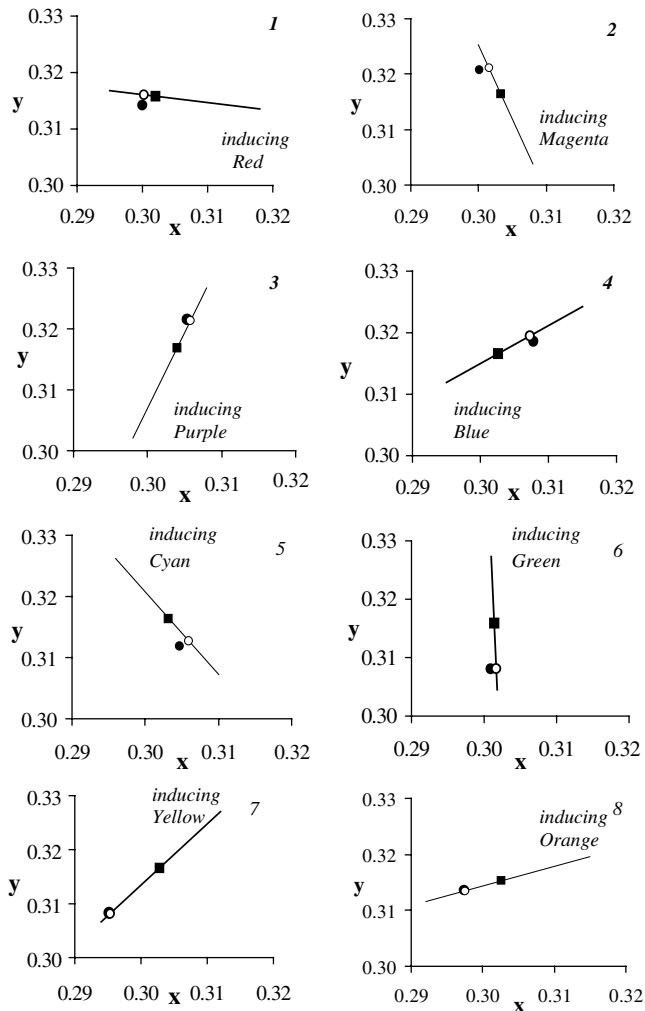


Fig. 3. Experiment 1: The CIE 1931 xy diagrams show the line connecting the inducing (lattice) colour of the comparison rectangle to the achromatic point (solid square), along which colours complementary to the inducer are expected to lie. Solid circles represent the obtained match; open circles the expected match (the point of the complementary colour line closest to the obtained match).

Table 2

Experiment 1: CIELAB- ΔE deviations of the obtained matches from the expected ones for the eight inducing colours of the comparison lattice, for the three observers

| Inducing colour | KP | ODP | GS | Mean |
|-----------------|------|------|------|------|
| Red | 1.11 | 0.43 | 0.14 | 0.56 |
| Green | 0.43 | 1.29 | 0.41 | 0.71 |
| Blue | 0.79 | 0.80 | 0.00 | 0.53 |
| Yellow | 0.17 | 0.43 | 0.32 | 0.31 |
| Orange | 0.13 | 0.02 | 0.13 | 0.09 |
| Magenta | 0.66 | 0.08 | 0.35 | 0.37 |
| Purple | 0.29 | 0.93 | 0.57 | 0.60 |
| Cyan | 0.19 | 0.52 | 0.08 | 0.26 |

(such as the CIE 1931 XYZ or xyY 3D colour space), in a position depending on the relative proportion of the two, two colours are complementary if the segment

connecting them passes through the achromatic point, which means that a particular mixture of them is achromatic. If they were complementary, then, the matching colours should lie on the same line of the inducing (lattice) colours, passing through the achromatic point but on the opposite side. This is precisely what obtains in three cases out of eight (inducing Purple, Yellow and Orange, see respectively panels 3, 7, and 8 in Fig. 3), while in the other five cases (inducing Red, Magenta, Blue, Cyan and Green, respectively panels 1, 2, 4, 5 and 6) the matching colours diverge slightly from the complementary colour lines. The points of the complementary colour line closest to the matching colours are shown by open circles in Fig. 3.

