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Chromatic induction and the layout of colours within a complex scene

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Abstract

A target's apparent colour is influenced by the colours in its surrounding. If the surrounding consists of a single coloured surface, the influence is a shift 'away' from the surface's colour. If the surface is more than 1° from the target area the shift is very small. If there are many surfaces, then not only the average luminance and chromaticity of the surfaces matters, but also the chromatic variability. It is not yet clear whether it makes any difference where the chromatic variability is within the scene, so we constructed stimuli in which the chromatic variability was restricted to certain regions. We found that it made very little difference where the chromatic variability was located. The extent to which the average colour of nearby surfaces influences the apparent colour of the target seems to depend on the average chromatic variability of the whole scene.

Keywords: Colour vision; Background colour; Colour opponency; Simultaneous colour contrast; Contrast gain control

1. Introduction

Since Land and McCann's fascinating demonstrations of how loosely the apparent colour of a surface is related to the light reaching the eye from that surface (e.g. Land & McCann, 1971) there has been a lot of interest in the way in which the colours within a scene influence a target surface's apparent colour. Much of this interest has been directed at the way in which a bias in the chromatic content of the surrounding shifts the perceived colour (e.g. Bäuml, 1999; Cornelissen & Brenner, 1995; Hurlbert, 1996; Land, 1983; Walraven, Benzschawel, & Rogowitz, 1987; Webster, Malkoc, Bilson, & Webster, 2002).

Despite the large number of studies concerned with this topic there is still controversy about quite fundamental aspects of chromatic induction, such as whether only the average chromaticity matters (supported by Brenner & Cornelissen, 1998; Brenner, Cornelissen, & Nuboer, 1989; Valberg & Lange-Malecki, 1990) or also the amount of chromatic variability in the scene (supported by Barnes, Wei, & Shevell, 1999; Jenness & Shevell, 1995; Shevell & Wei, 1998). Support for the latter view was recently obtained by combining a chromatic bias with either luminance variability or with both luminance and chromatic variability in the surrounding (Brenner & Cornelissen, 2002). There was a clear influence of the chromatic variability, despite the fact that both the average level and the variability of the stimulation of each kind of cone had been equated. This finding was combined with evidence that more chromatic variability makes surfaces look less saturated (Brown & MacLeod, 1997) to lead to the conclusion that cone-opponent responses are scaled to the range within the scene before the shift due to the chromatic bias in the surrounding takes place (Brenner & Cornelissen, 2002).

In the present study we examine whether the reduction in the magnitude of chromatic induction due to the scaling of cone-opponent responses (Barnes et al., 1999; Brenner & Cornelissen, 2002) is strongest when the variability is near the target. It is known that chromatic induction is primarily determined by the colour of

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directly adjacent surfaces (e.g. Brenner & Cornelissen, 1991; Jameson & Hurvich, 1961; Kirschmann, 1891; Walraven, 1973; Yund & Armington, 1975). This is consistent with the idea that information at the borders is critical in determining the perceived colour (Krauskopf, 1963). Relying on the ratio between the stimulation of the same kind of cone at both sides of a surface's borders provides a simple way to achieve approximate colour constancy (Brenner & Cornelissen, 1991; Foster & Nascimento, 1994; Foster et al., 1997; Land, 1986; Land & McCann, 1971; Nascimento & Foster, 1997). However more distant surfaces can also influence the perceived colour. Eye movements and cone adaptation could mediate some such global interactions (Cornelissen & Brenner, 1991, 1995; Lennie & D'Zmura, 1988). Other global interactions may be mediated by the above-mentioned scaling of cone-opponent responses. For that to be so, however, all chromatic variability in the scene would have to influence the scaling, rather than primarily the variability of the adjacent surfaces. We here examine whether the reduced chromatic induction in scenes with more chromatic variability depends on the layout of the colours within the scene.

