# The influence of chromatic and achromatic variability on chromatic induction and perceived colour

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**Abstract.** Judgments of the colour of a surface are influenced by the colour of the surrounding. To determine whether only the average colour of the surrounding matters, or also the chromatic variability, judgments in colourful scenes are often compared with ones in which a target is surrounded by a plain background that provides the same *average* physical illumination of the retina as the colourful scene. The variability sometimes makes a difference (eg Shevell and Wei, 1998 *Vision Research* **38** 1561–1566), and sometimes it does not (eg Brenner and Cornelissen, 1998 *Vision Research* **38** 1789–1793). Is this because of the nonlinearity in cone responses? We designed scenes that stimulated the cones in an equivalent manner, both on average and in terms of variability, and yet differed markedly in chromatic variability. The more colourful surroundings had considerably less influence on subjects' colour judgments. We conclude that early cone-specific regulation of sensitivity cannot be responsible for the change in perceived colour, and deduce that chromatic induction takes place after contrast gain control.

## 1 Introduction

Placing a grey surface within a green surround makes it look pink. This is known as chromatic induction. Its origin is best understood in relation to colour constancy (Hurlbert 1996; Walraven et al 1987). The colour of a surface is determined by how much light it reflects at each wavelength. However, one cannot directly perceive reflectance. One must infer the reflectance from the light that reaches the eye. Without knowing anything about the illumination, this is impossible (Ives 1912).

Since the same light that illuminates a surface will normally illuminate most of its neighbours, the ratio of stimulation of each kind of cone by light from adjacent surfaces hardly depends on the illumination (Foster and Nascimento 1994). Thus, basing the perceived colour on ratios at the borders between surfaces (Krauskopf 1963; Land and McCann 1971) would result in colour constancy. However, retrieving the reflectance of a surface from such ratios is impossible without making additional assumptions about the surrounding surfaces (D'Zmura and Lennie 1986), such as that their average reflectance is neutral. Subjects appear to compromise between making assumptions about the illuminant and making assumptions about the scene (Brenner and Cornelissen 1991), so that the perceived colour depends both on the illuminant and on the surrounding.

Chromatic induction arises when the colour of the surrounding is incorrectly attributed to the illumination. For instance, if part of the green colour of the surround is attributed to the illumination being greenish, then the fact that the light from the target is not greenish implies that the target surface must be pink (ie it must reflect less green light than red light). Where in the visual pathway the spatial interactions that result in chromatic induction take place is not known. It could be as early as the cone sensitivity being modulated by the activity of cones in neighbouring regions through the activity of horizontal cells (Kamermans et al 1998).

Placing a coloured target within a colourful surround makes it appear to be less saturated. Placing it within a surround in which only the luminance varies does not (Brown and MacLeod 1997). In both cases, the stimulation of each kind of cone is different for different parts of the surround. However, in the latter case the ratio of stimulation of the different types of cones is the same for light from all parts of the surround. In the former case, this ratio varies, which is what gives the surround its colourful appearance. Thus, it must be the variability in cone opponent signals in the surround that is critical. This implies that the underlying spatial interactions take place after the responses from the different kinds of cone have been combined into colour opponent channels.

We now have two spatial interactions that influence the perceived colour: a shift in the balance between signals from different kinds of cones due to a chromatic bias in the surround, and a change in the perceived saturation due to the chromatic variability in the surround. In the present study, we examine how these two effects interact. In particular, we examine how modulating the colour of the surround (figure 1) influences chromatic induction. This will allow us to determine whether the spatial interactions that are responsible for chromatic induction could take place before cone responses are combined in colour-opponent channels. If so, the shift in the neutral point must take place before the change in apparent saturation, so it will not be influenced by how colourful the scene is. To understand this, consider the change in saturation as a form of scaling relative to the neutral point. Chromatic induction is a shift in the neutral point. If the shift is first, the scaling will be relative to the shift takes place after the change the position of that point. In contrast, if the shift takes place after the change in saturation, it is likely to depend on how colourful the scene is.

# 2 Methods

The stimuli were presented on a high-resolution trinitron monitor (39.2 cm  $\times$  29.3 cm; 1280  $\times$  1024 pixels; 72 Hz; 10 bits per gun) in an otherwise dark room. Subjects sat 150 cm from the screen with their chins and foreheads supported. The stimulus consisted of a 2.5 deg  $\times$  2.5 deg target square at the centre of a 7.5 deg  $\times$  7.5 deg surround. The target square had a luminance of 21 cd m<sup>-2</sup> unless mentioned otherwise. The surround always had a mean luminance of 20 cd m<sup>-2</sup>. In some cases the surround was divided into a 20  $\times$  20 array of smaller squares (each subtending approximately 22 min of arc).

The influence of chromatic variability on perceived colour is often evaluated by comparing the appearance of a surface within a structured environment with its appearance within an equivalent surround: a uniform field with the same space-averaged luminance and chromaticity (Brenner and Cornelissen 1998; Brenner et al 1989; Jenness and Shevell 1995; Nascimento and Foster 1997; Shevell and Wei 1998; Valberg and Lange-Malecki 1990). This approach equates the average physical properties of the stimuli that are being compared. Response compression within the cones (Boynton and Whitten 1970) could already lead to different average responses to plain and colourful scenes, because an increase in stimulation in one region will have a smaller impact on the response than a physically identical decrease in another region. We therefore decided to take the notion of equivalent surrounds one step further, and create 'coneequivalent surrounds' (figure 1). These are surrounds that stimulate any given kind of cone with completely equivalent spatial patterns, so that any compression within cone responses is identical, but that differ in the correlation between the patterns for the different cones, so that they differ markedly in their chromatic variability. In this way we avoid having to quantify the compression. We also used a uniform field with the same space-averaged luminance and chromaticity for comparison.

The two authors and two naïve subjects each first set an isolated 7.5 deg  $\times$  7.5 deg, 21 cd m<sup>-2</sup> square to a neutral grey. This was done 20 times, and the average setting



**Figure 1.** The principle of cone-equivalent surrounds. Consider the regions of the surrounds indicated by the ellipses. The bars at the top represent the stimulation of each type of cone (L, M, S) from each of the regions within the ellipse (regions indicated by shading). To make structured surrounds, the stimulation from each region was set to between 8% more and 8% less than that from the plain background (*no modulation*). The precise amount of light from each region was either determined by the same random value for all three cones (*luminance modulation*; here we show values from left to right of -5%, 4%, and 1%) or by a different random value for each cone (*colour modulation*; same values but in different order, so that the leftmost region appears slightly greener, the middle region brighter and more purplish, and the rightmost region darker and redder). For each cone type on its own, the modulations within the scene are identical for the luminance and colour modulations. Only the correlation between the layout of the modulations of the three types of cone is different.

was used as the reference for that subject in all further experiments. We determined the extent to which this reference stimulates each of the three cone types (on the basis of the average spectral sensitivity of human cones; Pokorny and Smith 1986). All colours were subsequently defined in terms of their cone stimulation relative to this reference.

Surrounds differed, both in their average colour and in the way the colour was distributed. The simplest surround was a plain grey field (that subject's reference with no modulation). A greenish surround was obtained by simultaneously increasing the M cone and reducing the L cone stimulation by 0.2 cd  $m^{-2}$  with respect to the grey reference. Conversely, a pink surround was obtained by increasing the L cone and reducing the M cone stimulation by  $0.2 \text{ cd m}^{-2}$ . Blue and yellow surrounds were obtained by respectively increasing and decreasing the S cone stimulation by 0.02 cd m<sup>-2</sup>. Modulation across the 400 squares that formed the surround was achieved by increasing or decreasing the stimulation of each cone by a random amount for each square (figure 1). Luminance modulation was achieved by choosing a single random amount (between -8% and +8%) for each square, and using it for all three cone types. Colour modulation was achieved by choosing a new random amount for each cone type within each square. This results in identical modulation of each type of cone in the two conditions (hence 'cone-equivalent surrounds'), but the latter procedure results in a lower mean luminance modulation and introduces changes in the ratios of stimulation of different cones : colour modulation.

In all four experiments subjects had to judge the colour of the target square. In three of the experiments they simply had to name the colour (Troost and de Weert 1991). They could choose between *greenish*, *grey*, and *pink* in experiments with pink and greenish surrounds, and between *bluish*, *grey*, and *yellowish* in an experiment with blue and yellow surrounds. In the fourth experiment, subjects changed the distribution of luminance across the L and M cones themselves (the total luminance remaining constant). Their task was to find the 'perfect' grey. This nulling task was included to ensure that our findings were not due to some peculiarity of naming.

In the naming experiments, the chromaticity of the target square was varied in a similar manner to that described before for the surround. In the experiments with pink and greenish surrounds, the shift in target chromaticity consisted of simultaneously increasing L and decreasing M cone stimulation, or vice versa. In the experiment with blue and yellow surrounds, it consisted of either increasing or decreasing S cone stimulation. In each case there were 10 values. These were equally spaced either between a shift of 0.15 cd m<sup>-2</sup> in favour of the L cone and a shift of 0.15 cd m<sup>-2</sup> in favour of the M cone, or between a 0.015 cd m<sup>-2</sup> increase and a 0.015 cd m<sup>-2</sup> decrease in S cone stimulation.

## **3** Results

Figure 2 shows the number of times that one subject indicated that the central target field was *greenish*, *grey*, or *pink*, as a function of the physical colour of the target, both for a neutral and for a greenish (colour-modulated) surround. It is evident that a larger range of targets was judged to be pink when the surround was greenish. In order to determine how much the neutral point had shifted between these two conditions, the data for each surround were first transformed into a single curve. This was done by subtracting the number of greenish responses from the number of pink responses, and dividing the result by the total number of responses. This 'response frequency' was determined for each colour of the target square. The resulting curves are depicted with solid symbols in figure 3. We then determined how much the curve representing the responses for the greenish surround had to be shifted horizontally (ie how much the L and M cone stimulation in the centre had to be changed) to match the curve for the neutral surround.



**Figure 2.** Three-choice colour naming data for one subject (AB) in one condition (colour modulation) with two different average surround chromaticities. The neutral value was determined in advance for each subject. The greenish surround provides  $0.2 \text{ cd m}^{-2}$  more M and less L cone stimulation. The number of times that the subject selected greenish, grey, or pink as the most appropriate description for the central target field is shown as a function of its colour. Starting from the way the 2l cd m<sup>-2</sup> target luminance was distributed across L and M cones for the individual subject's neutral value, we made the target redder by increasing L cone stimulation while decreasing M cone stimulation (positive shift), and greener by doing the opposite (negative shift).

The results of the first three experiments are summarised in figure 4. For each kind of surround modulation the figure shows both the total number of 'grey' responses, and the shift in the perceived colour of the target square when the average colour of the surround was changed. The bars show the results of the naming task, and the circles those of the nulling task. To obtain a comparable measure for the nulling task, we determined the difference between the target colour that subjects set for the pink and greenish surrounds, and the colour that they set for the neutral surround.

In the first experiment (bars marked *Shift between L and M cone stimulation* in figure 4) we examined how luminance and colour modulation affect the influence that having a pink or greenish bias in the surround has on the perceived colour of the target (4 subjects, 3 surround colours, 3 surround modulations, 10 centre colours, each presented 20 times). The total number of grey responses increased when colour modulation was introduced into the surround, but not when luminance modulation was introduced. More importantly, there was considerably less chromatic induction with the more colourful backgrounds: smaller shifts in perceived centre colour for colour-modulated surrounds. The shifts are relative to the neutral surround, and are therefore in opposite directions for the pink and greenish surrounds.

In the second experiment, the smaller shifts for colour-modulated surrounds, but not for luminance-modulated surrounds, were confirmed by the results of the nulling task (*circles*; 4 subjects, 3 surround colours, 3 surround modulations, each set 5 times). In the third experiment (bars marked *More or less S cone stimulation* in figure 4) this was also found to be so for blue and yellow surrounds (3 subjects, 3 surround colours, 3 surround modulations, 10 centre colours, each presented 10 times). The smaller number of grey responses in this experiment is due to the smaller total number of responses.

In the first three experiments the luminance of the centre was  $21 \text{ cd m}^{-2}$ , 5% brighter than the surround. In the fourth experiment we examined whether this rather arbitrary choice was important. The experiment was similar to the first, but target luminance could be 16, 19, 20, 21, or 24 cd m<sup>-2</sup>, corresponding to contrasts with the mean luminance of the surround of -20%, -5%, 0%, 5%, and 20%. To limit the number of responses, we used only pink and greenish surrounds, and they were always modulated. Figure 5 shows the results of the fourth experiment (4 subjects, 5 luminance values, 2 surround colours, 2 surround modulations, 10 centre colours, each presented 10 times). The shift in the perceived colour of the target square was now determined for the pink surround relative to the greenish one, rather than each relative to the

match neutral surround our stimulus we generated semicontinuous curves by linear interpolation between adjacent points. Data from figure 2. our stimulation from figure 4. For each modulation the figure shows both the total number of 'grey' responses, the perceived colour of the target square when the average colour of

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Figure 3. Quantifying the shift in the responses when the average colour of the surrounding was changed. The three response categories were first combined into a single *response frequency* curve. We then determined how far the curve for a chromatically biased surround has to be shifted along the target-colour axis to match the curve for a neutral surround. The best match was defined as the one with the smallest squared vertical difference between the two curves. In order to evaluate smaller shifts than the steps in our stimulus we generated semicontinuous curves by linear interpolation between adjacent points. Data from figure 2.



**Figure 4.** Average results of all subjects. Subjects more often considered the target to be grey and were less susceptible to chromatic biases in the surround in the *colour-modulation* condition. This was so both for shifts along the L-M axis and for changes in S cone stimulation. The reduced susceptibility to chromatic biases in the surround in the *colour-modulation* condition was evident in both the naming task (bars) and the nulling task (circles). The increased number of grey responses in the same condition suggests that the smaller shift (ie reduced chromatic induction) may even be a consequence of the surround appearing to be less saturated. Error bars are between-subject standard errors.

neutral surround. A 20% change in mean luminance contrast between target and surround increased the number of grey responses (ie made the target appear less saturated) when luminance was modulated. Chromatic induction also decreased when the mean luminance contrast between target and surround was increased, but the difference between luminance and colour modulation remained.

# 4 Discussion

Our main finding is that there is less chromatic induction from a colourful surround than from a uniform surround of the same average luminance and chromaticity, or from a surround of the same average luminance and chromaticity that is modulated in luminance. This was not specific to certain colours, ways of measurement, or relative luminances. Thus the presence of chromatic variability in a scene matters.

The main conclusion we can draw from this is that chromatic induction cannot be the result of independent regulation of sensitivity within each class of cone (von Kries 1905; Hood 1998) as is proposed in many models of colour constancy (eg Bäuml 1999; Land 1983; Land and McCann 1971). If cone sensitivity were regulated exclusively by stimulation of the same type of cones, then the shifts in sensitivity would have been identical for our colour and luminance modulations, because they are completely equivalent for each cone type alone.

This conclusion hardly helps us localise the neural mechanisms involved, because even the very first spatial interactions—those mediated by connections between cones



**Figure 5.** Average results of the same 4 subjects for various target luminances. Luminance is expressed as the difference with respect to the mean value for the surround (5% brighter is the same as in the other experiments).

and horizontal cells—do not appear to be cone-specific (Dacey 1996; Lee 1996; Wässle et al 1989). However, the lack of effect of luminance modulation on chromatic induction suggests that the shift takes place after chromatic opponency (Krauskopf et al 1986). Luminance modulation maintains the ratios of stimulation of the different types of cones, so that chromatic opponency is not affected. The fact that luminance modulation has the same influence on chromatic induction as no modulation (figure 4) therefore suggests that chromatic induction takes place within chromatic opponent channels.

There was less chromatic induction when the surround was more colourful. As explained in section 1, this suggests that the shift in the neutral point takes place after the change in saturation. Thus the comparisons across space that are responsible for chromatic induction appear not only to take place after the local comparison between the different types of cones, but even after such comparisons have been scaled to suit the range within the scene (Brown and MacLeod 1997).

From a functional perspective we interpret chromatic induction to be a failure of colour constancy: an error that arises when a bias in the light arriving from surrounding surfaces is incorrectly interpreted as being due to a bias in the illuminant (Walraven et al 1987). Intuitively, we expect it to be easier to distinguish between biases in reflectance and biases in illumination when the scene is more complex. Highlights from shiny surfaces, mutual reflections, and light reflected from familiar objects, could all help make this distinction. Increased chromatic variability, however, can only help in combination with additional knowledge about likely spectral distributions of surfaces and illuminations (D'Zmura and Lennie 1986). An alternative consideration is that if a scene is very colourful it is more likely that the direct surrounding of the target will be strongly chromatically biased. Perhaps that is the reason that in such cases our visual system gives less weight to the colour of the surrounding.

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