Table 2 shows the deviations of the observed matches from the theoretical complementary colours, separately for the three observers. All mean deviations are significantly lower than 1 ΔE , a value that roughly corresponds to one just noticeable difference (one-sample t 's range from -2.9 , $p = 0.02$, to -11.1 , $p < 0.0001$; the null hypothesis tested is $\Delta E = 1$). However, since the deviations for individual observers were occasionally a little larger, we decided to run a second part of the experiment to check whether, in these cases, the theoretically exact complementary colour represented a better or worse match than the original one.

2.5. Second part of the experiment

In this part of the experiment, three stimulus rectangles were simultaneously displayed on the monitor (their original size was reduced by a factor of 0.87). The comparison rectangle (with the neon ring) was always in the middle. Two test rectangles, one with the theoretically expected match and the other with the match chosen by one of the three observer in the first part of the experiment, were randomly placed on either side. For each inducing colour of the lattice, the latter rectangle (the 'original' match) was the one representing the largest deviation from the expected colour (the largest value in each row in Table 2: for example, the match $\Delta E = 1.11$ for the Red lattice; the match $\Delta E = 1.29$ for the Green lattice; and so on). Thirty observers, blind as regards to which was which, took part in the experiment. They had to decide which of the test rectangles, the one on the left or the one on the right, represented the best match.

2.5.1. Results

No difference was perceived between the two test alternatives, and the choices were randomly distributed in all cases. The results of Experiment 1, then, show that the 'simple' neon colour generated in the vicinities of achromatic segments embedded in a chromatic lattice is complementary to the colour of the lattice.

Table 3
Experiment 2: Colorimetric data (CIE 1931) for the chromatic lattice and ring segments in the comparison rectangle, and for the achromatic lattice in the test rectangle (bottom row)

| | Ring segments | | | Lattice | | | Ring segments | | | Lattice | | | Ring segments | | | Lattice | | | |
|--------------|---------------|-------|-------|---------|-------|-------|---------------|-------|-------|---------|-------|-------|---------------|-------|-------|---------|-------|-------|-------|
| | R | B | G | Y | G | B | R | B | G | Y | G | B | R | B | G | Y | G | B | |
| <i>x</i> | 0.587 | 0.198 | 0.293 | 0.454 | 0.293 | 0.198 | 0.587 | 0.455 | 0.198 | 0.455 | 0.587 | 0.455 | 0.293 | 0.587 | 0.455 | 0.455 | 0.293 | 0.586 | 0.198 |
| <i>y</i> | 0.304 | 0.237 | 0.599 | 0.474 | 0.599 | 0.236 | 0.304 | 0.474 | 0.236 | 0.474 | 0.304 | 0.474 | 0.599 | 0.304 | 0.474 | 0.474 | 0.599 | 0.303 | 0.237 |
| <i>Y</i> | 0.21 | 0.28 | 0.60 | 0.65 | 0.60 | 0.28 | 0.21 | 0.65 | 0.28 | 0.65 | 0.21 | 0.65 | 0.60 | 0.21 | 0.65 | 0.60 | 0.60 | 0.21 | 0.28 |
| Test lattice | <i>Y</i> | 0.22 | 0.44 | 0.60 | 0.44 | 0.44 | 0.44 | 0.44 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.40 | 0.55 | 0.55 | 0.55 | 0.55 |

Y is a measure of relative luminance, being 1 for the white (118 cd/m²). The four panels show the colour combinations of lattice (first column of each panel: respectively R, G, B, and Y) and ring segments (second, third and fourth column of each panel) used in the experiment.

3. Experiment 2: chromatic segments in a chromatic lattice

Experiment 2 was performed to test the hypothesis that, when both segments and lattice are chromatic, the perceived neon colour is an additive mixture of the ‘simple’ neon colour induced by the lattice and the actual colour of the segments. Observers, apparatus, stimulus configurations and procedure were identical to those of Experiment 1.

