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Letter to the Editor

A Closer Look at the Dependence of Neon Colour Spreading on Wavelength and Illuminance

PAOLA BRESSAN*

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Ejima, Redies, Takahashi and Akita [(1984) *Vision Research*, *24*, 1719–1726], studying the dependence of the neon colour spreading effect on wavelength and illuminance, found a number of relationships that appeared of difficult interpretation. This paper shows that these relationships can all be logically predicted within Grossberg and Mingolla's [(1985) *Psychological Review*, *92*, 173–211] approach to the neon spreading problem, with no need of making *ad hoc* assumptions.

Visual illusion Colour vision Neon spreading effect Ehrenstein pattern Complementary colours

INTRODUCTION

The neon colour spreading illusion (van Tuijl, 1975) occurs when, in a line drawing, sections of the lines are replaced by segments of a different colour. This colour appears then to flow out of the segments, producing the impression of a slightly tinted transparent surface hovering above the pattern [see Fig. 1(a)]. A simple figure giving rise to a remarkable neon effect is a modified version of the Ehrenstein pattern: if the inner tips of four radially arranged black lines forming a central illusory figure are connected by a coloured cross, the illusory figure appears to be tinged in the colour of the cross (Redies & Spillmann, 1981).

Ejima, Redies, Takahashi and Akita (1984) conducted a series of experiments to explore the spectral and illuminance conditions under which the neon colour effect occurs. They used a stimulus configuration consisting of several light Ehrenstein figures on a dark backround. In the experiment varying spectral conditions, the wavelengths of the Ehrenstein patterns and of the central crosses were independently varied from 460 to 680 nm in 20-nm steps, and subjects had to judge the strength of the spread of colour around the crosses for each wavelength combination. In one of the experiments varying illuminance conditions, the illuminance of the crosses was kept constant while the illuminance of the Ehrenstein pattern was varied by the observer until the colour spreading around the crosses was maximal.

The experiments showed that: (1) the neon colour spreading effect is strong (a) for wavelengths of the crosses ranging from 460 to 500 nm when they are combined with wavelengths of the Ehrenstein pattern ranging from 520 to 640 nm; and (b) for wavelengths of the crosses ranging from 600 to 680 nm when they are combined with wavelengths of the Ehrenstein pattern ranging from 460 to 600 nm; (2) the effect is weak or absent for wavelengths of the crosses ranging from 500 to 580 nm; (3) the effect is weak or absent when the wavelengths of the crosses and the Ehrenstein pattern are similar or the same; (4) the effect is just detectable for illuminance ratios between the Ehrenstein pattern and the cross lower than 1, and is maximal for illuminance ratios ranging approximately between 1 and 4.

In this paper, I intend to show how these findings might make sense. Although new, the argument that follows merely represents a simple logical extension of the principles of Grossberg and Mingolla's (1985) explanation of the neon colour spreading phenomenon. Most of the reasoning will be done in purely perceptual terms, since mathematical and neurophysiological details are outside the scope of this note.

NEON SPREADING WITH ACHROMATIC SEGMENTS EMBEDDED IN A CHROMATIC PATTERN

The neon effect is usually produced by inserting coloured segments in a black pattern. The illusory neon colour has always the same hue as the segments. Van Tuijl (1975) was the first to note that, if the segments are black and the pattern is coloured, the illusory neon colour takes on a tinge *complementary* to the colour of the pattern.

Grossberg and Mingolla's (1985) model of form and colour perception accounts persuasively for this effect. Although the details of the model are complicated and

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*Dipartimento di Psicologia Generale, Università di Padova, Piazza Capitaniato 3, 35139 Padova, Italy [*Email* BRESSAN@-UNIPAD.UNIPD.IT].

