Perceptual transparency in neon colour spreading displays

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Abstract

In neon colour spreading displays, both a colour illusion and perceptual transparency can be seen. In the this study we investigated the color conditions for the perception of transparency in such displays. It was found that the data are very well accounted for by a generalization of Metelli's (1970) episcotister model of balanced perceptual transparency to tristimulus values. This additive model correctly predicted which combinations of colours lead to optimal impressions of transparency. Colour combinations deviating slightly from the additive model also looked transparent, but less convincingly so.

1 Introduction

The phenomenon of neon colour spreading was first noticed by Varin (1971) and van Tuijl (1975). This illusion owes its name to the apparent diffusion of colour, which can be seen in figure 1. This particular configuration consists of a black and blue grid on a ‘physically white’ background. Despite this fact the background close to the blue parts of the grid looks bluish. Other interesting phenomenal facts, pertaining to this illusion (see figure 1), are that the embedded part seems to be ‘desaturated’ compared to the same part viewed in isolation, and that one has the (sometimes rather vague) impression of a transparent layer (Bressan, Mingolla, Spillmann, & Watanabe, 1997; Varin, 1971) covering the region of the subjective colour spread.

Insert figure 1 about here

Different explanations have been proposed for the subjective colour spreading. Bressan (1993), for instance, proposed that the colour spreading is due to ordinary assimilation of the von Bezold type and that ”Bezold-type assimilation, when taking place within a surface that is further seen as transparent, turns into the neon spreading effect” (p. 360). In accordance with this, she suggested that neon colour spreading and Bezold-type assimilation ”should be parsimoneously interpreted as the same basic phenomenon” (p. 361).

Anderson (1997) proposed a different approach, which ”asserts that the geometric and luminance relationships of contour junctions induce illusory transparency and lightness percepts by causing a phenomenal scission of a homogeneous luminance into multiple contributions” (p. 419). The scission ”is assumed to cause changes in perceived lightness and/or surface opacity.”

With the term scission, he refers both to a perceptual decomposition of local luminance into a transparent layer and an underlying surface, as well as, a perceptual decomposition into the reflectance of a surface and the prevailing illumination conditions. This approach may also be considered theoretically parsimoneous, since it links the brightness illusion observable in neon colour spreading displays to mechanisms of transparency perception. A further advantage of this account is that it seems to be applicable to other well-known brightness and colour illusions, like the Munker-White illusion and Benary's[1] illusion (Anderson, 1997).

We have been pursuing an approach that bears some resemblance to that of Anderson, and is in part inspired by it. In particular, we consider the idea of connecting the colour and/or brightness illusions in neon colour spreading to the perceptual scission of local proximal colour information into a transparent layer component and a background component promising. A difference between our approach and that of Anderson is that he made the working assumption "that the achromatic contrast [...] is the primary determinant of scission", whereas we have been adopting the working hypothesis that chromatic properties also play an important role. This seemed natural to us given the fact that this has already been found to be true by several authors (Chen & D'Zmura, 1998; Da Pos, 1989; D'Zmura, Colantoni, Knoblauch, & Laget, 1997; Faul, 1996, 1997) in the four-region transparency displays, originally studied by Metelli (1970). Related to this is a further difference between our approaches. Anderson's model does not rest on Metelli's episcotister metaphor, but makes similar predictions for the special case of isochromatic and achromatic stimuli. In contrast, we have chosen to think in terms of the episcotister model. An important reason for this is that it can easily be generalized and applied to tree-dimensional colour codes (Chen & D'Zmura, 1998; Da Pos, 1989; D'Zmura et al., 1997; Faul, 1997).

An episcotister is simply a disk with an open sector. This apparatus has been a preferred device for modifying the effects of light reaching the eye from a given object in lawful ways since the very beginning of experimental psychology. Let α be the size of the open sector relative to the entire disk, i.e. $0 < \alpha < 1$. If we have an episcotister E rotating quickly in front of a bipartite field consisting of regions A and B, then perceptually four regions A, B, P and Q are given (see figure 2). It can be shown with reference to Talbot's (1934) Law of colour fusion that for this situation the equations

$$f(P) = \alpha f(A) + (1 - \alpha) f(E) \tag{1}$$

$$f(Q) = \alpha f(B) + (1 - \alpha) f(E) \tag{2}$$

hold, where $f(X)$ may be taken to be the light reflected from region X or any linear function of this light, like for instance luminance ℓ. For the sake of correctness, it should be noted that the expressions on the left side of the equations are only *effective* lights (or, for $f := \ell$, effective luminances), i. e. the temporally alternating lights, reflected from these regions, have the same effect on the photoreceptors as a steady light of the intensity and spectral composition given by $f(P)$ or $f(Q)$, respectively.

Insert figure 2 about here

Solving for α and chosing $f := \ell$ yields

$$\alpha = \frac{\ell(P) - \ell(Q)}{\ell(A) - \ell(B)} \tag{3}$$

Since the ‘transmittance’ α of the episcotister is subject to the natural restrictions $0 < \alpha$ and $\alpha < 1$ it follows

$$\ell(P) < \ell(Q) \Leftrightarrow \ell(A) < \ell(B) \tag{4}$$

and

$$|\ell(P) - \ell(Q)| < |\ell(A) - \ell(B)| \tag{5}$$

respectively. In summary, if a mosaic of colours as displayed in figure 2 is due to the presence of an episcotister, then equation 4, stating that the episcotister can not reverse the direction of contrast must hold, as well as equation 5, stating that the effect of an episcotister can only be to reduce (or, in the limiting case of $\alpha = 1$, preserve) the amount of contrast.

According to the episcotister model, perceptual transparency should be observed whenever these two conditions of *preservation of contrast direction* (equation 4) and *reduction of contrast* (equation 5) are met. The conditions for perceptual scission described by Anderson (1997) are consistent with, and in many respects equivalent to these two conditions.