3.1. First part of the experiment

In this experiment, both the lattice and the ring segments (Table 3) were chromatic. Lattices could be Red (presented in combination with Blue, Green, and Yellow segments); Green (with Blue, Red, and Yellow segments); Blue (with Green, Red, and Yellow segments); or Yellow (with Green, Red, and Blue segments).

The lattice of the test stimulus was always achromatic (Table 3, bottom row).

3.1.1. Results

Satisfactory matches were reached for all colour combinations. In a few instances, the highly saturated and luminous colour perceived in the neon ring could not be matched by any normal surface colour: in these cases, the main aspect reproduced by the match was the neon colour’s chromaticity.

The solid diamonds in the *xy* chromaticity diagram of Fig. 4 show the colours adjusted by observer KP in the test ring to match the perceived neon colours in the comparison ring (the solid square indicates the achromatic colour). The prediction is that each ‘composite’ perceived neon colour is an additive mixture of the actual colour of the ring segments and the neon colour perceived in the same display when the ring is achromatic. This means that the colours matched by the observers should lie on the line connecting the colour of the segments and the ‘simple’ neon colour (open circles).

Table 4 shows the deviations of the observed matches from the theoretical complementary colours, separately for the three observers. Deviations are not significantly different from 1 ΔE (all one-sample *t*’s < -1.1, n.s.). As in Experiment 1, we decided to run a second part of the experiment, to check whether, for the largest deviations, the theoretically expected colour represented a better or worse match than the original one.

3.2. Second part of the experiment

The procedure was the same as the one followed in the second part of Experiment 1. Thirty observers had to choose which of the two test stimuli (the expected vs the observed match) was closer to the neon colour perceived in the corresponding comparison stimulus. For each