2. Experiment 1

As in the previous study (Brenner & Cornelissen, 2002), we ensured that the stimuli were equivalent until the colour-opponent stage of visual processing. This was achieved by always stimulating the three types of cones with a similar spatial pattern of modulation. The only difference between the conditions is the extent to which these patterns are correlated between the cones (Fig. 1A). If the pattern of modulation is chosen at random for each type of cone (*100% independent modulation*) the background looks colourful (Fig. 2A). If the same pattern of modulation is used for all three types of cones (*0% independent modulation*) the background appears to have lighter and darker patches of a single colour (Fig. 2B). If part of the modulation is common to the three cone types, while the rest is chosen independently for each type of cone, we get intermediate levels of luminance and colour modulation.

In order to study the importance of the layout of the scene we compared two conditions in which the surround gradually changed from 0% to 100% independent modulation. In one case there was 0% independent modulation near the target and 100% independent modulation at the periphery (Fig. 2C). In the other case there was 100% independent modulation near the target and 0% independent modulation at the periphery (Fig. 2D). If the average colour modulation within the scene is critical (for the magnitude of chromatic induction for a given average chromatic bias in the surrounding) then these conditions should both have the same effect as a condition with 50% independent modulation throughout. If the maximal colour modulation within the scene is critical they should both be similar to the 100% independent modulation condition. If only the modulation near the target is important the two gradients should have very different effects.

2.1. Methods

The stimuli were presented on a high-resolution trinitron monitor (39.2 × 29.3 cm; 1280 × 1024 pixels; 72 Hz; 10 bits per gun) in an otherwise dark room. Subjects sat 80 cm from the screen with their chin and forehead supported. The stimulus consisted of a 5° target square at the centre of a 14° by 14° background (Fig. 1B). The background consisted of an array of 42 by 42 squares (each subtending approximately 20 min of arc). There were 21 different kinds of background (see below), which differed only in the luminance and chromaticity of the latter squares. All colours were defined in terms of the extent to which they stimulated each type of cone differently than did a grey reference. The grey reference (CIE $X = 0.28$, $Y = 0.29$) was chosen on the basis of the average of what 12 subjects considered a perfect grey in

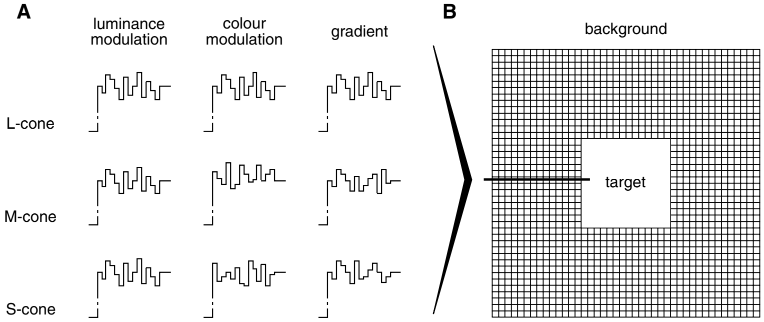

Fig. 1. Schematic representation of the stimulus configuration (B) and of the stimulation of each kind of cone by three kinds of modulation (A). Each figure in A shows the level of stimulation of one cone type as one moves along the thick line in B. The three kinds of modulation that are shown are *luminance modulation* (the three cones vary together), *colour modulation* (the three cones vary independently) and a *gradient* with colour modulation near the central target and luminance modulation at the periphery.