It has been shown, however, that the perception of transparency does not only depend on the luminance relations of the stimuli, but also on chromatic relations (Chen & D’Zmura, 1998; Da Pos, 1989; D’Zmura et al., 1997; Faul, 1997). These relations may be modelled using the episcotister model since it can easily be extended to tristimulus values. The cone excitation ϕ_L of the long-wavelength-sensitive L-cones is a linear function of light, and may thus be substituted for f in equations 1 and 2. The same holds for the cone excitations ϕ_M and ϕ_S of the M-cones and the S-cones. This yields

$$\overrightarrow{\phi}(P) = \alpha\overrightarrow{\phi}(A) + (1 - \alpha)\overrightarrow{\phi}(E) \tag{6}$$

$$\overrightarrow{\phi}(Q) = \alpha\overrightarrow{\phi}(B) + (1 - \alpha)\overrightarrow{\phi}(E) \tag{7}$$

with $\overrightarrow{\phi}(X) := (\phi_L(X), \phi_M(X), \phi_S(X))^t$. Although the models of Da Pos (1989), D'Zmura et al. (1997), Chen and D'Zmura (1998) and Faul (1997) differ in some respects, this natural extension of the episcotister model is a core element in all of them. This model, which we will refer to as the *strict additive model* lead to more restrictive conditions for the perception of transparency than equations 4 and 5. For instance, if one solves equations 6 and 7 for α componentwise one gets:

$$\alpha_i = \frac{\phi_i(P) - \phi_i(Q)}{\phi_i(A) - \phi_i(B)} \tag{8}$$

for $i = L, M, S$. Equations 6 and 7 imply that $\alpha_L = \alpha_M = \alpha_S$. Since the episcotister 'transmittance' α_i may be said to reflect the degree of contrast reduction for the cone-type i, this means that the degree of contrast reduction, computed separately for each class of cones, must be equal for all three cone classes. The strict additive model describes a very simple geometrical structure in three-dimensional colour space. The colour shifts caused by the episcotister, that is the difference vectors $\overrightarrow{\phi}(P) - \overrightarrow{\phi}(A)$ and $\overrightarrow{\phi}(Q) - \overrightarrow{\phi}(B)$, must converge to a common point $\overrightarrow{\phi}(E)$ if the region $P \cup Q$ is to be seen as a homogeneous transparent layer[2]. Consequently the model has been called a *convergence model* by D'Zmura et al. (1997).

The strict additive model describes available data for the perception of transparency in four-region stimuli rather well (Chen & D'Zmura, 1998; Faul, 1997). Thus, it seems reasonable to take this model as a point of departure for studying the perception of transparency in neon colour spreading displays.

A difference between the four-region stimuli originally studied by Metelli (1970) and neon color spreading displays is that the latter - in pure proximal terms - have only three differently coloured regions[3]. This may be appreciated in figures 3 and 4, which depict a well-known neon colour spreading display called the modified Ehrenstein-figure (Redies & Spillmann, 1981; Redies, Spillmann, & Kunz, 1984). In proximal terms, the colour of region Q is equal to the colour of region B. In perceptual terms however, the colour of region Q is different to the colour of region B. This illusory colour of region Q is the colour spreading effect. Besides colour information figural cues also seems to play a critical role. In neon colour displays, they give rise to a virtual contour that separates regions Q and B (Kanizsa, 1980; Schumann, 1900; de Weert & van Kruysbergen, 1987). An assumption implicit to our approach is that the separation of regions Q and B is due to figural cues.

Insert figure 3 about here

Insert figure 4 about here

The model of Anderson (1997) is equally applicable to this configuration as to four-surface stimuli because of its focus on contours instead of regions. However, it is also possible to apply the strict additive model (eqns. 6 and 7) to this configuration, a possibility which was clearly spelled out and investigated by Watanabe and Cavanagh (1993), and discussed by Grossberg (1987, p.132). Since in such configurations $\overrightarrow{\phi}(Q) = \overrightarrow{\phi}(B)$ always holds, the strict additive model may be rewritten as

$$\overrightarrow{\phi}(P) = \alpha\overrightarrow{\phi}(A) + (1-\alpha)\overrightarrow{\phi}(B). \tag{9}$$

The model is a model of *balanced* transparency and predicts that region $P \cup Q$ should look transparent whenever $0 < \alpha < 1$. The geometrical interpretation of this condition is that the tristimulus vector $\overrightarrow{\phi}(P)$ lies on the line segment connecting the tristimulus vectors $\overrightarrow{\phi}(A)$ and $\overrightarrow{\phi}(B)$ in tristimulus colour space. In the achromatic case, this means that $\ell(A) < \ell(P) < \ell(B)$ or $\ell(B) < \ell(P) < \ell(A)$. Since these relations are invariant with respect to monotonic transformations of ℓ, the same predictions follow if one assumes that perceived lightness, as opposed to luminance, is the relevant variable, which has been proposed by Beck and co-workers (Beck, Prazdny, & Ivry, 1984; Beck & Ivry, 1988). It is also apparent that this model makes exactly the same predictions as Anderson's (1997) model for achromatic (and isochromatic) stimuli, namely that the region $P \cup Q$ should look transparent whenever the luminance of P is between the luminances of A and B. In general, however, the present model is clearly more restrictive.

Before we describe the experiments performed to test the present model, some clarifying comments may be required. If one regards the modified Ehrenstein-figure depicted in fig. 3, it becomes clear that this stimulus fails to satisfy equation 9. If one assigns the tristimulus values $\overrightarrow{\phi}(A) := (0, 0, 0)^t$ to the outer cross A, which is black and the tristimulus values $\overrightarrow{\phi}(B) := (1, 1, 1)^t$ to the background B, which is white, then the model predicts that the tristimulus values of the inner cross P must be $\overrightarrow{\phi}(B) := (x, x, x)^t$ with $0 < x < 1$ - which has to be some shade of gray - if region $P \cup Q$ is to be perceived as a homogeneous transparent layer. Since P is not gray, the stimulus does not fit the strict additive model. It looks transparent, however. One may be tempted to conclude from this that the proposed model is wrong as it stands, and that it is a waste of time performing experiments to test it.