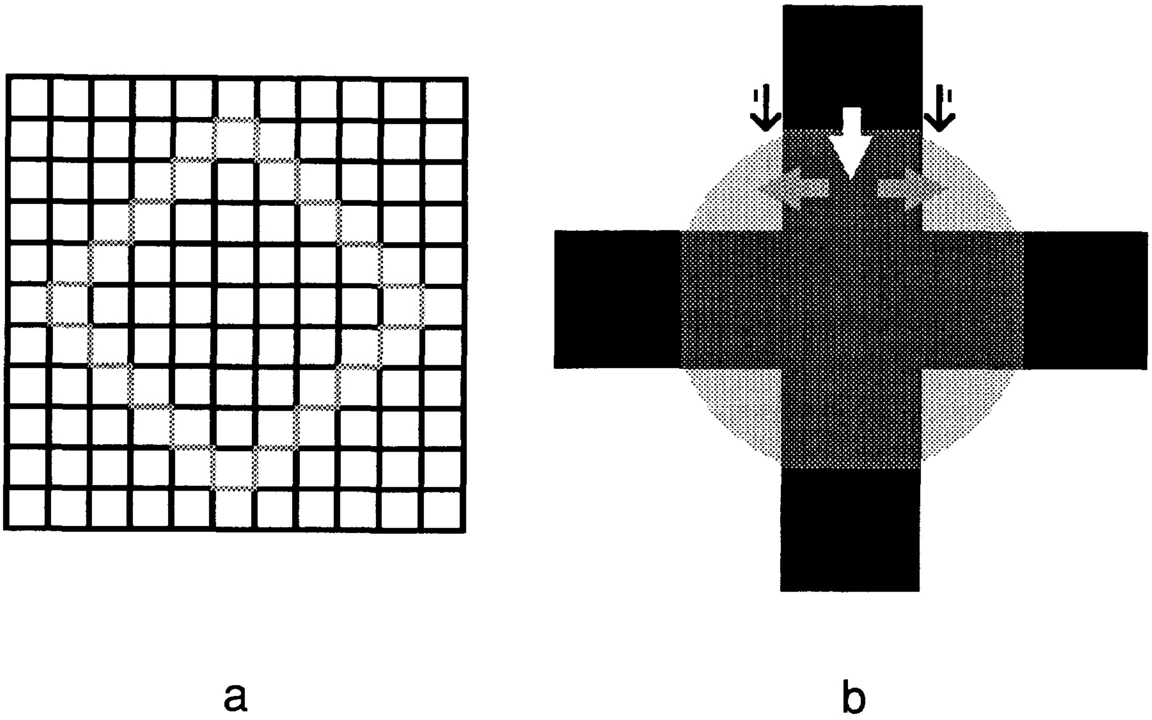

FIGURE 1. (a) Neon colour spreading. When the segments in the diamond are coloured and the matrix is achromatic, the illusory diamond takes on the same hue as the segments. When the segments are achromatic and the matrix is coloured, however, the illusory diamond takes on a hue complementary to that of the matrix. (b) A very simplified representation of how neon spreading may occur from the standpoint of Grossberg and Mingolla's (1985) model. The black Ehrenstein pattern induces complementary colour in the cross (white arrow); at the same time, its contours inhibit contiguous like-oriented contours of the cross (thin arrows with the minus sign). The colour of the cross can then flow out (grey arrows) and spread until it reaches the illusory contours induced by the Ehrenstein pattern.

would require a great deal of space, the basic idea is that everyday object perception is based on 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. The pattern lines, within the FCS, will induce complementary (chromatic or achromatic) colour into the segments; at the same time, within the BCS, they will inhibit the segments' boundaries. Weakened boundaries will let colour flow out and spread around; in the presence of illusory contours able to contain this spreading, such a mechanism will give rise to the neon effect [see Fig. 1(b)].

Now, it seems obvious that the flowing colour should be a *mixture* of the colour of the inhibited segments (in our case, the cross) and the colour complementary to that of the inducing lines (in our case, the Ehrenstein pattern). In fact, when the pattern is green and the cross is black (on a white background), the spreading is dark with a reddish tinge; the neon colour originated by black segments embedded in a blue pattern is dark yellow or brownish [see a sample figure in van Tuijl (1975)].

NEON SPREADING WITH CHROMATIC SEGMENTS EMBEDDED IN A CHROMATIC PATTERN

If the colour that flows outside the cross is a mixture of the colour of the cross and the colour induced by the Ehrenstein pattern, a configuration where both the cross and the pattern are coloured should represent a case of special interest. Assuming that other conditions are equal, it is reasonable to suppose that the visibility of the illusory colour—and hence the strength of the neon effect—will depend on its vividness, or saturation. In turn, being this colour a mixture, its saturation will depend on its components. This leads to a series of specific predictions.

Prediction 1. Dependence of the effect on wavelength combination

First, the effect should be weakest (or disappear altogether) when the colours of the mixture are complementary to each other. This is the case when the pattern and the cross have the same (or a similar) colour. If they are both green, for instance, the reddish colour induced in the cross by the pattern will mix with the green colour of the cross itself producing a maximally desaturated mixture.

Ejima *et al.* (1984) found that the effect is weak or absent when the wavelengths of the crosses and the Ehrenstein pattern are similar or the same.

Second, the effect should progressively increase as the difference between the colours of the mixture decreases, and should be strongest when the colours of the mixture are similar, or the same. This is the case when the pattern and the cross have colours complementary, or nearly complementary, to each other. If the pattern is greenish and the cross is red, for instance, the red colour induced in the cross by the pattern will mix with the red colour of the cross itself producing a maximally saturated mixture.