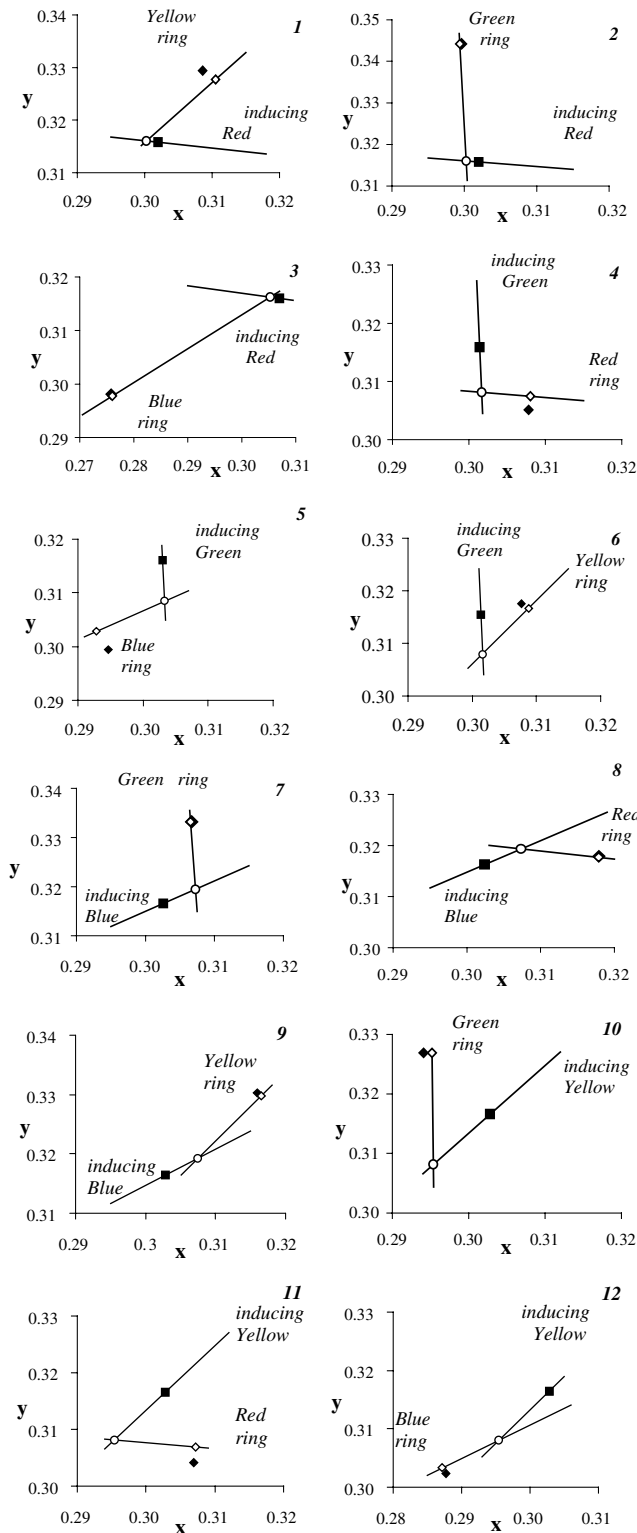


Fig. 4. Experiment 2: The CIE 1931 xy diagrams show the line connecting the inducing (lattice) colour of the comparison rectangle to the achromatic point (solid square), and the line connecting the colour of the ring segments to the 'simple' neon colour (open circle). The neon colour is expected to be a mixture of the 'simple' neon and the ring segment colour, and therefore to lie along the latter line. Solid diamonds represent the obtained match; open diamonds represent the expected match (the point of the line closest to the obtained match).

Table 4

Experiment 2: CIELAB- ΔE deviations of the obtained matches from the expected ones for all colour combinations (lattice/ring segments) of the comparison figure, for the three observers

| Colour combinations | KP | ODP | GS | Mean |
|---------------------|------|------|------|------|
| RG | 0.12 | 1.80 | 1.47 | 1.13 |
| RB | 0.33 | 2.42 | 2.59 | 1.78 |
| RY | 1.88 | 0.18 | 1.17 | 1.08 |
| GR | 1.47 | 1.70 | 0.00 | 1.06 |
| GB | 3.01 | 1.20 | 0.52 | 1.58 |
| GY | 1.03 | 2.01 | 0.18 | 1.07 |
| BG | 0.10 | 0.53 | 2.83 | 1.15 |
| BR | 0.12 | 1.44 | 1.58 | 1.05 |
| BY | 0.47 | 0.67 | 0.06 | 0.40 |
| YG | 0.62 | 0.74 | 3.13 | 1.50 |
| YR | 1.68 | 1.64 | 0.68 | 1.34 |
| YB | 0.78 | 0.47 | 0.09 | 0.45 |

colour combination, the observed match was the one representing the largest deviation from the expected one (the largest value in each row in Table 4). As before, observers were unaware of which of the two was the expected match.

3.2.1. Results

No difference was perceived between the two test alternatives, and the choices were randomly distributed in all cases. For a few displays, neither match was considered perfect, because the luminous appearance of the neon ring could not be reproduced by any actual colour. Yet, the chromaticity of both the original and the expected matches was considered equal to the chromaticity of the neon colour.

The results of Experiment 2, then, show that the neon colour generated in the vicinities of chromatic segments embedded in a chromatic lattice is an additive mixture of the 'simple' neon colour induced by the lattice and the colour of the segments.

4. Experiment 3: colour spreading with and without grids

Experiment 3 was performed to test whether the double-grid structure of a neon-colour-spreading stimulus, with its alignment of lattice and segments, produces more saturated induced colours than an otherwise comparable stimulus lacking either grid, or both.

4.1. Observers

Ten observers, all well-practised psychophysical observers, participated in the experiment. They had normal or corrected acuity, normal colour vision, and were naive regarding the purpose of the experiment.

4.2. Apparatus, calibrations and stimuli

The apparatus and calibrations were the same as in the previous experiments, as all stimulus sizes and line thicknesses.