However, this conclusion is only warranted if the strict additive model is taken to describe all stimuli that look transparent. In the present approach, we hypothesize that the strict additive model only describes stimuli that lead to an impression of balanced transparency that is optimally convincing. All impressions of transparency are not equally compelling. This point may be appreciated in fig. 5. In all four configurations, one is prone to say that one has an impression of transparency. However, most observers would probably agree that the impression of balanced transparency in the upper left configuration is less evident than in the three other configurations. This subtle, but in our opinion important distinction, may get lost in investigations where subjects are asked to make categorical yes-no judgements, since all the depicted stimuli look more or less convincingly transparent.

Insert figure 5 about here

The present approach is motivated by the empirical findings of Faul (1997). Studying four-region transparency, he found that stimuli which look transparent do not look equally convincingly so. Among the stimuli which look transparent some have a special status, namely those which look the most convincingly transparent. In Faul's data these stimuli conform closely to the strict additive model, whereas the 'goodness'[4] of the transparency impression decreased monotonically with increasing deviation from the predictions of the strict additive model, until transparency is no longer perceived at all.

It may be instructive to compare the predictions of the present approach with those of Anderson's (1997) model[5]. According to his model, transparency should be perceived whenever the luminance ℓ of the inner elements P is intermediate between the luminance of the outer elements A and the luminance of the background B, i.e. whenever

$$\ell(P) = \alpha\ell(A) + (1-\alpha)\ell(B) \qquad (10)$$

with $0 < \alpha < 1$. According to the present approach this is a necessary but not sufficient condition for the perception of transparency. We predict that among the stimuli satisfying this condition, some should not look transparent and some should look transparent, depending on the combination of chromaticities in the stimulus. Furthermore, we predict that if subjects are instructed to adjust the chromaticity of the inner elements P, such that the impression of transparency is the most convincing, they should reliably choose a chromaticity which is consistent with eqn. 9. These predictions were tested in Experiment 2. In Experiment 1 we replicated previous findings using purely achromatic stimuli.

2 Experiments

In order to examine our hypothesis, we performed two experiments. The first was basically a replication of the previously reported findings (van Tuijl and de Weert, 1979) concerning the luminance conditions for the neon colour spreading effect, and was performed with achromatic stimuli. The second experiment was performed with chromatic stimuli, and was designed to (a) test the hypothesis that configurations satisfying the conditions of the strict additive model look transparent with optimal subjective certainty, and (b) to get a first estimate of the limits of the impression of transparency as the deviation from the strict additive model increases.

From the many neon colour spreading displays that could potentially have been used for the investigation, a relatively new, animated version of the illusion was chosen, the so-called *dynamic* neon colour spreading display (Cicerone & Hoffman, 1997; Cicerone, Hoffman, Gowdy, & Kim, 1995; Hoffman, 1998), because it seems to produce a slightly more vivid effect compared to static displays. Figure 6 schematically shows three frames of such an animation, which is constructed in the following way: For the first frame, coloured dots are randomly or pseudo-randomly (Fidopiastis, Hoffman, Prophet, & Singh, 1998) distributed on a homogenous background. All dots receive the same colour - for instance red - except the dots located within a virtual circle which receive another colour, for instance green. In the next frame, all dots keep their position, the virtual circle, however, is translated by some small distance Δx, and thereupon the colourations of the dots are changed, such that the dots within the circle are all still green and the dots outside the circle all red. A number of such frames in sequence make up an animation in which a virtual circle moves back and forth at uniform speed. For appropriate choices of colours, one has the impression that the colour of the inner dots spreads inside the virtual circle. This neon colour spreading is accompanied by a more or less vivid impression of transparency. In regard to their role in producing the neon colour spreading, the inner dots correspond to the inner cross in the modified Ehrenstein figure, just as the outer dots correspond to the outer segments of the cross. We shall therefore refer to the inner dots as P, the outer dots as A and the background as B in analogy to the previous exposition of our model by means of the modified Ehrenstein figure[6]. The perceptually visible region Q in the modified Ehrenstein figure corresponds to the part of the background inside the virtual circle.

Insert figure 6 about here

2.1 Experiment 1 - achromatic stimuli

This experiment was performed to test our hypothesis using achromatic displays. It is essentially a replication of van Tuijl and de Weert's (1979) investigation using dynamic stimuli instead of static ones. The hypothesis states that the goodness of the transparency impression should only depend upon whether the episcotister 'transmission' α is physically possible. However, we also tried to control for other variables that could potentially exert an influence on the transparency impression.

Methods, procedure and stimuli For the special case of achromatic configurations equation 9 holds whenever