Ejima *et al.* (1984) found that strong effects occur (a) for wavelengths of the crosses shorter than 500 nm when they are combined with wavelengths of the Ehrenstein pattern ranging from 520 to 640 nm; and (b) for wavelengths of the crosses longer than 600 nm when they are combined with wavelengths of the Ehrenstein pattern shorter than 600 nm. Note that (a) wavelengths shorter than 500 nm correspond to the response range of yellow–blue opponent cells to shorter-wavelength light, while wavelengths ranging from 520 to 640 nm correspond to the response range of yellow–blue opponent cells to longer-wavelength light; and (b) wavelengths longer than 600 nm correspond to the response range of red–green opponent cells to longer-wavelength light, while wavelengths shorter than 600 nm correspond to the response range of red–green opponent cells to shorter-wavelength light. [See DeValois and DeValois (1975)]. In simplified terms, Ejima *et al.*'s results may be expressed by saying that (a) bluish crosses elicited strong colour spreading when embedded in yellowish patterns, whereas (b) reddish crosses elicited strong colour spreading when embedded in greenish patterns.

Figure 2 shows, for each wavelength of the cross that gives rise to a strong neon spreading, the wavelength of the Ehrenstein pattern that induces the best effect. Each data point is the mean of the values that produce the *strongest* effect, calculated from the plot of the strength of the illusion for each wavelength combination of crosses and Ehrenstein patterns provided by Ejima *et al.* (1984). The wavelengths of the cross used by these authors ranged from 460 to 680 nm; the mean strength of the effect for each wavelength ranged from weak to strong. Only values yielding medium-strong or strong effects have been plotted in Fig. 2—which is why all values corresponding to wavelengths of the cross between 500 and 580 nm are missing.

Figure 2 also shows, for each wavelength of the cross that gives rise to a strong neon spreading, the wavelength of the complementary spectral colour.* It can be easily seen that the two sets of values are very close; that is, that the best neon effect is obtained for combinations of colours that are complementary.

Prediction 2. Absence of the effect for certain wavelengths of the cross

Ejima *et al.* (1984) found that the effect is weak for wavelengths of the crosses ranging from 500 to 520 nm and virtually absent for wavelengths of the crosses ranging from 540 to 560 nm.

Note that for these wavelengths there exist no complementary spectral colours. It might well be that some neon effect could have been obtained with these crosses (that look yellowish green) using, for the Ehrenstein patterns, a mixture of short- and long-wavelength light (that looks purple).

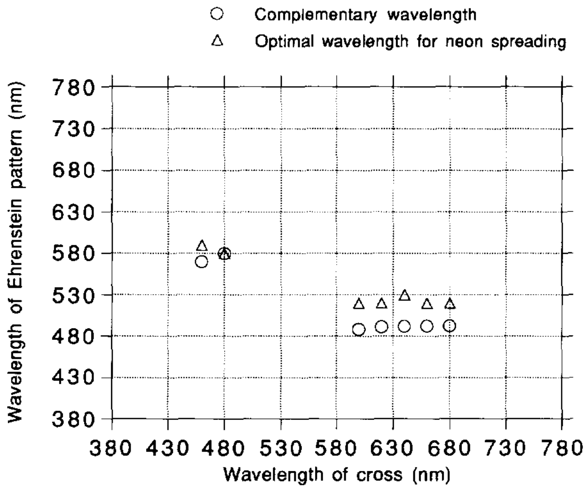

FIGURE 2. For each wavelength of the cross that gives rise to a strong neon spreading, triangles indicate the wavelength of the Ehrenstein pattern that induces the best effect (after Ejima *et al.*, 1984), circles indicate the complementary wavelength.

Prediction 3. Dependence of the effect on the spectral purity of the cross

Ejima *et al.* (1984) observed that the strength of the effect had a positive correlation with the spectral purity of the crosses, and a negative correlation with the spectral purity of the Ehrenstein pattern. On this basis they suggested that the strength of the effect may be related to the spectral purity difference between the cross and the Ehrenstein pattern (i.e. purity of the cross minus purity of the Ehrenstein pattern).

In Grossberg and Mingolla's (1985) explanation of neon spreading, the existence of some inhibition by the pattern on the cross is crucial. No flowing of colour would be expected if the boundaries of the cross were not weakened to begin with. The amount of this inhibition is assumed to depend on the luminance difference (relative contrast with respect to the background) between the pattern and the cross. In the chromatic case however—especially under isoluminance, that is when relative contrast is zero—it makes sense to think that inhibition may be mediated by the spectral purity difference instead (a remark also made by Grossberg, 1987). Evidence both psychophysical [indicating that chromatic analogues of achromatic contrast effects are obtained when purity (chroma) is substituted for luminance and saturation for brightness, see e.g. Levine, Spillmann and Wolf (1980)] and neurophysiological (DeValois & Marrocco, 1973) points in this direction. In other words, just as a pattern that has high contrast with respect to the background will inhibit nearby lower-contrast segments, a pattern that has high purity with respect to the background will inhibit near lower-purity segments. It follows though, that if the strength of the chromatic effect must have any relation at all with relative spectral

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*All values are taken from the table of pairs of spectral colours which are complementary with respect to the 1931 CIE standard observer and CIE source *C* (Wyszecki & Stiles, 1967, p. 334).

purity, it should have it with the purity difference between the Ehrenstein pattern and the cross (i.e. purity of the Ehrenstein pattern minus purity of the cross). The trouble here is that, indeed, this relation is exactly the opposite as that indicated by Ejima *et al.*'s findings.