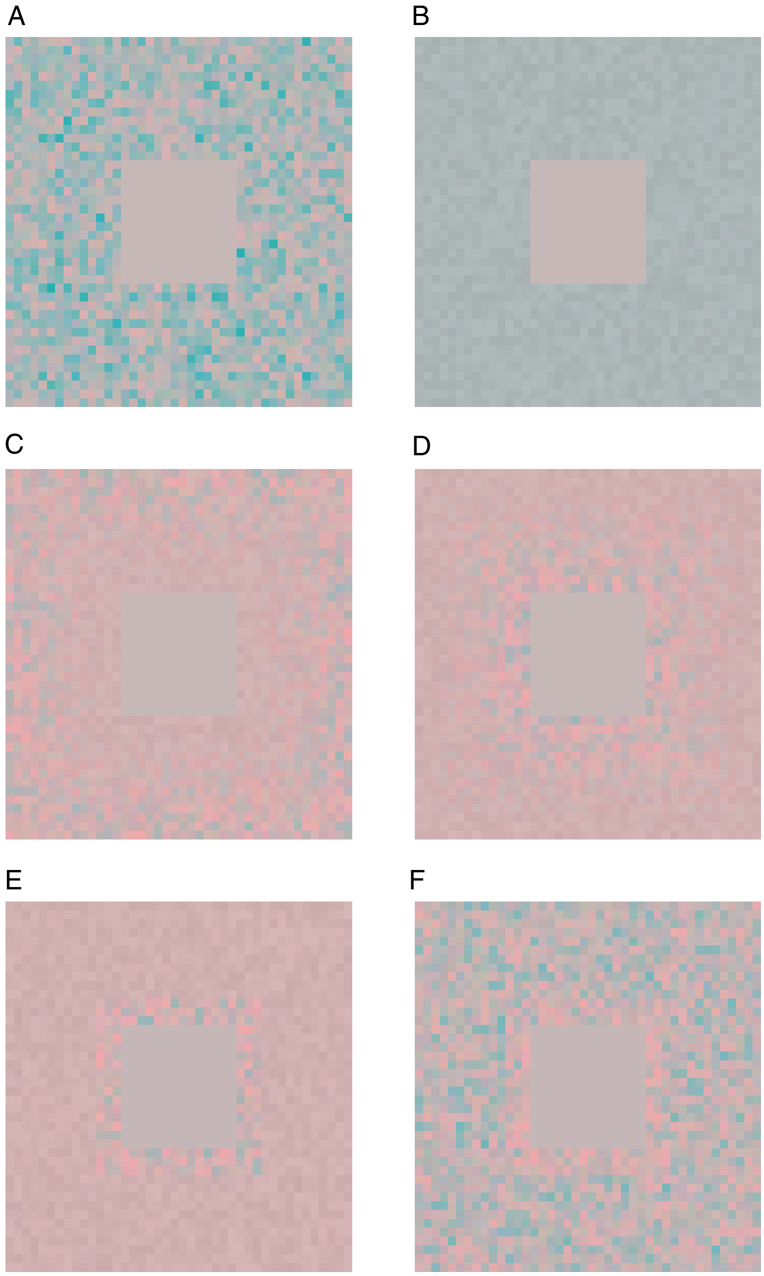

Fig. 2. Reproductions of some of the stimuli that we used. (A) Green bias; 100% independent modulation; Experiment 1. (B) Green bias; 0% independent modulation; Experiment 1. (C) Red bias; gradient with 0% independent modulation near the target and 100% independent modulation at the periphery; Experiment 1. (D) Red bias; gradient with 100% independent modulation near the target and 0% independent modulation at the periphery; Experiment 1. (E) Red bias; three rings with 100% independent modulation near the target; rest 0% independent modulation; Experiment 2. (F) Three rings with red bias near the target; 100% independent modulation; Experiment 2. (The targets for these reproductions were all set to the reference grey.)

an earlier study. The method that was used to find these values is described in a previous paper (Brenner & Cornelissen, 2002) and in the *reference* section of Experiment 2. The extent to which light from each surface stimulates each of the three cone types was determined on the basis of published average relative spectral sensitivity functions of human cones (Pokorny & Smith, 1986, Chap. 8).

2.1.1. The backgrounds

The background had a mean luminance of 20 cd/m^2. Backgrounds differed both in their average colour and in the way the colour was distributed across the small squares. The average colour could be grey (the reference), or it could be biased towards green (0.2 cd/m^2 more M cone and less L cone stimulation than the reference) or towards red (0.2 cd/m^2 more L cone and less M cone stimulation than the reference). These biases correspond with shifts in CIE X–Y-space of only about 0.02 for the green (Fig. 2A and B) and 0.03 for the red (Fig. 2C and D) backgrounds.

Each of the three average colours could be distributed across the individual squares in one of seven ways. Starting with the average colour, each square's colour was determined by increasing or decreasing the stimulation of each kind of cone by a random amount between −6.1% and +6.1%. The only difference between the distributions was in how the increase or decrease differed between the three types of cones.

Five of the seven distributions only differed in the percentage of modulation that was determined independently for the three kinds of cones. The possibilities ranged from 100% independent modulation (a new random increase or decrease was determined for each cone type for each square; Fig. 2A; *colour modulation* in Fig. 1A) to 0% independent modulation (the same random increase or decrease was applied to all three cone types for each square; Fig. 2B; *luminance modulation* in Fig. 1A). In the intermediate cases (75%, 50% and 25% independent modulation), part of the increase or decrease was determined for all three types of cones simultaneously, while the remaining increase or decrease was determined independently for each cone. This was the case for each square. Thus 50% independent modulation means that half of the modulation for each square is determined independently for each of the three cone types, whereas the remaining half of the modulation is common to all three cone types.

The last two distributions consisted of linear gradients in the extent to which the increase or decrease differed for the three types of cones. In one case the background looked colourful at the edges, but the colours 'faded' toward the centre, leaving only luminance modulation near the target (Fig. 2C). This was achieved by applying the same random increase or decrease to all three cone types for the rows of squares nearest to the target (*0% independent modulation*), and a new random increase or decrease for each cone type for those furthest from the target (*100% independent modulation*). For the rings of squares between these extremes the percentage of independent modulation was a linear function of the position between the nearest and furthest rings. In the second case the gradient was reversed, so that the background looked colourful near the target but the colours 'faded' into luminance variability toward the periphery (as in the *gradient* column in Fig. 1A; see Fig. 2D).

2.1.2. The target

The target square's luminance was 21 cd/m^2. The colour of the target was changed by simultaneously increasing L and decreasing M cone stimulation by exactly the same amount, or decreasing L and increasing M cone stimulation by exactly the same amount, with respect to the grey reference. Neither the luminance nor the S cone stimulation ever changed. The deviation of both cones' stimulation from the grey reference could be up to 0.45 cd/m^2.

2.1.3. Subjects and procedure

Twenty-six subjects with normal colour vision, including three of the authors, took part in the experiment. Other than the authors, none of the subjects had any idea of the purpose of the experiment. After dark-adapting for 10 min subjects each made 210 settings (21 kinds of background, each presented 10 times). The 210 trials were presented in random order. A new background was generated for each trial. Subjects were asked to set the target so that it would appear grey. They were told that if they could not find a setting that looked a perfect grey they should set the target to appear neither reddish nor greenish. They could change the target's colour by moving the computer mouse. They indicated that they were content with the set value by pressing a button. Once they did so a new stimulus appeared. The initial colour of the target was determined at random from within the range that they could set (see previous section). Subjects were not instructed to fixate the target, but we expect them to direct their gaze at it most of the time anyway (Cornelissen & Brenner, 1995).

2.1.4. Analysis

We first determined the median value of each subject's settings for each of the 21 background conditions. To obtain a measure of how the average colour of the background influenced what was perceived as grey, we calculated the difference between the values for backgrounds with red and green biases. This was done separately for each subject and for each of the seven distributions of colours within the background. Paired t-tests were used to evaluate specific hypotheses regarding the influence of the distributions of colours within the background.

2.1.5. Checking the monitor

Aside from carefully calibrating the centre of the monitor, we also checked for spatial interactions within the stimulus presentation by asking six subjects to repeat the experiment with the same stimuli on the screen but with black cardboard exactly covering the background so that only the target was visible. Under these conditions the differences between mean settings for red and green biased backgrounds were unsystematic (no significant differences across the six subjects for any of the distributions of variability in cone stimulation) and were all between −0.02 and +0.04 cd/m^2.