$$\ell(P) = \alpha\ell(A) + (1 - \alpha)\ell(B) \tag{11}$$

holds. The strict additive model predicts that transparency is seen when $0 < \alpha < 1$, that is, when the luminance of the inner dots is intermediate between the luminance of the outer dots and that of the background. The luminance of the inner dots was set according to 8 different levels of 'transmittances' α (-0.4, -0.2, 0.2, 0.4, 0.6, 0.8, 1,2 and 1.4) for different pairs of luminances for the background and the outer dots. Obviously, the transmittance levels $-0.4, -0.2, 1.2$ and 1.4 are not physically realizable. As background and outer dots luminance pairs, all 6 possible pairs of the three luminances 11.6, 23.3 and 35 $\mathrm{cd} \cdot \mathrm{m}^{-2}$ were used, thus allowing us to check for possible asymmetries resulting from a) the background being darker than the outer dots or conversely, b) differences in the absolute distance between background and outer dots luminance and c) different levels of mean luminance. The three luminances were chosen so as to exploit the monitor gamut maximally. Twenty repetitions of the resulting 8×6 stimulus conditions, yielding a total of 960 trials, were presented in random order. The subjects were instructed to rate the goodness of the transparency impression on a scale from 0 to 5. It was emphasized that they were only to express the strength of their subjective confidence that the circular region appeared transparent as opposed to opaque. They were thus *not* to rate the degree of transparency in terms of apparent layer density or layer ‚transmittance', or let this influence their judgments. We explicitly instructed the subjects to look for balanced transparency, which was explained to them as the impression that a transparent layer appears in front of the dotted background, through which the latter is seen in its original colour. Since pilot experiments had shown that the inner and the outer dots were perceptually indiscriminable at values of α near 1 (an α value equal to 1 implies that they are physically equal), the subjects were allowed to discard the presentation and declare it invalid if this was the case. This explains the unequal number of observations for different α conditions shown in table 1. The subjects were allowed to view each presentation as long as they wished. They recorded their judgments using the up and down keys of the keyboard and pressing return, upon which the next presentation immediately followed. Breaks could be made at the subjects' own discretion. Each subject finished the experiment in two or three sessions, lasting for a total of approximately 3 hours. All of the seven subjects had normal colour vision and normal or corrected-to-normal visual acuity, and all were naive regarding the purposes of the experiment except three, one of them being the first author of this paper. The stimuli were presented on a CRT computer monitor, which was carefully calibrated using an LMT C1210 colormeter and controlled by a Cambridge Research Systems VSG 2/3 graphics card, operating in a mode with 8 bits per channel. The 2500 dots in each presentation were 3 mm and distributed pseudo-randomly over a region of the monitor measuring 395 by 270 mm. The (virtual) target disk moved back and forth on a horizontal path, 235 mm in length, at a constant speed of 10 cm per second. A reduction tunnel, fixing the viewing distance to 125 cm, was used to prevent light reflections from the monitor, which was the only source of illumination in the room.

Results The mean ratings of transparency goodness as a function of α are shown in fig. 7, which is based on the pooled data from all subjects except one.

Insert figure 7 about here

This subject failed to see stimuli with the lighter background as transparent. Visual examination showed that the transparent layers all appear whitish in this kind of stimuli, just like the background, whereas the layers of the other stimuli appear "darkish" or clear like a windowpane. When this subject was shown the stimuli again and asked why he had not rated the stimuli with the light backgrounds as transparent, he stated that he had only looked for clear, window-pane-like transparency.

For the rest of the subjects ratings were high for α values between 0 and 1, and low for α values outside of this range, as can be seen in fig. 7. This result is predicted both by Anderson's (1997) and the present model.

In order to check for influences on perceived transparency other than α, the data were also plotted separately according to the following criteria: a) whether the difference between the luminances of background and the outer dots was large or small, and b) whether mean luminance was high, medium or low. Since none of these variables had an influence, these plots are not shown.

One finding appearing in the data not explicitly predicted by the model is the moderate transparency ratings at $\alpha = 0.8$. However, as already mentioned, pilot experiments had shown that the outer and the inner dots were rendered perceptually indiscriminable at α values close to one. For this reason the subjects were given the opportunity to declare such stimuli invalid. As table 1 shows, the percentage of invalid cases at an α of 0.8 is as high as 38, suggesting that these stimuli are at the limit of perceptibility due to low visible contrast. It is not surprising that the ratings turn out to be a bit lower for these stimuli, since uncertainty is to be expected at the limit of perceptibility and the subjects were supposed to judge the degree of subjective certainty to which the display looked transparent. In summary, the findings of this experiment are in good agreement with the proposed model.

Insert table 1 about here

2.2 Experiment 2 - chromatic stimuli

This experiment was performed in order to test our hypothesis for the general case of chromatic stimuli. We wanted to find out whether the proposed model correctly predicts the colour conditions that make stimuli look transparent with optimal subjective certainty. Furthermore, we wanted to get a first estimate of the limits of the impression of transparency as the deviation from the strict additive model increases.

Methods, procedure and stimuli The model states that for a given pair of background and outer dot colours, the set of inner dot colours producing optimally convincing impressions of transparency is defined by the line segment in colour space connecting them (cf. equation 9). Fixing the luminance of the inner dots to a given value between the luminances of the background and the outer dots is tantamount to defining an equiluminant chromaticity plane in colour space, intersecting this line segment at exactly one point S (see figure 8). If the subjects are instructed to adjust the chromaticity of the inner dots inside this equiluminant plane so that the configuration appears as convincingly transparent as possible, they should choose this point S, provided the model holds. In order to avoid the usual problems associated with two-dimensional adjustments - such as possible local minima and extremely time-consuming searches - we restricted the possible settings to a circle in the CIE 1976 $(u', v') - UCS$ diagram (cf. Wyszecki and Stiles, 1982, p. 824), in the chosen plane of equiluminance, passing through the predicted intersection point S and centred around the chromaticity of the outer dots.

Insert figure 8 about here

We used the following four-step procedure for each stimulus: First, the initial chromaticity of the inner dots was randomly set somewhere on the circle. The subject's task was to adjust the chromaticity of the inner dots – using the 'left' and 'right' keyboard buttons – such that the configuration appeared transparent with optimal subjective certainty. Starting with this optimal chromaticity, the subject's task in the second step was to change the chromaticity of the inner dots in the anti-clockwise direction along the circle – by pressing the 'left' button – until the configuration did not appear transparent at all. The task in step three was exactly the same as in step two, only now, the chromaticity was to be changed in the opposite direction, starting once again with the chromaticity chosen as optimal in step one. In step four, the chromaticity chosen as optimal in step one was reproduced by the computer program, and the subject was instructed to rate the goodness of the transparency impression on a scale from 0 to 5 according to the same criterion as in experiment 1. The following information was thus collected: The data recorded in step 1 allowed us to estimate the point leading to an optimally convincing impression of transparency. The data collected in steps 2 and 3 provided information about the approximate range of chromaticities leading to a transparency impression. This yields an estimate of how much a configuration can deviate from the optimal point before the phenomenon can no longer be observed at all. The goodness of transparency ratings collected in step 4 allowed us to verify that the settings in step 1 actually led to a good impression of transparency, and were not merely best choices based on only bad alternatives.

