Cone contributions to colour constancy

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Abstract. Colour constancy refers to the stable perception of object colour under changing illumination conditions. This problem has been reformulated as relational colour constancy, or the ability of the observer to discriminate between material changes and changes in illumination. It has been suggested that local cone excitation ratios play a prominent role in achieving such constancy. Here we show that perceptual colour constancy measured by achromatic adjustments is to a large part complete after 25 ms. This speaks against a prominent role for receptor adaptation, which takes significantly longer. We also found no difference in colour constancy between colour changes that were compatible with a change of illuminant, and between colour changes where local cone ratios were uncorrelated between the two illuminants. Our results show that constant cone ratios are not necessary for colour constancy.

1 Introduction

The colour of an object, when part of a complex scene, is determined not only by its spectral reflectance, but also by the colours of all other objects in the scene (Helmholtz 1867; Ives 1912; Land 1959). By taking global colour information into account, the visual system is able to maintain constancy of the object's colour appearance, despite large variations in the light incident on the retina that arise from changes in the spectral content of the illuminating light (Hurlbert 1998; Maloney 1999). The neural basis of this colour constancy is, however, poorly understood. While there seems to be a prominent role for retinal, cone-specific adaptation mechanisms (von Kries 1902/1970; Pöppel 1986; Foster and Nascimento 1994), the contribution of cortical mechanisms (Land et al 1983; D'Zmura and Lennie 1986; Clarke et al 1998; Rüttiger et al 1999) to colour constancy is still unclear.

The most prominent models use the von Kries principle and are based on cone response scaling. This results in a desensitisation to the spectral components that are predominant in an illuminated scene. In colour-constancy experiments, this means that an observer's achromatic settings under different illuminants are related by a transformation with a diagonal matrix, when colour coordinates are expressed in cone space. Although this often gives a satisfying description of the data (Brainard and Wandell 1992; Bäuml 1999) it does not necessarily imply a physiological mechanism acting at the cone level. In a more general von Kries concept, the scaling could also take place at a higher level, even in cortical areas (Cornelissen and Brenner 1995).

Whereas chromatic adaptation in principle acts locally, there are interactions between adjacent regions of the visual field which regulate sensitivity. Kirschmann (1891) recognised this and classified chromatic-induction phenomena into successive and simultaneous contrast. The significance of contrast for colour-constancy phenomena was recently shown by Kraft and Brainard (1999). They examined achromatic matching under nearly natural viewing conditions in a Ganzfeld setting. With systematic variations

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of the stimulus configuration, they showed that contributions of local and global contrasts to colour constancy can be separated. Similarly, we have shown that different processes involved in colour appearance can be distinguished by examining the time course of colour appearance after changing illuminants (Rinner and Gegenfurtner 2000). We identified a rapid process that is probably not based on local adaptation but rather on higher-order computation of global contrast in a scene. Also, two slower adaptational processes were identified, which could be based on local (cone) adaptation.

There is another class of cone-based models which does not use adaptive processes but rather exploits the intrinsic constancy of cone excitation ratios under varying illumination (Foster et al 1997). Foster and Nascimento (1994) simulated the cone ratios for two adjacent surfaces a and b under changing illumination. It turns out that absolute cone excitations vary largely but the cone ratios L_a/L_b, M_a/M_b, and S_a/S_b remain virtually invariant. The same argument can be applied to a single surface under temporarily changing illuminants. The idea behind this concept is to use this constant signal to achieve colour constancy. But there are difficulties in testing the effect of this cone excitation ratio with appearance matches, the classical paradigm in colour constancy research. The natural experiment would be to present two scenes where the correlation between cone excitation ratios is manipulated and to look for effects of this manipulation on colour constancy, for example with achromatic matches. The problem with these appearance matches is that under steady-state conditions each scene stands for its own and there is no direct connection per se between the different scenes. Therefore, the idea of constant cone ratios has been reformulated as relational colour constancy by Foster and colleagues (Craven and Foster 1992; Foster et al 1997). Relational colour constancy refers to the ability of observers to discriminate between illuminant and material changes in scenes. Although formally equivalent to perceptual colour constancy (Foster et al 1997) it remains unclear whether the signal arising from constant cone excitation ratios is actually involved in colour perception.

If colour constancy evolved with a similar fast time course to that described for chromatic induction (Rinner and Gegenfurtner 2000) then it should be possible to measure directly the effect of cone excitation ratios on *perceptual* colour constancy with appearance matching by comparing the kinetics of achromatic adjustments as a function of background composition ie cone excitation ratios. Therefore, we examined perceptual colour constancy within the first second after changes to the adapting background, and varied cone excitation ratios as an independent variable.

2 General methods
Colour constancy was measured with simulated Mondrian patterns on a CRT with a large uniform surround illuminated by computer-controlled fluorescence lamps. Observers performed achromatic adjustments as a function of adaptation time and background configuration. Basically, two paradigms were used to measure colour constancy in steady state and with dynamic adaptive changes. To measure the time course of colour constancy, subjects adapted to a reference background consisting of a simulated Mondrian pattern under defined illumination conditions, then the background and the lamps simultaneously switched to the adapting background and, at different times after onset of the adapting background, subjects performed a matching task. Colour constancy in steady state was measured with constant backgrounds.