The conclusion to be drawn is that different strengths of neon spreading in the chromatic case cannot be explained by different amounts of inhibition mediated by spectral purity. This has two separate implications. First, if under isoluminance no purity-dependent inhibition comes in to replace luminance-dependent inhibition, and a full neon effect is still observed, then relative contrast must be less crucial for inhibition than it has been believed.

Second, the correlation between strength of neon spreading and purity of the crosses must mean something else. I think that, again, this finding does make sense within the explanatory framework described above. If the visibility of the illusory colour depends on its saturation, stronger effects will be obtained when the colour of the cross is more saturated to begin with. (Purer lights appear more saturated.) The definition of purity implies that much more white light has to be added to spectral blue or red than to spectral green or yellow before they completely desaturate. Then, if the colour induced in the cross by the pattern tends to desaturate the colour of the cross, green and yellow crosses (beside looking less saturated in the first place) will lose their hue faster than blue and red crosses when coupled with any non-complementary patterns, yielding higher thresholds and weaker effects. (Also bear in mind that, in Ejima *et al.*'s experiments, green and yellow crosses were never coupled with a complementary pattern.) The most saturated colours correspond to the very short- and very long-wave parts of the spectrum, that is to those wavelengths of the crosses for which the best neon effect is obtained.*

Prediction 4. Dependence of the effect on luminance ratio

Ejima *et al.* (1984) found that a just noticeable effect requires illuminance ratios between the Ehrenstein pattern and the cross of less than 1, and that the neon effect is maximal at illuminance ratios ranging from about 1 to 4, with a decrease for smaller and larger values.

In other words, neon spreading does not need the contrast of the pattern to be higher than that of the cross, but the strength of the effect *is* modulated by contrast.

There are at least three separate ways in which luminance contrast may come into play here: by providing more inhibition of the cross boundaries, thereby facilitating the flow of colour; by increasing the sharpness and clarity of the illusory contours, thereby better restricting the flow of colour; by providing lightness induction (i.e. achromatic contrast) which will add to colour induction (i.e. to the already occurring chromatic contrast). An increase in inhibition and sharpness of contours should lead to an increase in the strength of the effect, reasonably up to a plateau. An increase in induced lightness, on the contrary, should progressively desaturate the illusory colour, thus making it less and less visible. Inverted-U curves like those reported by Ejima *et al.*, indeed, may well be the result of some trade-off between these contrasting factors.

CONCLUSIONS

The dependence of neon colour spreading on wavelength and illuminance can be expected if one adopts a theoretical perspective similar to Grossberg and Mingolla's (1985). This approach implies that two separate colours will spread in the area of the subjective figure, one identical to that of the inner segments and the other complementary to that of the external lines. I have observed above that the strength of the neon effect—i.e. the visibility of the illusory colour—must depend on the saturation of this mixture, which in turn depends on its components and therefore on the specific wavelengths chosen for the inner and outer segments. In particular, the effect should be at its worst with pairs of similar colours and at its best with pairs of complementary colours, which is exactly what was found by Ejima *et al.* (1984). Also, the effect should be strongest when the flowing colour is most saturated to begin with, that is for wavelength of the crosses with high spectral purity. This is, again, what was found in this study.

It should be noticed that the general consistency of Ejima *et al.*'s main psychophysical data with Grossberg and Mingolla's model has already been pointed out by Grossberg (1987). As far as I can tell, however, no specific predictions concerning the dependence of the neon effect on wavelength combination have ever been explicitly formulated. That the terms of this dependence should be all straightforwardly derivable within Grossberg and Mingolla's model—with no need of making *ad hoc* assumptions—represents, it seems, an independent demonstration of how good the model is.

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*Only the positive correlation between the effect and the spectral purity of the crosses is commented on here. Ejima *et al.* also reported a negative correlation between the effect and the spectral purity of the Ehrenstein patterns. Such a symmetrical correlation, however, may be expected simply on the grounds that short- and long-wavelength crosses, that elicited the strongest effect, did so when embedded in middle-wavelength (i.e. complementary) Ehrenstein patterns. The negative correlation between the effect and the spectral purity of the Ehrenstein patterns, therefore, does not necessarily mean anything. Nor does, for the same reason, the correlation between the effect and the spectral purity difference between the crosses and the Ehrenstein pattern.

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