The independent variables were chromaticity and luminance of the background and outer dot colour pairs, and the level of α defined by the point S. The levels and combinations of the independent variables were chosen in the following manner. First, we determined the maximal luminance l_{max} for which a close to maximal gamut of chromaticities was still realizable on the monitor used. The two luminances $l_{max} := 11.3 \text{ cd} \cdot \text{m}^{-2}$ and $l_{max}/2$ were used for the background and the outer dots. Then three chromaticities were sought, lying as far apart as possible, but still ensuring that the major parts of the circles, defining the possible settings, were within the monitor gamut. The radii of these circles were, of course, dependent on the choice of the α-levels which were set to 0.2, 0.4 and 0.6. The α-level 0.8 was not used, owing to problems of discriminability (see experiment 1). Background and outer dots always differed in both chromaticity and luminance. We balanced the role of background and luminance, which yields 2×2 luminance pairs. This combined with the three possible (unordered) pairs drawn from the chosen set of three (x,y)-chromaticities $\{(0.26, 0.18), (0.45, 0.31), (0.33, 0.37)\}$ and the three α levels yields 36 stimuli. Ten repetitions of each stimulus were presented, resulting in a total of 360 presentations for each subject. The subjects were six out of the seven who participated in experiment 1, i.e. one subject did not perform experiment 2. Again, breaks could be made at the subject's own discretion. Each subject finished the experiment in two to four sessions, lasting a total of approximately 6 hours. Technical data, concerning viewing conditions and apparatus, were identical to those of experiment 1.

Results

Insert figure 9 about here

Insert figure 10 about here

Insert figure 11 about here

Insert figure 12 about here

Some typical data are shown in figure 9. Each plot in the figure shows the data resulting from three stimulus conditions having the same background and outer dot colours but different α-levels. The inner circle always represents $\alpha = 0.2$, the middle circle $\alpha = 0.4$ and the outer circle $\alpha = 0.6$. The square represents the chromaticity of the background, and the triangle the chromaticity of the outer dots. The intersection between the dotted line and a circle represents the optimal point of transparency on this circle, as predicted by the model. The mean[7] adjustments made for each stimulus condition and pooled over all subjects are shown as dots. The smaller shaded region represents one standard deviation[8] to each side. The larger shaded region is confined within the means of the adjustments made in step 2 and 3 of the four-step procedure. Outside of this region transparency was no longer seen.

The mean chromaticity adjustments made for the point of optimally convincing transparency are very close to the prediction. The transparency ratings corresponding to these adjustments were close to maximal in all conditions, with a grand mean of 4.09 and a standard deviation of 1.04.

The right-hand plot in figure 9 shows the data with the worst fit between data and prediction. This can be verified by reference to figure 10, which shows the Euclidian distance in (u', v')-coordinates between prediction and mean adjustment for each of the 36 stimulus conditions. The error bars represent the (u', v')-distance between the mean and one standard deviation to each side. The fact that all values are positive reflects merely the fact that distances are always positive. Since the worst fit shown in the right-hand plot of figure 9 is still very good, it can be stated that the data are very close to the predictions made by the model.

3 Discussion

In this paper, we adapted an existing model of balanced perceptual transparency, which was originally formulated for patterns consisting of four colour regions, to configurations in which only three differently coloured regions can be identified. The predictions of the model concerning the colour conditions for perceptual transparency in such configurations were tested in two experiments using dynamic neon colour spreading displays.

The data of the first experiment, which used achromatic stimuli, show that convincing impressions of balanced transparency result when the luminance of the inner elements is intermediate between the luminance of the outer elements and the background. Stimuli with other luminance relations did not produce convincing impressions of balanced transparency. These results are compatible both with Anderson's (1997) model and the present model. They are, however, seemingly at odds with the data of Bressan (1993), which show that balanced perceptual transparency may be observed in some stimuli where the luminance of the inner elements is not intermediate between the other two luminances in the display. We are not able to give a conclusive explanation of this discrepancy, but it may be noted that the experimental procedure adopted in the present investigation differs from that of Bressan (1993) in many respects. For instance, Bressan's subjects were instructed to assign the stimulus to one of four categories, which were found to be possible percepts in a pilot experiment (one of them being the impression of a transparent filter in the region $P \cup Q$), whereas in our experiment the subjects were instructed to report how certain they were that this region looked transparent using a subjective scale from 0 to 5. Since the discrepancies between Bressan's and our experimental findings are critical for the evaluation of the validity of her model, on the one hand, and the validity of Anderson's[9] (1997) and the present model, on the other hand, independent replications using identical stimuli and experimental procedures would be of great value.

In Experiment 2, we used chromatic stimuli, which allow a comparison of the predictions of Anderson's model with the predictions of the present model. In all of the stimuli used in this experiment, the luminance of the inner elements was intermediate between the two other luminances in the display. Therefore all possible settings for the chromaticity of the inner elements should lead to the impression of transparency according to Anderson's (1997) model[10]. Our data clearly show that this is the case only for some combinations of chromaticities, which is to be expected from known models of colour transparency (Chen & D'Zmura, 1998; Da Pos, 1989; D'Zmura et al., 1997; Faul, 1997). Furthermore, it is evident that a real subset of the colour combinations which lead to an impression of transparency have a special status, since the subjects reliably found a unique setting for each stimulus that lead to an impression of transparency which is more compelling than the others. This subset of colour combinations is well described by the strict additive model. It may thus be safely concluded that all impressions of transparency are not equally compelling, which is consistent with the findings of similar investigations using four-region stimuli (Faul, 1997).