We used four different stimuli: lattice/segments, lattice-only, segments-only, homogeneous (see Fig. 5, left panel). The first (lattice/segments) consisted of a white rectangle (84.7 cd/m², approximately $x = 0.334$ and $y = 0.346$ CIE 1931) overlaid by a magenta grid (22.4 cd/m², $x = 0.413$ $y = 0.212$). The grid segments corresponding to the central virtual ring were achromatic (37.7 cd/m²). The area of the virtual ring appeared filled by neon colour. The second stimulus (segments-only) was identical to the first, except that the area of the

lattice was uniformly pink (76.6 cd/m², $x = 0.337$ $y = 0.336$, i.e. it had the same average luminance and chromaticity as the corresponding area in the lattice/segments stimulus). The third stimulus (lattice-only) was identical to the first, except that the area of the ring was uniformly grey (79.6 cd/m², i.e. it had the same average luminance and chromaticity as the corresponding area in the lattice/segments stimulus). In the fourth stimulus (homogeneous), both lattice and ring were uniform, and of the same average luminance and chromaticity as the corresponding areas in the lattice/segments stimulus.

4.3. Procedure

Observations were performed in a semi-darkened room, whose walls and ceiling were white, lit by natural light coming through two windows almost completely obscured by Venetian blinds (an average of 50 lx on the walls). The monitor was placed in front of a dark grey background (1 cd/m²) and observed from a distance of about 1.8 m.

We used the method of paired comparisons. The six possible stimulus pairs were presented in random order. The two members of each pair were displayed side by side on a black background; relative positions (left vs right) were determined at random. For each pair, subjects were asked to choose the stimulus whose ring appeared more “colourful” (Hunt, 1987), that is farther from grey.

4.4. Results

Statistical comparisons of the transformed data (angular transformation: Edwards, 1985) showed that in the lattice/segments stimulus the illusory colour appeared more saturated than in the homogeneous one, $t(9) = 7.62$, $p < 0.0001$. In turn, the illusory colour appeared more saturated in the homogeneous stimulus than in either the lattice-only ($t(9) = 2.39$, $p = 0.04$) or the segments-only ($t(9) = 2.86$, $p = 0.02$) stimuli. There was no difference between the latter two stimuli ($t < 1$).

5. Experiment 4: colour spreading with and without grid alignment

Experiment 4 was performed to test the role of alignment of lattice and segments on the saturation of induced colours.

5.1. Observers

Ten observers (the same who had served as subjects in Experiment 3), all well-practised psychophysical observers, participated in the experiment. They were all naive regarding the purpose of the experiment.

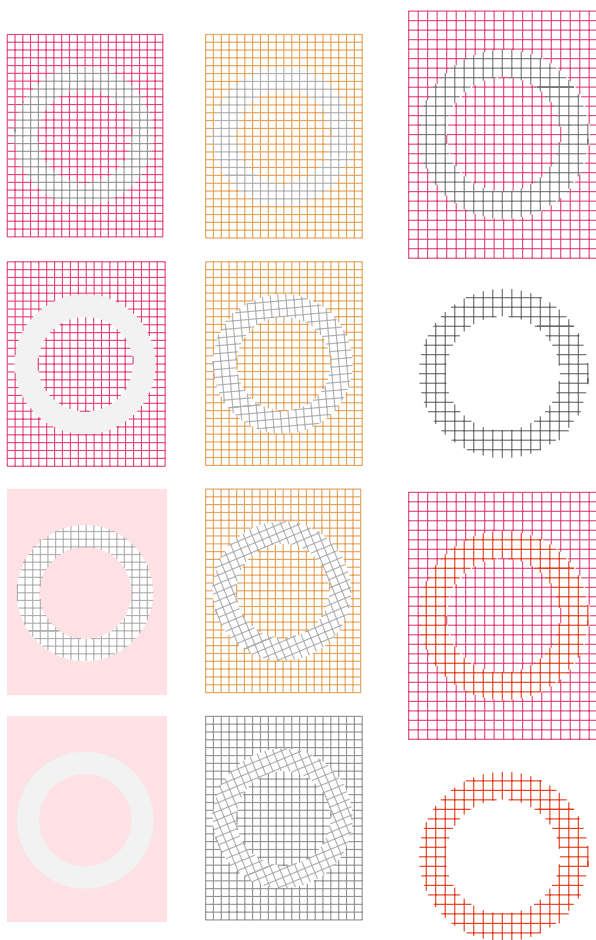


Fig. 5. Left panel: the stimuli used in Experiment 3 (top to bottom: lattice/segments, lattice-only, segments-only, homogeneous). Middle panel: the stimuli used in Experiment 4 (top to bottom: aligned, 5°-rotated, 22.5°-rotated, 22.5°-rotated achromatic). Colours and thicknesses are representative of, but do not correspond exactly to, those used in our experiments. Right panel, top: a chromatic (magenta) lattice with achromatic segments (also shown below, in isolation), a stimulus similar to those used in our Experiment 1, produces greenish neon colour spreading. Right panel, bottom: a chromatic (magenta) lattice with chromatic (red) segments (also shown below, in isolation), a stimulus similar to those used in our Experiment 2, produces yellowish neon colour spreading.

5.2. Apparatus, calibrations and stimuli

The apparatus and calibrations were the same as in the previous experiments. We used three different stimuli (aligned, 5°-rotated, 22.5°-rotated) where the lattice was chromatic, plus a control stimulus where the lattice was achromatic (Fig. 5, middle panel). The first stimulus (aligned) consisted of a white rectangle, 69 mm (2° 12') in width and 94 mm (3°) in height, covered by a grid of lines, 0.3 mm thickness, 3.3 × 3.3 mm (6' 21") inter-line distance. The rectangle was white (84.7 cd/m², approximately $x = 0.331$ and $y = 0.346$ CIE 1931) and the grid was orange (22.9 cd/m², $x = 0.570$ and $y = 0.378$). The grid segments corresponding to the central virtual ring were achromatic (23.9 cd/m²).

The second and third stimuli were identical to the first, except that the segments of the central virtual ring were rotated counterclockwise relative to the segments of the lattice (5° and 22.5°, corresponding respectively to vernier offsets of 1' 54" and 2' 51" between the mutual end-points). The fourth, control stimulus was identical to the third (22.5°-rotated), but both lattice and ring segments were achromatic (23.9 cd/m²).

5.3. Procedure

The observation conditions (lighting, surrounding luminances, and eye-to-screen distance) and the procedure (paired comparisons) were the same as in Experiment 3. Again, subjects were asked to choose the stimulus in each pair whose ring appeared more "colourful", that is farther from grey.

5.4. Results

Subjects were unanimous in all choices. The aligned stimulus (traditional neon-spreading configuration) was regarded as the most "colourful", followed by the 5°-rotated, the 22.5°-rotated, and the control stimuli. All differences were significant (10 vs 0 choices in all cases). Subjects reported that, apart for being more "colourful", the aligned stimulus had a special (neonish) appearance that the other stimuli lacked.

The result that rotation impairs neon perception replicates a similar finding by Redies and Spillmann (1981). The significant difference between our rotated stimuli and our control (achromatic) one, however, additionally shows that colour assimilation survives rotation even though the neon effect does not.

6. Discussion

In Experiment 1, we found that the 'simple' neon colour generated around achromatic segments inserted in a chromatic lattice is complementary to the colour of

the lattice. In Experiment 2, we found that the 'composite' neon colour generated around chromatic segments inserted in a chromatic lattice is an additive mixture of the 'simple' neon colour induced by the lattice and the actual colour of the segments. The most parsimonious explanation for these results is that the neon colour should always be regarded as 'composite', but when segments are achromatic the colour induced by the chromatic lattice will mix with grey, resulting in a desaturated complementary colour rather than in a hue shift. A magenta lattice with grey segments (see Fig. 5, right panel, top), for example, produces a desaturated greenish neon (resulting from an additive mixture of grey and green, where grey is the colour of the segments and green is the colour complementary to magenta). A magenta lattice with red segments (see Fig. 5, right panel, bottom), however, produces a surprising yellow neon (resulting from an additive mixture of red and green, where red is the colour of the segments and green is the colour complementary to magenta).

The additive-mixture idea may also clarify Redies and Spillmann's (1981) contradictory report of blackish, rather than complementary, spreading. In a poor neon-colour-spreading stimulus such as a cross (only four inducing lines, rather than a whole lattice), they used red or blue paint for the external segments of the arms, and black ink for the center of the cross, which must have produced an extremely dark illusory colour (resulting from an additive mixture of black and yellow, or black and blue-green).

Our results, then, support the implicit predictions of the model by Grossberg and Mingolla (1985), as explicitly formulated by Bressan (1995) and described in the Introduction. The same idea could also be expressed by saying that the inducing lines produce, just outside their ends, a button of complementary colour signal in the FCS representation—a generalization of the "brightness buttons" suggested by Gove, Grossberg, and Mingolla (1995). Neurophysiologically, such buttons could be the result of a feedback circuit from visual area V1 to the lateral geniculate nucleus; such a circuit would amplify the responses of on-center, off-surround LGN cells when thin lines fall within their surrounds. Perceptually, this would translate into the amplification of colour contrast at the ends of thin lines, becoming visible only when several thin lines are arranged so as to give rise to a subjective figure.

The results of our Experiment 3 indicate that the largest amplification occurs when two adjoining lines separately stimulate the center and the surround of such cells (strongest effect for the lattice/segments stimulus). Stimulation of the center only (segments-only stimulus), or of the surround only (lattice-only stimulus), produces the smallest effects. In addition, the results of our Experiment 4 indicate that the lines stimulating the cell's center and surround must have the same orientation for

the largest amplification to occur (strongest effect for the aligned stimulus), and that such amplification decreases as the orientation difference increases (as also reported by Redies & Spillmann, 1981).

Our findings have also implications for the two alternative accounts of neon colour spreading that have, to date, been offered—the colour-scission explanation (Anderson, 1997) and the assimilation-plus-transparency explanation (Bressan, 1993a,b).

6.1. Implications for a colour-scission interpretation of neon spreading

Anderson (1997) has suggested that neon colour spreading is generated by a change in contrast along aligned contours, and is due to (chromatic or achromatic) colour scission of the lower-contrast region into a near (transparent) layer, and a distant surface that continues behind this near layer.

Our results are at odds with this approach, in at least two separate respects. First, although complementary spreading is not addressed in Anderson's model, it is unclear how the model could be expanded to include it. Consider for example a subset of grey segments embedded in a blue lattice. We found that this combination produces the percept of a yellowish filter superimposed on grey segments, in an otherwise blue grid. It is difficult to understand how a colour scission mechanism could split an achromatic region, such as the segments, into grey and yellow. One may object that the colour assigned to the segments must actually be blue, as the rest of the lattice, rather than grey (although this is not what observers report), so that the achromatic region is actually split into the complementary colours yellow and blue. This kind of argument runs quickly into trouble, however: for example, a subset of green segments in a magenta lattice yields a greenish filter on green segments, within an otherwise magenta grid. Claiming that the colour assigned to the neon layer is green, but that assigned to the segments must actually be magenta as the rest of the lattice, would leave us with a process that splits green into green and magenta, something very difficult to envision.

Second, Anderson's (1997) model assumes that contrast relative to the background must be larger for the inducers than for the segments, since it is the region whose contrast with the background is lower that splits.¹ But our Experiment 2 shows that, in fully

chromatic configurations, neon spreading was observed both for a given combination of colours (and thus luminances) and for their reverse. For example, the neon effect was perceived both with red segments in a green lattice and when red and green were exchanged (green segments in a red lattice). This was true for all the chromatic combinations we used.