2.2. Results

The set values for the grey average backgrounds were expected to be the same for all distributions. This was not the case. On average, subjects systematically set the target "greener" than the reference that we had chosen. In most cases they set it to give between 0.04 and 0.06 cd/m^2 less L cone stimulation. However, when there was only luminance modulation in the grey background they set it to give 0.01 cd/m^2 less L cone stimulation. For the gradient with luminance modulation near the target, they set an intermediate value. The fact that, on average, subjects set a different value than we had chosen just means that our choice of reference was not perfect for these subjects. However the fact that they set values closer to the reference when there was no chromatic modulation near the target makes us doubt the validity of the settings with the unbiased background. It suggests that subjects matched the target's colour to that of the adjacent grey background. If so, determining the influence of each bias with respect to the grey background would incorrectly indicate that there is a systematic difference between the two colours. We circumvent this issue by using the difference between the values for the backgrounds with the red and green biases as our measure of chromatic induction, rather than reporting the influences of the two biases separately.

Fig. 3 shows the difference between the set target colour for the two chromatically biased backgrounds as a function of the amount of modulation that was chosen independently for the three cone types. A higher percentage of independent modulation means that the background has more chromatic variability. The symbols show the values for the seven distributions of colours within the background. The circles are for the five uniform distributions, and are connected by lines for clarity. As predicted, there was less chromatic induction (a smaller *shift in perceived colour*) when there was a lot of chromatic variability (large percentages of independent modulation) than when there was not (little independent modulation). This effect was gradual, with possibly a threshold level of chromatic variability.

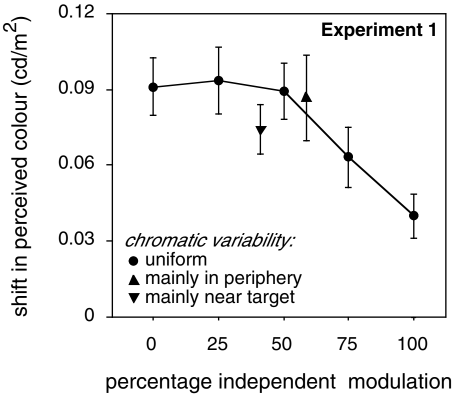

Fig. 3. Average increase in L cone stimulation from the target when settings are made with a reddish rather than a greenish background, as a function of the percentage of the modulation that was independent for the three cone types (with the 26 subjects' inter-subject standard errors). 0% independent modulation means that only luminance is modulated. 100% independent modulation gives the maximal colour modulation. Circles: uniform distribution of modulation across the background. Triangles: gradient between 0% independent modulation for squares at the periphery and 100% independent modulation for ones near the target (triangle pointing downwards), or 0% independent modulation at the target and 100% independent modulation near the periphery (triangle pointing upwards).

The triangles are for the two gradients. Their horizontal positions correspond with their space-averaged percentages of independent modulation. These are not exactly 50%, because there are more squares in the outer rings than in the inner rings. (These percentages refer to the area on the screen. The inner rings may well stimulate more cones when subjects look at the target.) If the region directly adjacent to the target had dominated the influence of colour modulation on the perceived colour, we would expect the two gradients to have very different effects. The gradient with colour modulation in the periphery would have about the same effect as 0% independent modulation, while the gradient with colour modulation near the target would have about the same effect as 100% independent modulation. We found no such difference. The shifts for the two gradients did not differ significantly from each other ($p = 0.34$). Moreover both did differ from the condition with 100% independent modulation ($p = 0.0003$ and $p = 0.0012$ for modulation near the target and at the periphery, respectively). The latter finding implies that it is unlikely to be the maximal colour contrast in the scene that is critical. For neither of the gradients was the shift different from that with 50% independent modulation, suggesting that the average modulation may be critical.

2.3. Discussion

It appears that the influence of chromatic variability is not limited to a certain region of the scene, but that the average colour contrast within the scene determines the magnitude of chromatic induction. This could explain why increasing the number of similarly coloured surrounding fields hardly influences a target's apparent colour (Brenner et al., 1989; Valberg & Lange-Malecki, 1990; Wachtler, Albright, & Sejnowski, 2001), while adding fields with more chromatic variability does (Barnes et al., 1999; Shevell & Wei, 1998). It also explains why extending a uniform background beyond 1° does not change the amount of chromatic induction (Brenner & Cornelissen, 1991; Brenner et al., 1989), while adding other colours beyond this range does (Wachtler et al., 2001).

3. Experiment 2

The shift for the gradient with colour modulation near the target did appear to be smaller than both that for the other gradient and that for 50% independent modulation. This was not significant, and even if it had been this could have been due to the fact that we did not consider the retinal cone density when calculating the average modulation. However we found this enough reason to try again with a more extreme difference between the two spatial distributions. Moreover, in order to be able to present exactly the same stimuli to all our subjects we had used a single shade of grey as the reference for all our subjects. In order to make sure that the choice of grey is not critical (in particular since it was probably not entirely appropriate for the subjects of the first experiment) we let each subject set his or her own reference in the second experiment. Note that this means that the stimuli now differed slightly between subjects. In the second experiment we also tried to confirm that even if the scene is colourful, extending the chromatic bias beyond 1° will not increase the magnitude of chromatic induction.

3.1. Methods

The equipment and general procedures were identical to that of the first experiment. The only differences were that subjects now set their own grey reference, and that we had four new kinds of backgrounds. Twelve subjects took part in the experiment, half of whom had also taken part in the first experiment, including two of the authors.

3.1.1. The reference

Before we started the real experiment we asked the subjects to set an isolated 14°, 21 cd/m^2 square to appear grey. They changed the square's colour (but not its luminance) by moving the computer mouse. Moving the mouse laterally changed the proportion of stimulation of L and M cones. Moving it in depth changed the S cone stimulation. Subjects could set any colour that could be rendered (at this luminance) on the computer screen. They indicated that they had found a satisfactory colour by pressing a button. This was done 20 times, and the average setting was used as the reference for that subject. The values differed slightly from the reference in the first experiment: $X = 0.29$ (SD = 0.01); $Y = 0.30$ (SD = 0.01).

3.1.2. The background

As in the first experiment, we first determined the extent to which the reference stimulates each of the three cone types (Pokorny & Smith, 1986, Chap. 8). Since the reference was different for each subject, this was now done separately for each subject. All other colours were defined by changing the stimulation of specific cones relative to these values. Thus all the colours on the screen were influenced by the initial grey settings, but most of their relationships were not. The value of 6.1% for the maximal variability in cone stimulation in the background during the first experiment was the largest value that could be applied in all conditions (for the fixed reference of that study) without exceeding the range that we could present on the screen. We now determined the maximal variability that we could use on the basis of each subject's individual reference. These values ranged from 5.1% to 7.3% (mean = 6.5; SD = 0.7).

There were four kinds of backgrounds. The first was identical to the luminance modulated background of the first experiment (0% independent modulation), but the three most peripheral rings of squares were modulated in colour (100% independent modulation). In the second kind of background the three rings of squares nearest to the target were modulated in colour instead (Fig. 2E). In both cases the average colour of the background could be the subject's individually chosen shade of grey, or it could be biased towards green (0.2 cd/m^2 more M cone and less L cone stimulation than this grey) or towards red (0.2 cd/m^2 more L cone and less M cone stimulation than this grey; Fig. 2E). The third and fourth kinds of backgrounds were colourful throughout (100% independent modulation). Their average colour was grey except for either the three rings of squares nearest to the target (covering about 1° of visual angle from the target), or the three most peripheral rings of squares, which could be biased towards red (Fig. 2F) or green. The four kinds of background and the three biases were each presented 10 times, in random order.

3.2. Results

When the average colour of the surrounding was grey, subjects set a colour that was close to what they had chosen as their reference. The deviations from the reference were about half of what they were in the first experiment. However subjects still set a colour that was closer to the reference when the squares near the target were all grey (colour modulation in the three most peripheral rings) than when they were not (all other conditions). It seems that subjects minimise the colour contrast at the target's borders if the background looks grey, which is not too unreasonable.

The symbols in Fig. 4 show the shift between the set target colour for the two chromatic biases. The triangles are for the different regions of colour modulation. Their horizontal positions correspond with the space-averaged percentages of independent modulation. Again there was a tendency for the shift to be smaller when the

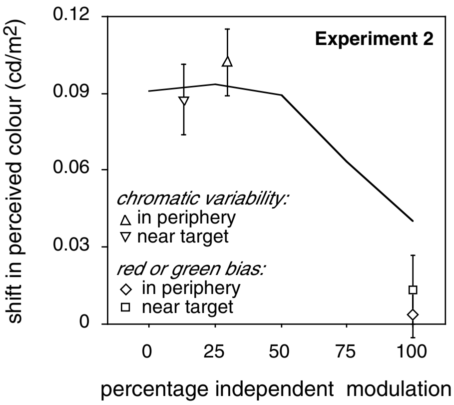

Fig. 4. Average increase in L cone stimulation from the target when settings are made with a reddish rather than a greenish background, as a function of the percentage of the modulation that was independent for the three cone types (with the 12 subjects' inter-subject standard errors). The line from Fig. 3 is also shown for comparison. Triangles: 0% independent modulation in all but the three rings of squares nearest to (triangle pointing downwards) or furthest from (triangle pointing upwards) the target, which have 100% independent modulation. Square and diamond: 100% independent modulation throughout, but only the inner (square) or outer (diamond) three rings of squares are reddish or greenish (the average chromaticity of the rest is grey).

colours were adjacent to the target, but again the difference was small and was not consistent across subjects ($p = 0.24$). The magnitude of the shift was similar to that for a background with the same space-averaged percentage of independent modulation in the first experiment.

The diamond and square in Fig. 4 show the shifts caused by the rings of chromatic bias. When only the most peripheral rings were biased the colour of the bias was clearly irrelevant (shift close to zero). When the rings near the target were biased there appears to be a shift, but it is not consistent across subjects, and it is considerably smaller than the shift that we had found when the whole background was biased in Experiment 1 (indicated by the height of the line at 100% independent modulation). Whether the bias was in the rings nearest the target or furthest from the target did not influence the magnitude of the shift consistently across subjects ($p = 0.54$).

3.3. Discussion

The second experiment confirms that it is not very important where in the background the colours are varied. The magnitude of chromatic induction (the "shift in perceived colour" in Fig. 4) is no larger when there is maximal colour modulation right next to the target than when it is as far away as possible, or when there is a lower level of modulation throughout (Experiment 1). Altogether, if we assume that we can compare the values across the two experiments, we can conclude that the ring of colour modulation has very little effect. This implies that not only surfaces near the target matter. Whether the layout is completely irrelevant remains to be demonstrated, but it is clear that our impression from the first experiment that the main factor is the average level of colour modulation is correct.

A more surprising finding is that a chromatic bias in a 1° ring surrounding the target results in so little chromatic induction. This is inconsistent with the notion that only the average colour within 1° of the target's border matters (Brenner & Cornelissen, 1991; Brenner et al., 1989). However, it does not necessarily demonstrate that the *average* chromaticity of more distant areas matters. The lack of consistent chromatic induction could be caused by the fact that the localised bias adds substantial colour contrast to the scene, because of the change in colour at the border between the biased and the unbiased region. It could be this increase in chromatic variability that reduces the shift so dramatically. To get an impression of whether this additional contrast could be responsible for the reduced magnitude of chromatic induction we estimated the maximal physical contrast in our stimuli. We did this by determining the largest and smallest L–M cone ratio that could be present in each kind of background (we assumed that we could ignore S cone variability; Barnes et al., 1999). The difference between the two is our estimate of the maximal colour contrast.

If we compare the estimated maximal colour contrast for the *localised* bias in the second experiment with that for the different percentages of independent modulation in the first experiment, we see that the latter would have to have 116% *independent modulation* for it to have the same contrast. Shifting the square in Fig. 4 to this value places it close to an extrapolation of the line. Thus if the maximal contrast had been critical, the reduced influence of the bias when it was limited to a narrow ring could have been attributed to the increased chromatic variability at the border of the biased region. However, we already know from Experiment 1 that it is not the *maximal* contrast that is critical, but some kind of *average* colour contrast.

The average colour contrast of our uniform chromatic modulation is about a quarter of the maximal colour contrast. The influence of the localised bias on the average colour contrast depends on which contrasts are averaged. If the contrasts between adjacent squares are averaged then the influence of the border of the localised bias will be less than 10% of its influence on the maximal contrast. On the other hand, if all possible contrasts between squares are averaged then the average contrast will be about a third of the maximal contrast. In the former case the reduced shift could not be attributed to the additional chromatic variability at the border of the biased region, but in the latter case it could.

4. General discussion

We found smaller shifts in perceived colour when there was more colour modulation within the scene (high percentages of independent modulation). This confirms that the influence of the average colour of neighbouring surfaces (on the apparent colour of a surface of interest) is small if the scene contains a lot of variation in colour. Where the chromatic variability is within the scene hardly seems to make a difference. The critical factor cannot be the range of cone ratios within the scene, because a small area with chromatic variability (triangles in Fig. 4) is much less effective than a large one (circle at 100% independent modulation in Fig. 3). It is also unlikely to be the space-averaged level of chromatic modulation, because all previous studies agree that increasing the number of edges in the background does not necessarily decrease the magnitude of chromatic induction (Barnes et al., 1999; Brenner et al., 1989; Valberg & Lange-Malecki, 1990; Wachtler et al., 2001).

Could the average chromatic contrast at detectable borders be critical? The vertical separations between the solid circles on the right side of Fig. 3 suggest that increasing the chromatic variability of the background even further would have reduced the magnitude of chromatic induction even more. In the discussion of Experiment 2, we suggested that an increased range of colours might be the reason why the ring of chromatic bias surrounding the target gave rise to so little chromatic induction (square in Fig. 4). If the average chromatic contrast at detectable borders were critical we would not have expected the border with the bias to have had so much effect, because only the borders at the edge of the biased area have a higher chromatic contrast. However, the variability may not be related to the borders at all. Moreover, the spatial scale of the contrasts may also matter. Barnes et al. (1999) found the strongest influence when the surrounding surfaces were the same size as the target. Our surrounding squares were much smaller than the target, and the bias was three squares wide, which may have given the contrast caused by the bias a stronger influence.

The positions of the circles in Fig. 3 suggest that there is a threshold below which increasing the colour contrast does not make a difference (this can also be seen in Fig. 6 of Barnes et al., 1999). This may have to do with the colour contrast at the edge of the target itself. If subjects set the target to the reference colour, the difference in L–M cone ratio between the target and the (reddish or greenish) background is about equal to the maximal ratio between the background squares for 20% independent modulation, or the average ratio between the squares for 70% independent modulation. Thus in some of our stimuli with little chromatic variability, the chromatic contrast at the target's border (and at the edge of the background) is larger than the chromatic contrast between the background squares. However here again it should be noted that the edges of the target and background are only a small proportion of the borders.

If all borders contribute to the scaling of chromatic contrast then adding borders with no chromatic contrast (luminance modulation) should decrease the average chromatic contrast at detectable borders considerably. We know that having or not having luminance contrast borders in the scene makes no difference for the magnitude of chromatic induction (Brenner & Cornelissen, 2002). This suggests either that average values of chromatic contrast below that between target and background are not effective (which would explain the above-mentioned apparent threshold) or that only the average chromatic contrast of borders that involve a change in colour matter. We are not yet able to distinguish between such possibilities.

In summary, we can explain all our data and much of the previous controversy about the spatial characteristics of chromatic induction by assuming that chromatic induction arises from local spatial interactions between cone-opponent signals that have been scaled by a global measure of the chromatic variability within the scene.

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