A possible interpretation of the present findings is that the colour combinations described by the strict additive model lead to an impression of balanced transparency, whereas other colour combinations, which were also seen as transparent, lead to an impression of anomalous, incomplete or partial transparency (Metelli, Da Pos, & Cavedon, 1985). Since the subjects of the present experiments were instructed to make settings and ratings for balanced transparency, it is possible that the unique settings of optimally convincing transparency correspond to cases of balanced transparency, whereas the other colour combinations lead to impressions of unbalanced transparency, which under this instruction may be seen as transparent but less convincingly so. Indeed, it can be observed in fig. 5 that the colour combination of the upper left configuration, which deviates from the strict additive model, leads to an impression of transparency which is not balanced[11], whereas the impression in the three other configurations - which are intended to fit the strict additive model as far as reproduction allows it - is rather one of a homogeneous transparent layer through which the grid is seen in its true colour.

From the present experiments, it may be concluded that Anderson's (1997) working hypothesis which maintains that achromatic contrast is the primary determinant of scission is an oversimplification. However, this does not imply that his general ideas are wrong. It is merely implied that they have to be modified in detail. We hope that the present findings will be helpful in guiding future investigations into the relations between perceptual scission and colour illusions.

A point that should be taken into account in future research is that the perception of a transparent layer is at its most convincing in stimuli which differ from those which give the most *conspicuous* demonstrations of neon colour spreading. According to the present approach this is due to the fact that stimuli which conform to the additive model, and thus also look most convincingly transparent, the color (or brightness) spreading has the same perceived chromaticity as the background, whereas in stimuli which are non-optimal for the perception of balanced transparency, the perceived chromaticity of the spreading is different from that of the background, and may thus be more noticeable. This important distinction can easily be observed in figure 5.

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Notes

[1]It may be appropriate to note that reference to the connection between perceptual scission and Benary's illusion has also been made by Musatti (1953).

[2]According to D'Zmura et al. (1997) $\overrightarrow{\phi}(E)$ must not necessarily lie within the colour cone, and may even be the infinitely distant point. This means that the difference vectors may be parallel in this limiting case.

[3]In perceptual terms, neon colour spreading displays have four differently coloured regions, as Bressan (1993) notes. It seems natural to regard these perceptual variables as relevant for mechanisms of transparency perception within her theoretical approach. Within our theoretical approach, however, it is natural to refer only to proximal variables.

[4]This should not be confused with the perceived degree of transparency, i.e. the 'transmittance of the filter'. What is meant, is the subjective certainty of the subject that the configuration looks homogeneously transparent irrespective of the perceived 'transmittance' of the transparent layer.

[5]This comparison may not be completely fair to Anderson's model, since he predicts perceptual scission which may refer to both a decomposition of local luminance into a transparent layer and an underlying surface as well as a perceptual decomposition into the reflectance of a surface and the prevailing illumination conditions. In contrast we only refer to and investigate perceptual transparency.

[6]A demonstration of the dynamic colour spreading effect is included in

Hans Irtel's *Colour Vision Demonstrations (CVD)* which can be downloaded at *http://www.uni-mannheim.de/fakul/psycho/irtel/cvd.html*

[7]It was computed as the projection of the centroid (mean_u, mean_v) to the circle.

[8]The standard deviation was computed as the mean square of the distances between the mean and each adjustment along the circle.

[9]cf. Anderson (1997), p. 448.

[10]In fairness, Anderson's model only state that some kind of perceptual scission should appear in this case, which must not necessarily be a scission into transparent layer and background. Still the comparison is interesting, since the present results would allow distinction between different kinds of scission.

[11]This is also noted by Bressan et al. (1997) p. 1355.

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Figure 1: Neon colour spreading as it was presented by van Tuijl (1975). Note that the blue colour on the left and on the right is physically the same.

Figure 2: The episcotister model (Metelli, 1970). On the left side, the episcotister is depicted, on the right side, the perceptual impression resulting from the rotation of the episcotister.

Figure 3: The modified Ehrenstein figure.

Figure 4: The modified Ehrenstein figure with a schematic depiction of the four perceptually defined regions.

Figure 5: Four instances of neon colour spreading stimuli (van Tuijl, 1975). The upper left configuration has a combination of colours that is often used for demonstrations of the neon colour spreading effect. This colour combination does not fit the strict additive model. Still, one has the impression of transparency. However, the impression is rather vague, and it it is not balanced, i. e. one does not see the grid in its original colour through an homogeneous transparent layer. The other three colour combinations fit the strict additive model as far as reproduction allows it. In these configurations the impression of transparency is more convincing and balanced.

Figure 6: Three frames from a Dynamic Colour Spreading Display (Hoffman, 1998).

Figure 7: Results from Exp. 1. Mean ratings of the subjects' subjective certainty that the configuration looked transparent is given as a function of α. According to the model, transparency ratings should be highest for values of α between 0 and 1. The data are plotted separately for the two levels of the first control variable: Outer dots A lighter than background B or conversely. The error bars show the 95-% confidence intervals.

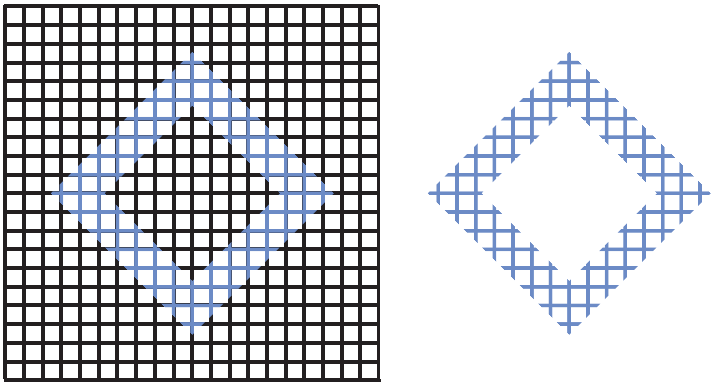
Figure 8: Illustration of the logic used in experiment 2. Arrows A and B represent possible colour codes for the outer dots and the background respectively. The plane represents the equiluminant chromaticity plane defined by the fixed luminance of the inner dots P. The line connecting A and B represents the set of colour codes for the inner dots P, which according to the model should lead to an optimal impression of transparency. The possible settings were restricted to the depicted circle in the equiluminance plane. The model predicts that the subjects should choose the point of intersection S, between this circle and the line connecting A and B.