It might be objected that, when the displays are entirely chromatic, contrast should be interpreted in terms of spectral purity difference, rather than in terms of luminance difference (Grossberg, 1987). This claim is consistent with several sets of data, both psychophysical (e.g. Levine, Spillmann, & Wolf, 1980) and neurophysiological (e.g. DeValois & Marrocco, 1973). Yet, this implies that neon colour spreading should be observed for low-purity segments embedded in high-purity lattices, but not the other way around (as remarked by Bressan, 1995). This prediction is disconfirmed by our results. Spectral purity values for some of the colours we used were, for example, 0.45 (Blue), 0.58 (Red), 0.73 (Green), and 0.81 (Yellow). Neon colour spreading was reported by all observers for all colour combinations, including those where the segments had higher purity than the lattice, such as Yellow rings inserted in Blue lattices.

6.2. Implications for interpretations of neon spreading based on assimilation plus transparency

Bressan (1993a,b) proposed that the prerequisites for classical neon spreading (such as segment alignment) are simply the prerequisites for perceptual transparency, in a configuration that would otherwise generate assimilation. Perceptual transparency would increase the illusory colour's saturation by detaching such colour from the plane of the inducers (a detachment that may be obtained in other ways, e.g. via depth stratification through motion: see Bressan & Vallortigara, 1991). Note that, unlike Anderson (1997), Bressan does not advocate a colour-scission mechanism, nor one based on contrast differences.

While silent on the perceptual detachment issue, our data are consistent with the interpretation of neon colour spreading as a case of assimilation where: (i) the subjective region assimilates the colour of the segments, with complementary colour induction contributing to the resulting colour (as shown by our Experiments 1 and 2); (ii) such colour is enhanced by the same spatial attributes that would support perceptual transparency (as shown by our Experiments 3 and 4). Note that, notwithstanding the obvious differences in explanation level and articulation, such a description is not in contradiction with Grossberg and Mingolla's account.

Recently, the visually obvious fact that, on a white background, the neon colour has a tinge but appears, at the same time, brighter than the background itself has mistakenly been offered (Albert, 1998) as evidence

¹ Grossberg and Mingolla's (1985) model also assumes that contrast relative to the background must be larger for the inducers than for the segments. This apparently follows from the requirement that the inhibition of the inducers on the segments be stronger than the inhibition of the segments on the inducers. However, stronger inhibition of the inducers on the segments might be simply a consequence of lack of symmetry in spatial layout (being segments typically shorter than inducers, and 'weakened' by inducers on both ends).

against the assimilation idea. This claim was based on the notion that diffusion of the colour of the segments would produce an illusory colour darker, not brighter, than white. Our results provide a simple explanation to this apparently paradoxical percept. The traditional black lattice with red segments generates a reddish, glowing neon, as the result of an additive mixture of red and increased brightness. The latter derives from complementary induction coming from the black lattice: the same kind of induction that would give rise to a glowing subjective figure if the gaps in the black lattice were not bridged by segments. This also holds in the achromatic case, where a neon colour *brighter* than the white background is generated by the addition of grey (diffusing from the segments) and increased brightness (induced by the black lattice).

7. Conclusions

We found that the neon colour generated around segments embedded in a lattice is an additive mixture of the colour of the segments and the colour complementary to the lattice. We found that, although it also appears when the external and internal segments are either absent or misaligned, this illusory colour is significantly more saturated in the neon effect. Finally, our data show that the external lines need not have a higher contrast than the segments, in terms of either luminance or spectral purity.

Our findings are consistent with explanations of neon colour spreading based on the simultaneous occurrence of colour diffusion and complementary colour induction (such as Grossberg & Mingolla's, 1985), but not with accounts based on colour scission (such as Anderson's, 1997).

Acknowledgements

This paper benefited considerably from the comments and advice of two anonymous reviewers. Experiment 3 was suggested by one of them. We are also grateful to Ennio Mingolla for useful discussion, and to Stefano Vezzani for devising the 'ring on lattice' configuration used in these experiments.

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