2.1 Stimulus configuration
Stimuli were displayed on a BARCO CCID 121 colour CRT monitor that was driven by a Cambridge Research VSG 2/3 graphics board at a refresh rate of 120 Hz non-interlaced. The images were generated on the monitor by reading through the picture

memory in a raster scan and then interpreting the numbers in each location as a colour defined in a 256-element colour lookup table. Two 8-bit digital-to-analogue converters, which were combined to produce an intensity resolution of 12 bits, were used to control the intensity of each of the three monitor primaries. The luminances of each of the phosphors were measured at various output voltage levels with a Graseby Optronics Model 370 radiometer with a model 265 photometric filter. A smooth function was used to interpolate between the measured points and lookup tables were generated to linearise the relationship between voltage output and luminance. We also made sure that additivity of the three phosphors held over the range of intensities used in these experiments (Brainard 1989). All the displays in the present experiments had a space–time averaged luminance of 26.0 cd m^{-2}. A Photo Research PR650 spectro-radiometer was used to measure the spectra of the red, green, and blue phosphors at their maximum intensity setting. The spectra were multiplied with the CIE 1931 colour-matching functions, as revised by Judd (1951; see Wyszecki and Stiles 1982, section 5.5.3, table 1), to derive CIE x, y chromaticity coordinates and the luminance Y of the phosphors (Irtel 1992). All further references to luminance and photometric luminance refer to the $V(\lambda)$ curve as modified by Judd (1951).

The primaries of our monitor had x, y, Y coordinates of: 0.617, 0.346, 15.52 (red); 0.281, 0.604, 34.90 (green); and 0.153, 0.069, 4.223 (blue). The monitor spectra were multiplied by the Smith and Pokorny (1975) cone fundamentals to calculate absorptions and contrasts in the long- (L), medium- (M), and short- (S) wavelength-sensitive cones. The front wall of the dark room where the experiments took place was painted with a neutral gray. Two sets of 3 Osram L36W/66 fluorescence lamps (red, green, and blue) illuminated this wall from two sides. The lamps were controlled by 6 digital-to-analogue converters with a resolution of 12 bits per channel. Even though the relationship between voltage and intensity was almost linear for the lamps, small residual nonlinearities were corrected by using lookup tables. The chromaticities of the three lamp-pairs were measured on the painted wall with the Photo Research PR650 spectroradiometer. The paint of the wall was chosen to make the lamp primaries similar to the monitor primaries, resulting in nearly the same gamut for the background illumination and monitor.

The red–green–blue (*rgb*) triplets used to control the lamps were transformed into the colour space of the monitor, in order to obtain identical colours on the monitor and the adjacent parts of the wall. For each given vector of monitor phosphor values, $\textbf{\textit{rgb}}_{M}$, the corresponding vector for the lamps, $\textbf{\textit{rgb}}_{L}$, could be calculated by performing a matrix transformation. It consisted of a linear transformation and an additive correction for the offset $\textbf{\textit{xyz}}_{0}$ (0.33, 0.30, 0.63 in CIE coordinates) delivered by the lamps with no voltage input. This offset was treated as constant additional source of illumination. With $[\textbf{XYZ}]_{M}$ being the 3×3 matrix containing the primaries of the monitor and $[\textbf{XYZ}]_{L}$ being the matrix of the lamp primaries, the uncorrected vector $\textbf{\textit{rgb}}_{L}$* was calculated as $\textbf{\textit{rgb}}_{L}* = [\textbf{XYZ}]_{M}[\textbf{XYZ}]_{L}^{-1} \cdot \textbf{\textit{rgb}}_{M}$. To correct for the offset of the lamps, the rgb values that would produce the given offset were subtracted: $\textbf{\textit{rgb}}_{L} = \textbf{\textit{rgb}}_{L}* - [\textbf{XYZ}]_{L}^{-1} \cdot \textbf{\textit{xyz}}_{0}$.

2.2 Colour space

Illumination changes occurred along the L–M isoluminant colour axis of the DKL colour space (Krauskopf et al 1982; Derrington et al 1984), which is based on the MacLeod and Boynton (1979) chromaticity diagram. This colour space is derived from cone contrast spaces, where colour values are defined relative to a neutral gray point. The chromaticity of the gray point was (0.33, 0.35) in CIE x, y coordinates as revised by Judd (1951), and its luminance was 26.0 cd m^{-2}.

Two chromatic axes intersect at the gray point, which span an equiluminant plane through the gray point. All lights in this plane have the same luminance as defined by the $V(\lambda)$ photopic luminosity function (Judd 1951; see Wyszecki and Stiles 1982). Modulation of light along the L–M-cone axis changes the excitations of the L and M cones so that their sum (luminance) is kept constant, and the change is invisible to the S cones. Lights along this axis typically appear reddish and bluish-green. Modulation along the S–(L+M) cone axis changes the excitation of S cones only and is invisible to L and M cones. Lights along this axis typically appear yellow-greenish or purplish. The length of a vector that lies along a particular half axis can be described in terms of contrast delivered to the cone mechanisms (Smith and Pokorny 1975). By modulating lights along the L–M axis, 9.1% contrast for the L cones and 17.5% contrast for the M cones could be provided.

2.3 Experimental setting

Subjects were sitting 114 cm away from the front wall, which was illuminated by fluorescence lamps. These illuminated about 64 deg × 45 deg of the viewing field in a fairly homogeneous fashion. In the centre of the wall there was a 25.5 cm × 20 cm (10 deg × 8 deg) rectangular hole through which the monitor, placed 65 cm behind the wall in a felt tunnel, was visible. Light from the fluorescence lamps could not reach the monitor surface directly (see figure 1a). Observers saw only the light emitted from the monitor phosphors and the light reflected from the wall. In all experiments the adapting monitor background had the same mean chromaticity as the surround consisting of the illuminated wall. When the adaptation conditions changed, the lamps changed their chromaticity synchronously with the monitor, synchronised to the vertical refresh signal of the monitor.

The background we used for the colour-constancy experiments was made up of 400 0.8–1.1 deg squares, randomly distributed over the monitor background (see figure 1b). The chromaticities were taken from a set of spectra from 314 Color-Aid colour chips measured with a Photo Research PR650 spectroradiometer under different illuminations that were generated by the lamps. The effect of the different illuminations was to change the chromaticity of the wall along the cardinal axes, by using the maximal possible modulation that could be reached with the lamps. They were measured on the front of the wall where, in the experiments, the monitor was visible. For all other chromaticity of illumination delivered by the lamps, simulated chromaticities of the patches were calculated by linear interpolation.

2.4 Paradigm

To measure the dynamics of colour constancy we used a reference background to which subjects adapted initially, and an adapting background to which subjects adapted to over time. For steady-state experiments, there was only one background.

The task for the subjects was to adjust a central 3.3 deg patch on the Mondrian background until it appeared achromatic (see figure 1b). In the experiments with changing background conditions a set of colour chips was chosen that was displayable under both illumination conditions within the gamut of the monitor and within a luminance range of 20–32 cd m^{-2}. When, for example, a saturated red chip is simulated under a saturated red illumination, the colour coordinates will probably be out of displayable range. In this case only chips with reflectances which are not too saturated can be displayed within the gamut of the monitor. Depending on chromaticities of reference colour and adapting colour 45–85, different colour chips were used for the Mondrian background.

The test patch was presented for 83 ms (10 frames) embedded in the adapting Mondrian background. After this brief presentation subjects could adjust the appearance of the patch for the next presentation, along the colour axes along which adaptation

(a)

(b)
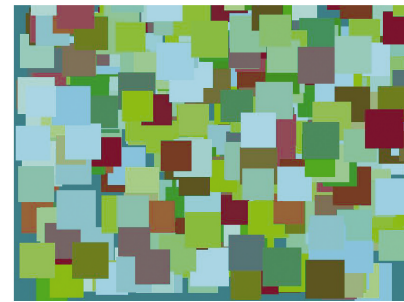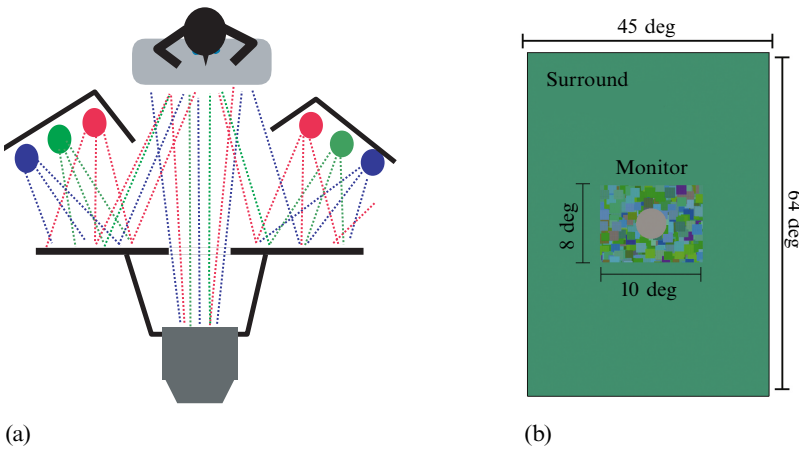
(c) Correlated

(d) Uncorrelated

Figure 1. (a) Setting used in all experiments. Observers are sitting in front of a gray painted wall looking binocularly at a monitor screen. The wall is illuminated by computer-controlled fluorescent lamps. Observers see only the reflected light. Through a felt tunnel observers see the CRT display. The light from the lamps cannot reach the monitor. The spatial arrangements of the stimuli for the achromatic adjustment tasks are shown in (b). The illumination of the colour-chips background is simulated according to the real illumination visible on the wall. The central patch can be adjusted by the observer. In (c) and (d) background changes for the correlated and uncorrelated conditions are shown. The simulated illumination changes are from green3 to red as described in table 2. In both conditions the spatial locations of the colour chips are preserved when the adaptation conditions change. Under the correlated condition, each chip changes its chromaticity according to the illumination. Simulated reflectances remain constant. For uncor-related background changes the same lookup tables are used, but their entries are randomly assigned to the colour chips, giving the same mean chromaticity shift but breaking cone excitation ratios.

took place. After each stimulus presentation the position of the Mondrian squares changed randomly to avoid local adaptation. The chromaticity of the patch was adjusted by the observers along only the L – M cardinal axis, thus considerably reducing the complexity of the task. Simple tasks are an essential need in temporal paradigms which suffer immanently from the necessity of large trial numbers. In our case restricting adjustments along one axis only is not a severe restriction. It has been shown that isoluminant adaptation along a single cardinal axis results in matches that differ mainly along the same axis (Würger 1996). Our own preliminary experiments, where observers were allowed unconstrained three-dimensional adjustments in colour space, confirmed this result for our experimental settings.

In the different experiments, achromatic adjustments were measured either in steady state or at fixed times after switching to an adapting background. Steady-state adjustments and adjustments with changing adaptation conditions were measured within the same experimental session. Subjects initially adapted to the reference background for 120 s. In the steady-state condition, test patches were presented for 83 ms and observers had to make a decision after each presentation. Subjects signaled the direction in which the chromaticity of the central patch should be changed to obtain an achromatic appearance. After 15 s the test patch was presented again with a chromaticity adjusted by an adaptive procedure with decreasing step size after each reversal. The procedure continued until 10 reversals had occurred, and subsequently the achromatic loci were determined by a probit analysis (Finney 1971).

In the dynamic condition, after adaptation to the reference background, the monitor background and the lamps switched synchronously to the adapting background. At fixed times after switching to the adapting background (adaptation time) test patches were presented for 83 ms. The illumination switched back to the reference background 250 ms after the stimulus was displayed, and 15 s of readaptation occurred (see figure 2). This ensured that adaptation always started from a defined steady state, differing only slightly by the length of the interval between switching to the adapting background and presentation of stimulus. A comparison of the steady-state measurements without any changes to adaptation showed that the 15 s readaptation period erased completely any effect of adaptation.
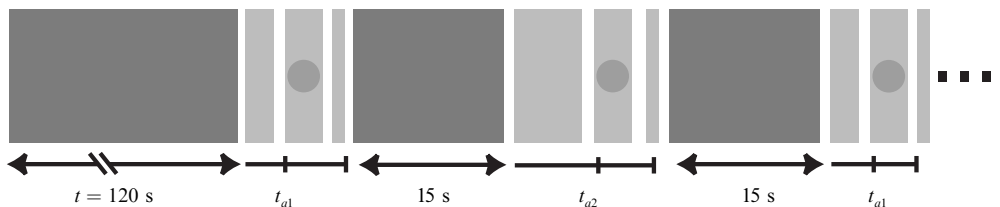

$t = 120$ s t_{a1} 15 s t_{a2} 15 s t_{a1}

Figure 2. Paradigm for measuring the kinetics of colour constancy. Observers initially adapted to a reference background (symbolised by dark gray). After switching to the adapting background (light gray), the central patch was displayed at fixed adaptation times t_a for 83 ms. A 15 s readaptation period occurred after each stimulus presentation.

As an index for the achieved colour constancy the ratio between the adjusted contrast of the test patch and the contrast of the simulated illumination was calculated.

2.5 Correlated and uncorrelated background changes

Two different modes of background changes were performed. In one condition the colour chips changed their chromaticity according to the new illumination conditions. This results in a strong correlation of the cone excitations between the two adaptation conditions. In the other condition the cone excitations under the changing backgrounds were calculated as before and the chips also kept their positions. But the entries of

the lookup tables were shuffled to break the spatial correlation of cone excitation ratios. Figures 1c and 1d show an example of reference and adapting backgrounds under correlated and uncorrelated conditions. The correlation of cone excitations under two different illuminations is shown in figure 3 for both conditions. The mean chromaticity changes are the same, but the changes are completely decorrelated for individual chips. Therefore cone excitation ratios (Foster and Nascimento 1994) are also decorrelated.
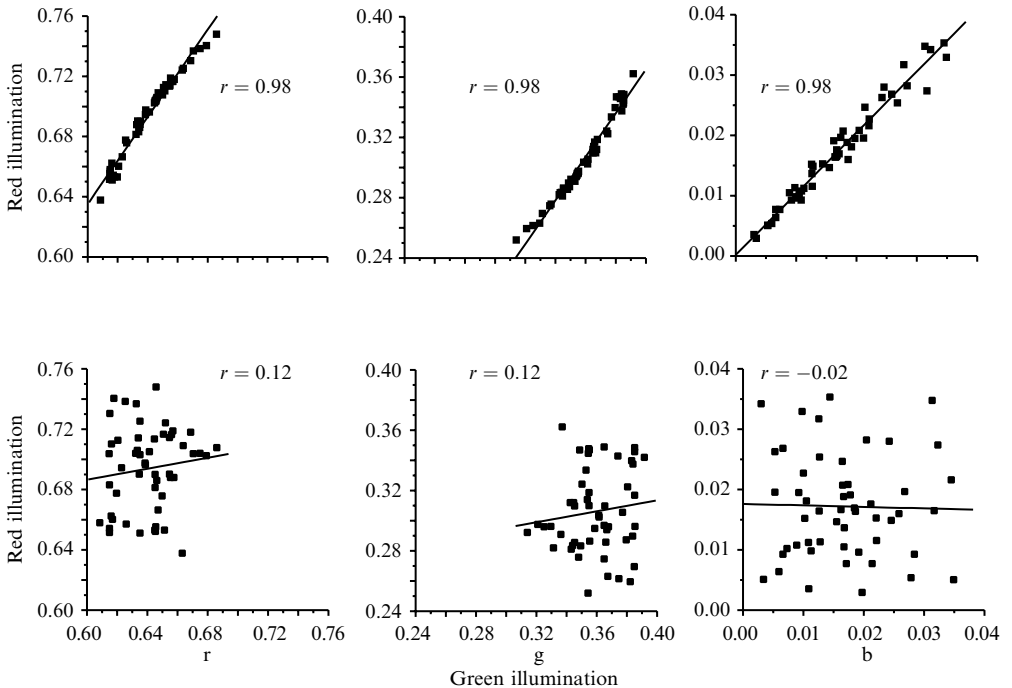

Figure 3. Example for changes in cone excitations for chromaticities of the colour chips caused by changing the background illumination from green3 to red as described in table 2 along the L – M cardinal axis. The associated screen shots are shown in figures 1c and 1d. Axes are labeled with Boynton – MacLeod colour coordinates. Under correlated conditions (upper row) chromaticity changes are simulated as illumination changes, preserving the reflectances. This results in an additive shift according to the shift in mean chromaticity. The relationship between cone excitations is highly correlated. For the uncorrelated condition there is also an additive shift in chromaticity, but the correlations between coned excitations are broken.

2.6 *Observers*
One author (OR) and three naïve female subjects (AS, AL, LL) with normal colour vision, two of them with corrected acuity, participated in this study.

3 Results
All experiments were performed for illuminant changes along the L – M axis of colour space. In the first experiment, we measured the amount of colour constancy that was obtained in our setting. This was done in a steady-state experiment with illumination conditions at different levels of saturation.

In the second experiment the time course of colour constancy was determined for the initial 250 ms of adaptation time. It has been reported that about 50% of the total adaptation is complete after 1 s adaptation to a new background (Fairchild and Reniff 1995; Arend 1993). We have reported an even faster process for colour induction with more than 60% adaptation after only 25 ms (Rinner and Gegenfurtner 2000). Therefore, we were interested in the dynamics of colour constancy, to see how much of the

total colour-constancy effect, reached under full adaptation, was complete after 250 ms. Particularly, we were interested to see if colour constancy shows a slow exponential time course as observed in discrimination experiments (Hayhoe et al 1987; Rinner and Gegenfurtner 2000) or the instantaneous behaviour mentioned above.

In the third experiment we directly examined the influence of the degree of correlation in cone excitation ratios for fast colour-constancy processes. Under one condition, the two different backgrounds had a high correlation in cone contrast ratios. Under the other condition, the change in background produced no correlation at all. In this experiment, on the basis of earlier results, colour constancy was measured after 100 ms adaptation to the new background.

3.1 Steady-state achromatic adjustments with Mondrian-like backgrounds

The amount of colour constancy obtained in our setting was explored by using the achromatic adjustment method, described in the method section, with constant backgrounds and full adaptation to the adapting illumination. Achromatic adjustments were measured for the five background conditions defined in table 1: two greenish, two reddish, and an achromatic gray. Observers adapted for 2 min to the Mondrian background under a fixed illuminant. The neutral adjustment field was presented every 5 s. After each presentation of the adjustment field the chromaticity for the next presentation could be adjusted by indicating that either more red or more green should be added for an achromatic appearance. After 8 reversals, the background patches changed their chromaticities and readaptation occurred for 2 min before the presentation of the next stimulus. The results of this procedure give us an estimate of the degree of colour constancy under a steady-state illumination condition.

Figure 4 shows the results for two observers (OR, AS). In 5 Mondrian backgrounds with chromaticities varying on the L−M axis, adjustments demonstrate close to perfect

Table 1. Cone contrasts of adapting colours used for achromatic adjustments under steady-state conditions. The space-averaged luminance of all illuminations was 26.0 cd m^{-2}.

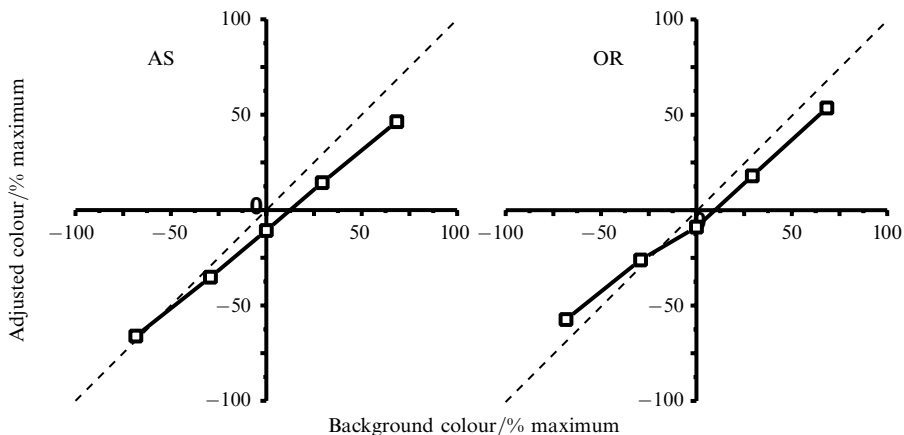|	Hue				
	green saturated	green unsaturated	gray	red unsaturated	red saturated
L	−6.2%	−2.7%	0	2.7%	6.2%
M	11.7%	5.0%	0	−5.0%	−11.7%
S	−0.24%	−0.07%	0	0.07%	0.24%

Figure 4. Steady-state colour constancy, measured under full adaptation for two observers (OR, AS). The dotted line indicates the theoretical line for 100% colour constancy.

colour constancy. The dotted line with a slope of 1 indicates the theoretical line for 100% colour constancy. The best-fitting lines for the two observers had slopes of 0.79 (OR) and 0.81 (AS), indicating a high degree of constancy. These findings are in agreement with other studies using achromatic adjustment as a method to quantify colour constancy with large surrounds and nearly natural illumination conditions (Brainard et al 1997; Kraft and Brainard 1999).

3.2 *Fast adaptation changes with correlated and uncorrelated cone ratios*

We have reported a fast development of colour induction with more than 60% of total colour induction in steady-state illumination conditions occurring within the first 25 ms of adaptation to a new homogeneous background (Rinner and Gegenfurtner 2000). The remaining adaptation evolved with a slower time course and was complete after about 2 min. We argued that the component acting almost instantaneously was due to higher-level computations of global contrast rather than photoreceptor adaptation, because it occurred only in an induction task, and not for colour discrimination.

For colour constancy, we were interested if there was also such a fast component, that would make a large contribution to colour constancy. This would indicate that colour constancy is not primarily constituted by calculations based on photoreceptor scaling.

In the latter case, this fast component could be based on another cone principle, namely local cone contrast ratios. Therefore, we varied the degree of correlation of cone excitation ratios between the two backgrounds.

The time course of colour constancy was measured with adaptation times of 25 ms and 250 ms for two observers (OR, AS). The basic methods are described in section 2. We used three different greenish reference backgrounds, described in table 2. The adapting background was always the same reddish background (red in table 2). To calculate the amount of colour constancy as a function of adaptation time, the steady-state adjustments with full adaptation to the reference and the adapting background were measured as in experiment 1. With this procedure we can obtain the temporal characteristics of successive colour constancy, relative to the settings in steady state where observers are fully adapted to the adapting background. By using three different adaptive conditions with different cone contrast changes, we can figure out if the fast adaptation processes act in a subtractive or in a multiplicative manner. If the adaptational processes involved here are multiplicative, then the curves for the different reference backgrounds should completely overlap when colour constancy is plotted as a function of adaptation time. If a subtractive process is contributing, then the different curves will not overlap, but will be shifted relative to each other.

Table 2. Cone contrasts of adapting and reference colours used in experiments with fast adaptation changes. Adapting colours remained the same along a colour axis. The reference colours varied from only slightly saturated to highly saturated. The space-averaged luminance of all illuminations was 26.0 cd m^{-2}.

	Adapting colour	Reference colours		
Hue	red	green1	green2	green3
L	6.2%	−1.8%	−3.5%	−6.2%
M	−11.7%	3.3%	6.7%	11.7%
S	0.24%	−0.05%	−0.09%	−0.24%

Two different types of background changes were performed. In one condition, the simulated colour chips making up the background changed their chromaticity according to the new illumination conditions. This results in a strong correlation of the cone excitations between the two adaptation conditions (Foster and Nascimento 1994). In the other condition, the correlation between cone excitations under the changing backgrounds

was destroyed by randomly exchanging chromaticities of the different colour chips (see section 2.5). This comparison between correlated and uncorrelated background changes tells us whether relationships between local cone excitations are necessary for fast colour-constancy processes. If the correlation is required, we should see a breakdown, or at least a significant reduction, of colour constancy in the uncorrelated condition.

Figure 5a shows the result for one observer (OR) for the correlated-background condition. Results for the other three observers are essentially the same. Achromatic adjustments are scaled to total adaptation with 0% being the steady-state adjustment for the reference background, and 100% as steady-state adjustment for the adapting background.

Independent of the reference background, a constant component of total colour constancy is complete after 25 ms adaptation time (on average 55% for OR and 76% for AS under the correlated condition, 53% and 79% under the uncorrelated condition). Colour constancy improves further after 250 ms adaptation but at a much slower rate.
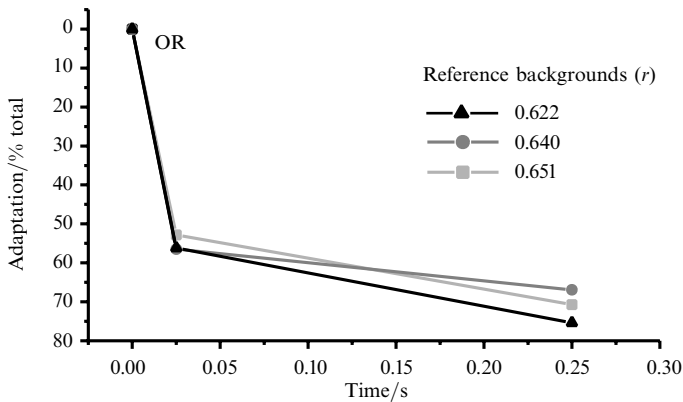
(a) Spatial correlated background change
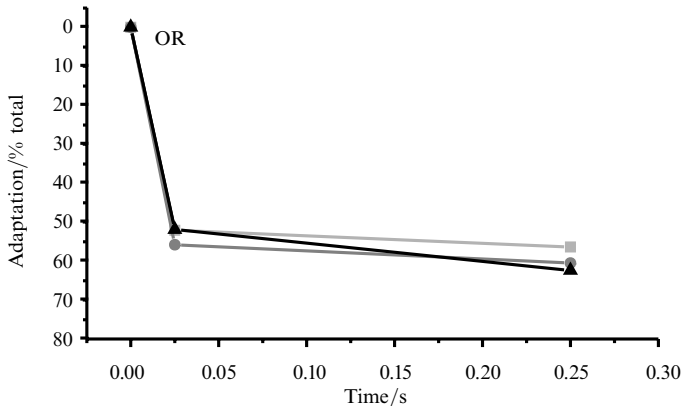
(b) Spatial uncorrelated background change

Figure 5. Time course of colour constancy for changes from three different greenish reference backgrounds, indicated by their Boynton–MacLeod coordinate r, to a single reddish adapting background. Achromatic adjustments are expressed as a percentage of total colour constancy achieved by the observers in steady state. The adjustments made when adapted to the reference backgrounds in steady state are indicated by 0%. The adjustments made when adapted to the adapted background in steady state are indicated by 100%. For both correlated and uncorrelated background conditions, a constant ratio of total colour constancy is reached after presentation of the adapting background for 25 ms. Colour-constancy settings are on average 54% for observer OR and 76% for observer AS (data not shown) relative to the settings when fully adapted to the reddish adapting background. The patterns for correlated (a) and uncorrelated (b) background changes are very similar.

This indicates a very fast, multiplicative process that explains the major part of the adaptational changes contributing to colour constancy. The patterns for correlated and uncorrelated background changes are virtually identical (see figure 5b). With uncorrelated background changes, more than 50% of the colour constancy in steady-state conditions is reached after 25 ms. A more rigorous comparison between correlated and uncorrelated background changes was conducted in the last experiment.

3.3 Randomised presentation of correlated and uncorrelated background changes

Since colour constancy in the Mondrian world is largely explained by a nearly instantaneous adaptation process, we can use the above temporal paradigm to test hypotheses about colour constancy as a whole. Under background conditions, where colour constancy is impaired, the effect of this component should be decreased. It has been argued that cone excitation ratios for a large class of surfaces are almost invariant under changes of illumination (Foster and Nascimento 1994). The relations of fixed objects under different illumination conditions could be used as invariant signals, as a basis for perceived colour constancy. We addressed this question by exploring the effect of decorrelated cone excitation ratios on the fast phase of colour constancy.

The methods used here were identical to the earlier ones, except for the following changes. Three subjects, one author (OR) and two naïve female subjects (LL, ML) performed achromatic adjustments in the steady state and 100 ms after a background change. Two different reference backgrounds (green1 and green3 in table 2) and one adapting background (red in table 2) were used. With 100 ms adaptation time an effect of decorrelating the spatial cone excitation ratios should be visible if there is a reduction in the instantaneous or other fast adaptation phases. Adjustments for both conditions were measured in a single experimental run. Correlated and uncorrelated switches to the adapting background were randomly interleaved.

Figure 6 shows the results for correlated and uncorrelated conditions for the three subjects. Achromatic adjustments with 100 ms adaptation time are scaled as a percentage of total adaptation relative to steady-state settings, just as in experiment 2.

Decorrelating the cone excitation ratio has no systematic effect on achromatic adjustments after 100 ms. The spatial correlation of local chromaticity changes under changing illumination conditions seems to be irrelevant for colour constancy in this task.
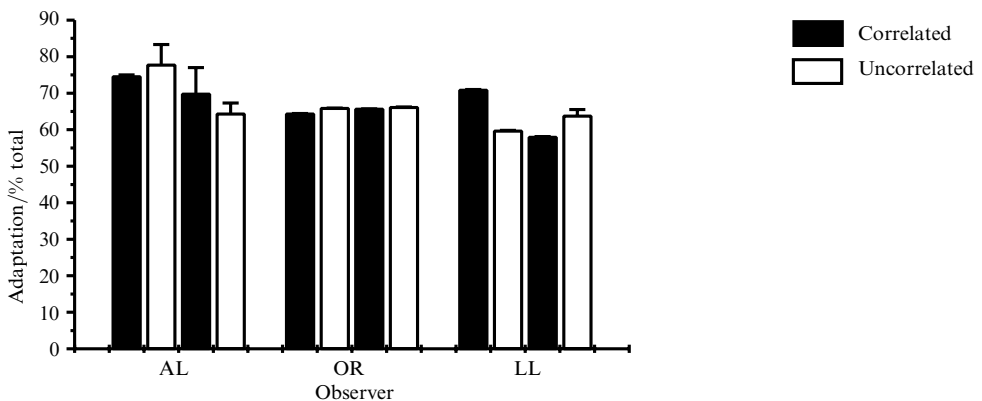

Figure 6. Percentage of total adaptation after 100 ms of adaptation to the adapting background relative to the settings in the steady-state condition, fully adapted to the adapting background. Black bars indicate the settings for correlated background changes, white bars show the settings for uncorrelated background changes. Error bars are derived from the slope of the probit analysis. For each observer the left two bars indicate adaptation changes from red to green1 in table 1, and the right two bars indicate adaptation changes from red to green3. For all three observers there is no overall effect of decorrelating spatial relationships of cone excitation on fast colour-constancy processes.

4 Discussion

We have shown that colour constancy is a fast process. More than 50% of the appearance change due to a changing background is completed after 25 ms adaptation time. This process is too fast to be explained by adaptive cone sensitivity changes. Furthermore, the maximal rms cone contrast along the red–green axis in our experiments was only about 11%, which speaks against a sensitivity adjustment as it is seen in lightness experiments (Hayhoe et al 1987) where cone excitations differ by logarithmic units. Higher-order spatial interactions seem to contribute to a stable percept under fast-changing illumination conditions. This instantaneous adaptational process contributes a large part to colour constancy, which implies that only a minor part of colour constancy can be attributed to retinal processes, such as von Kries receptor scaling of cones or opponent channels. The data on the temporal dynamics of colour induction (Rinner and Gegenfurtner 2000) and colour constancy argue against a strict interpretation of the von Kries law as adaptation occurring in the photoreceptors themselves. They agree with a more general version of the von Kries law, which assumes the scaling to occur along three arbitrary lines in colour space (see, for example, Bäuml 1999).

The instantaneous component of perceptual colour constancy is also independent of spatial correlations of cone excitations under changing illumination conditions. Decorrelating the spatial cone excitation ratios (Foster and Nascimento 1994) did not influence the time course or affect the size of this mechanism. Even with spatially uncorrelated cone excitation ratios the largest part of the total colour-constancy effect is reached almost instantaneously. These results show that constancy of perceived colour under changing illumination conditions is not equivalent to relational colour constancy. This is also supported by an experiment in Cornelissen and Brenner (1995) which was not designed to deal with this question. Subjects had to perform a colour-matching task with a reference and a test screen simulating illuminated coloured Mondrian surfaces. When patches changed their colour every 0.5 s to prevent the subjects from using colour distances between corresponding patches, performance was virtually unaffected. This is an example of yet another dissociation between perceptual and relational colour constancy. In experiments where observers have to discriminate between material changes and illuminant changes, performance is best for almost instantaneous changes of Mondrian images (Linell and Foster 1996) and becomes worse if the illuminant changes are applied gradually over time. For perceptual colour constancy, the constancy index increases with adaptation time—and is not influenced by simulated material changes. Clearly there is a dissociation between perceptual colour constancy and the knowledge of the nature of chromaticity changes in a scene.

Contrary to some of the studies mentioned above, our naïve observers did not report any noticeable difference between correlated and uncorrelated presentations. This could stem from the different statistical properties of the colour displays used in these studies. In our case the mean and the variance remained unchanged between correlated and uncorrelated display configurations, whereas in Craven and Foster (1992) and Linell and Foster (1996) only the mean was kept constant. The chromatic variance of the overall scene was always larger for the case of a combined reflectance and illuminant change. Brown and MacLeod (1997) have shown that the variance of the patches in a colour display can have a profound effect on colour appearance.

On the basis of our results, we argue that colour-constancy computations are not performed by the cones themselves, or at least only to a minor part. Neither photoreceptor adaptation nor the statistical interrelations between cone excitations under different illumination conditions can explain the colour-constancy effect in our experiments. This independence of local correlation of cone excitation ratios certainly does not speak against an influence of structure and especially contrast in a scene on colour appearance. Shevell and Wei (1998) showed that contrast in the periphery of a scene

markedly influences colour induction in a chromatic matching task. Also, Kraft and Brainard (1999) have demonstrated how colour constancy can be titrated between 83% and 39% by manipulating local and global contrast. This is somehow similar to the results we obtained with our temporal paradigm where we differentiate between mechanisms on the base of their kinetics (Rinner and Gegenfurtner 2000). It would be interesting to classify these different contributions according to their kinetic properties and to manipulate the time course and the size of the colour-constancy effect together.

The question arises whether a mechanism with such a rapid time course could be useful for colour constancy. Daylight changes are slow. Sensitivity could be adjusted by a slower adaptation mechanism like the one we described in Rinner and Gegenfurtner (2000), with a half-life of about 20 s. But for rapid eye movements in complex illuminated scenes the instantaneous mechanism may be useful to ensure stable percepts.

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