Figure 9: Results from Exp. 2 for 9 representative stimuli plotted in the (u', v')-UCS diagram. Background and outer dot colours were the same for the three stimuli in each plot. The different radii of the circles reflect different levels of α. For each of the stimuli, the model prediction is given by the intersection of the circle with the line connecting the background and outer dot colours.

Figure 10: Deviations between prediction and mean setting for all 36 stimuli. Δ (u',v') is euclidian distance in the (u',v')-chromaticity plane. See text for further details.

α	-0,4	-0,2	0,2	0,4	0,6	0,8	1,2	1,4
invalid cases (%)	0	0	0	0	0	38	47	6
valid cases (n)	720	720	720	719	717	445	380	680

Table 1:



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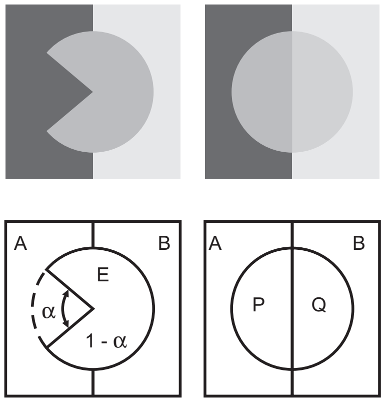

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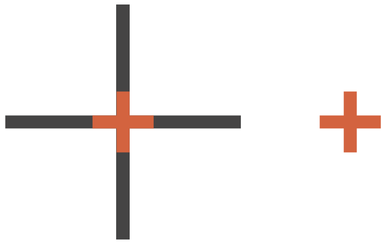

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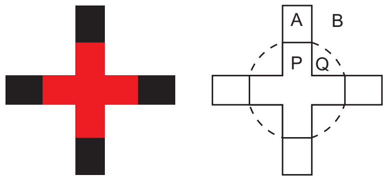

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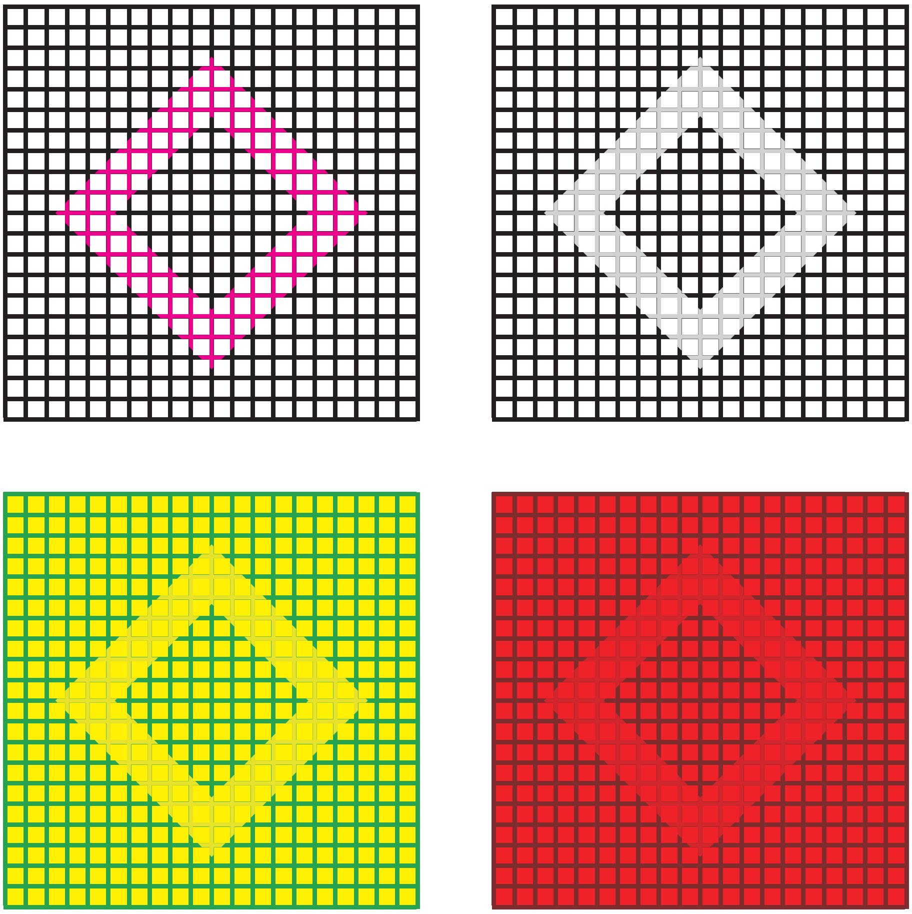

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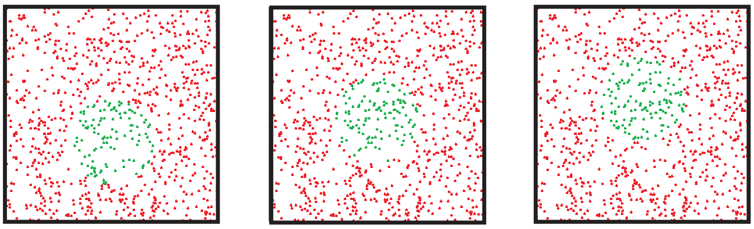

Figure 6:

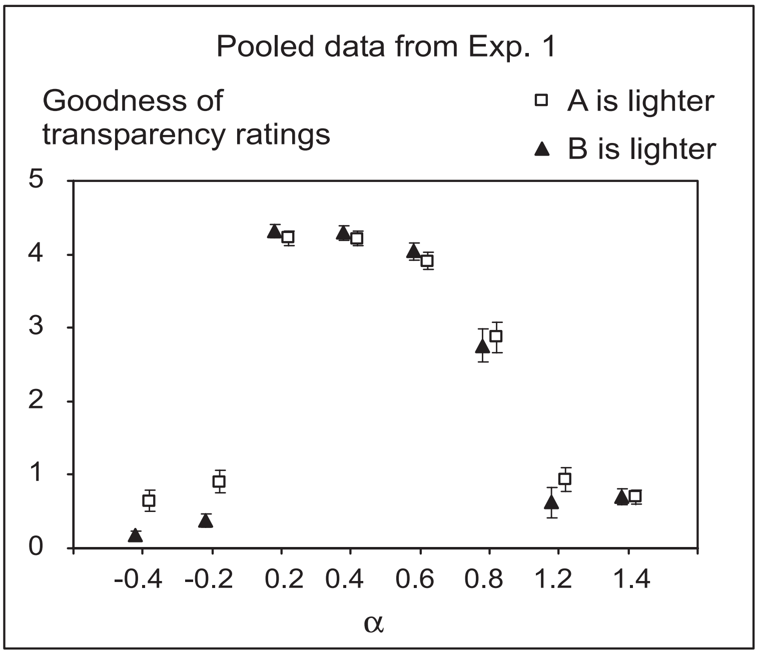
Pooled data from Exp. 1
Goodness of transparency ratings
A is lighter
B is lighter
5
4
3
2
1
0
-0.4
-0.2
0.2
0.4
0.6
0.8
1.2
1.4
α

Figure 7:

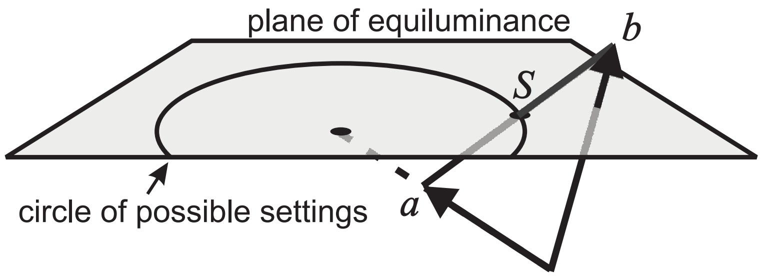

Figure 8:

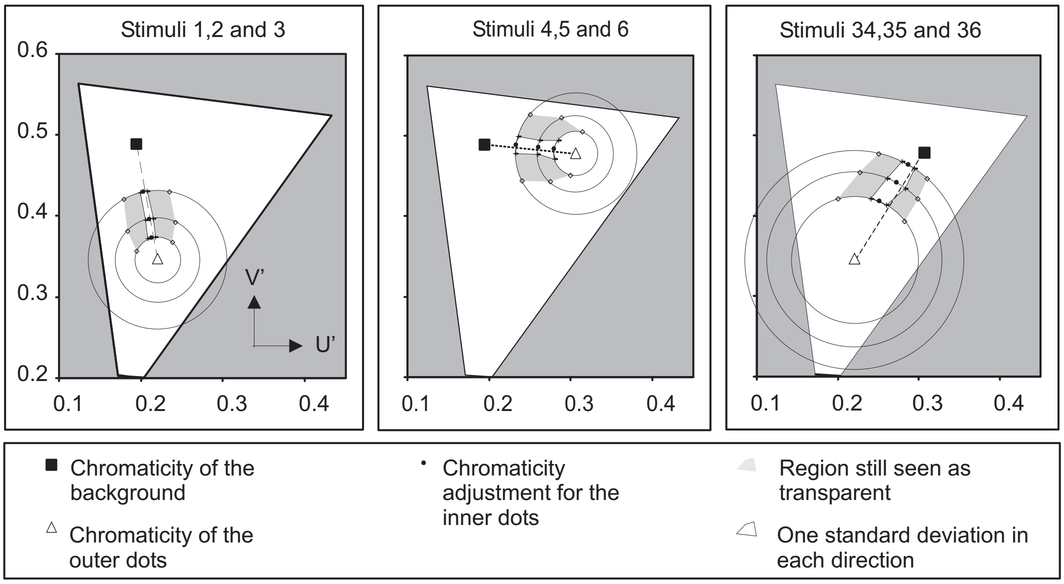
Stimuli 1,2 and 3
Stimuli 4,5 and 6
Stimuli 34,35 and 36
0.6
0.5
0.4
0.3
0.2
0.1
0.2
0.3
0.4
V'
U'
Chromaticity of the background
Chromaticity of the outer dots
Chromaticity adjustment for the inner dots
Region still seen as transparent
One standard deviation in each direction

Figure 9:

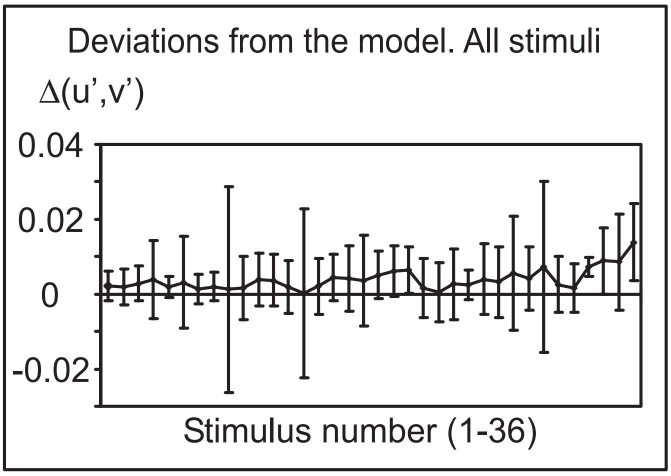
Deviations from the model. All stimuli
Δ(u',v')
0.04
0.02
0
-0.02
Stimulus number (1-36)

Figure 10: