PERGAMON

Vision Research 41 (2001) 285–293

Vision Research

www.elsevier.com/locate/visres

Colour constancy from temporal cues: better matches with less variability under fast illuminant changes

David H. Foster [a,*], Kinjiro Amano [a], Sérgio M.C. Nascimento [b]

[a] *Visual and Computational Neuroscience Group, Department of Optometry and Neuroscience, University of Manchester Institute of Science and Technology, Manchester M60 1QD, UK*
[b] *Department of Physics, Gualtar Campus, University of Minho, 4710-057 Braga, Portugal*

Received 12 April 2000; received in revised form 31 August 2000

Abstract

To test whether temporal transient cues could improve colour-constancy estimates, surface-colour matches were made across two Mondrian patterns illuminated by different daylights: the patterns were presented either in the same position in an alternating sequence or, as a control, simultaneously side-by-side. The degree of colour constancy was significantly higher with sequential stimulus presentation than with simultaneous presentation, in the best condition reaching 0.87 on a scale of 0 to 1 for matches averaged over 20 observers. The variance between observers was also markedly reduced with sequential stimulus presentation. The visual system appears to have mechanisms not requiring adaptation that can provide almost unbiased information about surface colour under changing illuminants.

Keywords: Cone-excitation ratios; Relational colour constancy; Successive constancy; Simultaneous constancy; Transient signals

---

1. Introduction

At least two kinds of visual processes underlie the perception of surface colour under changes of illuminant (Arend & Reeves, 1986): one depends on the eye becoming accustomed to the new illuminant and involves light adaptation (von Kries, 1905; Bramwell & Hurlbert, 1996; Whittle, 1996) and contrast adaptation (Webster & Mollon, 1995; Brown & MacLeod, 1997) and another which is more immediate and involves little of this adaptation, as when the eye moves rapidly over a scene with varying light and shade (Zaidi et al., 1997). The extent to which the latter yields a colour-constant percept has been tested in the laboratory by simultaneously presenting pairs of differently illuminated Mondrian patterns on a computer-controlled colour display monitor: an observer attempts to match the surface colour of a patch in one pattern against the surface colour of the corresponding patch in the other pattern (Arend & Reeves, 1986); the gaze is moved repeatedly from one pattern to the other to avoid adapting to either (Cornelissen & Brenner, 1995). Reported levels of constancy assessed by simultaneous asymmetric colour matching have rarely exceeded 0.6–0.7, where 1.0 would be perfect constancy (Arend et al., 1991; Troost & de Weert, 1991; Cornelissen & Brenner, 1995). Similar values have been obtained with physical three-dimensional illuminated surfaces as stimuli, rather than their simulations on a colour monitor (Brainard et al., 1997). Higher levels have been reported in an achromatic matching task (Brainard, 1998; Kraft & Brainard, 1999), although the connection with chromatic matching is not yet resolved (Maloney, 1999; Speigle & Brainard, 1999).

Introducing high-level cognitive cues about stimulus surfaces may not be the only way to improve performance in the unadapted eye. An alternative approach to the problem comes from a different kind of experiment on discriminating illuminant changes on a scene from changes in the reflecting properties of the surfaces comprising it; observers can perform this task rapidly and effortlessly (Craven & Foster, 1992; Foster et al., 1992). Illuminant changes appear to produce a “wash” over the scene and reflectance changes a “pop-out”

---

[*] Corresponding author. Tel.: +44-161-200 3888; fax: +44-161-200 3887.
E-mail address: d.h.foster@umist.ac.uk (D.H. Foster).

PII: S0042-6989(00)00239-X

effect. Critically, performance improves with the speed of the illuminant and reflectance changes (Linnell & Foster, 1996), which presumably generate a transient signal that is exploited by the visual system (Foster et al., 2000). In simultaneous colour constancy, however, useful transient cues are unlikely to be produced, but they should be evident in the temporal analogue of simultaneous colour constancy, that is, when stimuli are presented in rapid temporal sequence. This laboratory arrangement might model the natural viewing condition when a cloud passes over the sun, or when someone or something moves in front of the light and casts a shadow.

Notice that in this sequential presentation of stimuli, as in simultaneous presentation, the eye is assumed not to be adapted to the separately illuminated patterns; thus the task should be distinguished from that performed in traditional measurements of successive colour constancy in which the eye is first fully adapted to one illuminated pattern and then fully adapted to a differently illuminated pattern, observers making either an achromatic setting (e.g. Brainard, 1998) or a memory match (e.g. Troost & de Weert, 1991; Brainard & Wandell, 1992; Arend, 1993; Jin & Shevell, 1996). Colour appearance has been assumed to take tens of seconds or longer to stabilize after a change in viewing context (Fairchild & Lennie, 1992; Fairchild & Reniff, 1995; although see Rinner & Gegenfurtner, 2000).

In the experiment described here, 20 observers made surface-colour matches across two Mondrian patterns. A daylight of 25 000 K illuminated one pattern and a daylight of 6700 K illuminated the other, except for its centre patch, which was illuminated independently by a variable local light whose colour was controlled by the observer. Patterns were presented either in the same position in an alternating sequence with period of 2 s or, as a control, simultaneously side-by-side. Fresh patterns were generated in each trial and precautions were taken to reduce the possibility of observers taking advantage of accidental similarities in the colour of the centre and surround patches (Maloney, 1999). Particular care was taken in the analysis to distinguish between the effects of bias and variance in observers' matches. It was found that the degree of colour constancy was significantly higher with sequential presentation than with simultaneous presentation and that the variance between observers was markedly lower.

2. Methods

2.1. Stimuli and apparatus

The stimuli were computer-generated images of illuminated Mondrian patterns (subsequent references to surfaces, materials, and illuminants used in the experiment apply to these computer simulations). The patterns were square, of side 7° visual angle, and comprised an array of 49 (7 × 7) square Lambertian coloured surfaces of side 1° visual angle, as illustrated in Fig. 1 (a) and (b). The surfaces were randomly drawn from 1269 samples in the *Munsell Book of Color* (Munsell Color Corporation, 1976), each reflectance function being sampled at 10-nm intervals. The original spectral reflectances rather than compositions of spectral basis functions were used (Parkkinen et al., 1989). The Munsell set includes a large sample of naturally occurring reflectance functions: the set of spectral reflectances spanned by its basis functions includes spectral reflectances of flowers, flower clusters, leaves, and berries (see e.g. Jaaskelainen, et al., 1990). Moreover, data on spectral reflectances in natural pastoral scenes and scenes of the built environment suggest that the Munsell set may provide a more demanding test of visual competence (Nascimento et al., 1999). As explained later, the random sampling producing each Mondrian pattern was repeated, if necessary, to eliminate any accidental similarities between pairs of surfaces. The only constraint placed on the sampling was that the surfaces should be displayable on the colour monitor under the fixed and variable illuminants used.

The patterns were presented in a dark surround and were viewed binocularly at 100 cm. The ambient luminance in the room was less than 0.3 cd m^{-2}. One pattern was presented under a fixed, spatially uniform daylight of correlated colour temperature 25 000 K and luminance 50 cd m^{-2}; the other pattern was made of the same materials and was presented under a fixed, spatially uniform daylight of correlated colour temperature 6700 K and luminance 50 cd m^{-2}, except for the centre patch where the 6700 K daylight was replaced by an adjustable, independent, spatially uniform local illuminant (the "match" illuminant) constructed from the daylight spectral basis functions of Judd et al. (1964) with variable coefficients. By varying these coefficients with a joypad connected to the computer, the observer could vary the colour (and luminance) of the match illuminant over a large convex region of the CIE 1931 (x, y) chromaticity diagram ($0.250 \leq x \leq 0.400$; $0.230 \leq y \leq 0.400$) containing the coordinates (0.250, 0.255) and (0.310, 0.326) of the fixed 25 000 K and 6700 K illuminants. The centre patch in the pattern under the 25 000 K illuminant defined the test surface and the centre patch in the pattern under the 6700 K illuminant defined the match surface[1]. The initial setting of the match illuminant in each trial was chosen randomly.

---

[1] This nomenclature is common (e.g. Valberg & Lange-Malecki, 1990; Lucassen & Walraven, 1993; Cataliotti & Gilchrist, 1995; Kuriki & Uchikawa, 1996; Brainard et al., 1997; Bäuml, 1999), but not universal (e.g. Arend & Reeves, 1986; Arend et al., 1991; Cornelissen & Brenner, 1995).

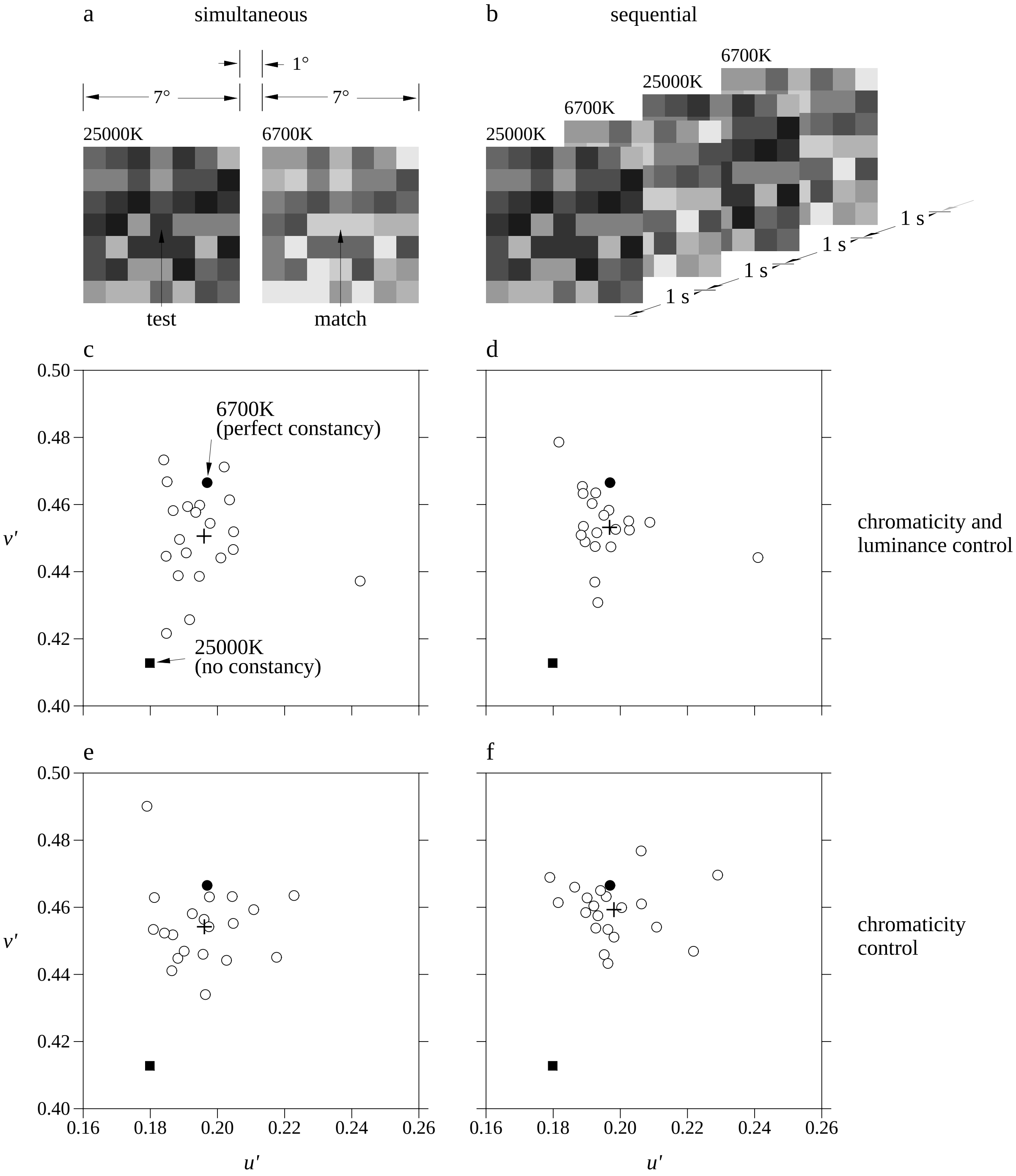

Fig. 1. Colour-constancy settings made by 20 observers with Mondrian-pattern stimuli. (a) and (b) show the configurations of the stimuli for simultaneous and sequential presentation respectively. The illuminants were daylights with correlated colour temperatures 25 000 K and 6700 K, luminance 50 cd m^{-2}. (c)–(f) show observers' surface-colour matches in the CIE 1976 (u', v') uniform chromaticity diagram. Each point (open circles) in each of the four chromaticity diagrams represents for each individual observer the mean illuminant setting for 16 randomly selected Munsell surfaces used for the test patches. The means of the matches made by observers are shown by crosses. The locations of the 25 000 K and 6700 K illuminants are shown by the filled squares and filled circles respectively. Perfect colour constancy for a match would be indicated by the open circle falling on the filled circle. In (c) and (e), the Mondrian patterns were presented simultaneously, side-by-side, as in (a); in (d) and (f) they were presented sequentially, in an alternating sequence, with period 2 s, as in (b). In (c) and (d), observers had control of the chromaticity and luminance of the match illuminant (for these plots, the luminance value for each match was discarded); in (e) and (f), observers had control of just the chromaticity of the match illuminant.

The gamut of test surfaces was the maximum possible subject to the display constraints described earlier: 448 different chromaticities distributed over 76 different luminance levels.

To aid comparison with previously published data, matches were made under two conditions: in one condition, the observer varied both the chromaticity and luminance (x, y, Y) of the match illuminant; and, in the other condition, just the chromaticity (x, y) of the match illuminant, for which the luminance Y was set to that of the 25 000 K and 6700 K illuminants. Varying the chromaticity and luminance of the match illuminant is closely related to varying the chromaticity and luminance of the match patch (depending on the particular spectral reflectance of the patch and the basis functions of the illuminant), but this parameterization in terms of the match illuminant had the advantage that settings could be compared directly with each other, independent of the spectral reflectance of the centre patch, and averages could be calculated both over illuminant settings made by individual observers and over observers[2]. This device is used later to separate observer variance from observer bias.

The two Mondrian patterns were presented either simultaneously and continuously, side-by-side, or sequentially, in the same position, alternating sharply with each other every 1 s, with no blank interval interposed. The fixed 25 000 K and 6700 K illuminants were chosen to give a reasonable shift in chromaticity, but not so extreme that the colour gamut of either pattern was compromised. (Good constancy may be independent of the chromaticity of the illuminant change, at least for modest changes; see Brainard (1998).)

The stimuli were generated on the screen of a 20-in., 1024 × 768 pixels, RGB colour display monitor (Trinitron, model GDM-20SE2T5; Sony, Japan), controlled by a computer with a raster-graphics card (VSG2/3F; Cambridge Research Systems, Cambridge, UK) providing a nominal 15-bit intensity resolution per gun. The central 28 cm (11 in.) of the screen was used for stimuli. The screen refresh rate was approx 100 Hz. A telespectroradiometer (SpectraColorimeter, PR-650; Photo Research Inc., California, USA) that had previously been calibrated by the UK National Physical Laboratory was used to calibrate the display system. This calibration was performed sufficiently frequently that errors in the displayed CIE (x, y, Y) coordinates of a white test patch were < 0.005 in (x, y) and $< 3\%$ in Y ($< 5\%$ at low light levels).

2.2. Observers

There were 20 observers, seven male and 13 female, aged 19–30 years. Each had normal colour vision, verified by Rayleigh and Moreland anomaloscopy, and normal spatial acuity. All except observer KA (coauthor) were unaware of the purpose of the experiment and unpractised in making colour matches.

2.3. Procedure

Each observer made 16 matches in each of the four conditions: simultaneous and sequential stimulus presentation, with control of the chromaticity and luminance (x, y, Y) of the match illuminant and with just control of its chromaticity (x, y). The order of conditions was balanced over observers.

Particular care was taken in defining the task (Arend & Reeves, 1986). Observers were instructed as follows: "Your task is to adjust the colour of the central light to make the piece of paper look as if it is cut from exactly the same sheet as the corresponding piece of paper in the other pattern. When you have finished, the two patterns should look as if they are made up of exactly the same pieces of coloured paper but illuminated by different, spatially even lights". To ensure that the instructions were understood, observers were then asked to explain the task back to the experimenter.

In contrast to the practice in some experiments using asymmetric colour matching (e.g. Arend & Reeves, 1986; Arend et al., 1991; Cornelissen & Brenner, 1995; Bäuml, 1999), observers were not instructed to look for patches in the pattern containing the test patch that were similar in colour to it and then attempt to adjust the match patch in the other pattern so that the colour relations between it and the surrounding patches were similar to the colour relations between the test patch and its surrounding patches[3]. The problem is that, in the extreme, if there were a patch in the test-patch pattern very close in colour to the test patch, then the matching task could be reduced to a simple hue–saturation–brightness match between just the match patch and the corresponding surround patch in the other pattern. Such a procedure could yield apparently high levels of colour constancy in a visual system that in reality had none (Maloney, 1999). To reduce the possibility of observers using this strategy here, each random sampling of Munsell surfaces in the test-patch pattern was repeated until the difference between the centre

---

[2] If, instead, settings were expressed in terms of the chromaticities of the centre patch, a corresponding equivalent illuminant would need to be calculated, for example, by assuming that its effect could be described by a von Kries transformation; see Brainard et al. (1997, Appendix A).

[3] This is actually an appeal to relational colour constancy. In theory, the constancy estimates obtained in this and other matching experiments where opportunity exists for comparisons of perceived colour relations are strictly measurements of relational colour constancy, not colour constancy (Foster & Nascimento, 1994, Appendix 1).

Table 1
Variances ($\times 1000$) of colour-constancy matches over 20 observers[a]

		Simultaneous[b]	Sequential[b]
Match variables	Chromaticity and luminance (L^* u^* v^* space)	0.346 (0.113)	0.239 (0.095)
	Chromaticity (u', v' space)	0.272 (0.079)	0.205 (0.057)

[a] Variances of colour-constancy matches for simultaneous and sequential presentation of Mondrian patterns with observer control of the chromaticity and luminance of the match illuminant and of just the chromaticity of the match illuminant. Matches were expressed in CIE 1976 (L^* u^* v^*) and CIE 1976 (u', v') spaces.

[b] SEs are indicated in parentheses (because observers' performances were correlated over conditions, the estimated variances of the differences in indices were less than the sums of the corresponding squared SEs; see footnote 6).

patch and each other patch in the pattern was greater than a certain distance in the CIE 1976 (u', v') chromaticity diagram. This minimum distance was 0.55 times the distance between the positions of the 25 000 K and 6700 K illuminants in that space. There was no rating of observers' matches (cf. Speigle & Brainard, 1999).

3. Results and comment

3.1. Means and variances over observers

As each match made by an observer is an illuminant estimate, it may be represented in a common diagram containing the 25 000 and 6700 K illuminants. Fig. 1, panels (c)–(f), shows observers' surface-colour matches in the CIE 1976 (u', v') uniform chromaticity diagram. Each point (open circles) in each of the four chromaticity diagrams represents for each individual observer the mean illuminant setting for 16 randomly selected Munsell surfaces used for the test patches[4]. In (c) and (d), observers had control of the chromaticity and luminance of the match illuminant (for these plots the luminance value for each match was discarded); in (e) and (f), observers had control of just the chromaticity of the match illuminant. The means of the matches made by observers are shown by crosses. The locations of the 25 000 and 6700 K illuminants are shown by the filled squares and filled circles respectively. Where data points would have overlapped and obscured each other, a small amount of random jitter was added (Cleveland, 1994).

The extent of observers' colour constancy can be gauged by how close the open circles are to each of the filled circles. In all cases, the positions of the mean matches do not deviate much from a line joining the 25 000 and 6700 K illuminants (Arend & Reeves, 1986). Matches with sequentially presented stimuli can be seen to be closer to the ideal colour-constant values (compare positions of crosses and filled circles), an improvement that is quantified in the next section.

Matches with sequentially presented stimuli can also be seen to be less variable than with simultaneously presented stimuli. Table 1 shows variances[5] of the matches over the 20 observers for each of the two match conditions and for simultaneous and sequential presentation of the patterns. Thus, with observer control of the chromaticity and luminance of the match illuminant, the variance for sequential presentation was about 0.69 times that for simultaneous presentation, an improvement that was statistically significant ($P = 0.02$); with observer control of just the chromaticity of the match illuminant, the variance for sequential presentation was about 0.75 times that for simultaneous presentation (but not statistically significant)[6].

3.2. Colour-constancy index

The degree of colour constancy was quantified by a constancy index due to Arend et al. (1991). The index is defined for the stimuli used here as follows. In a suitable colour space, let a be the distance between the observer's setting and the 6700 K illuminant and let b be the distance between the 25 000 and 6700 K illuminants. Then the constancy index is $1 - a/b$. This index was calculated for each observer for each of the four experimental conditions. As matches were expressed in terms of the adjustment of the match illuminant, colour-constancy indices were calculated directly for the match illuminant (cf. Brainard et al., 1997). (Indices

---

[4] In two matches, one of the 20 observers chose extreme luminance values of the match illuminant (2 cd m^{-2}, 715 cd m^{-2}), which, on a log luminance scale, were over 15 SDs away from the corresponding mean (54 cd m^{-2}) for that condition. These two matches (out of $16 \times 20 \times 4 = 1280$ matches in all) were omitted, as they produced biased estimates of the population SD.

[5] The variance was taken as the mean square distance of the illuminant settings from the centroid of the settings, equivalent to the sum of the variances of the settings in the u' and v' directions.

[6] Here and elsewhere P-values were calculated by the bootstrap percentile method (Efron & Tibshirani, 1993) for matched samples, with resampling over the 20 observers. Where t-tests could be calculated, the corresponding P-values were almost identical. To improve the precision of the variance estimates, the number of observers would have to be increased.

Table 2
Average colour-constancy indices over 20 observers[a]

		Simultaneous[b]	Sequential[b]
Match variables	Chromaticity and luminance (L^* u^* v^* space)	0.600 (0.068)	0.690 (0.040)
	Chromaticity (u' v' space)	0.663 (0.032)	0.750 (0.031)

[a] Colour-constancy indices for simultaneous and sequential presentation of Mondrian patterns with observer control of the chromaticity and luminance of the match illuminant and of just the chromaticity of the match illuminant. Indices were calculated for CIE 1976 (L^* u^* v^*) and CIE 1976 (u', v') spaces.

[b] SEs indicated in parentheses (see footnote b, Table 1).

Table 3
Colour-constancy indices for averages of matches over 20 observers[a]

		Simultaneous[b]	Sequential[b]
Match variables	Chromaticity and luminance (L^* u^* v^* space)	0.704 (0.060)	0.771 (0.039)
	Chromaticity (u', v' space)	0.781 (0.044)	0.872 (0.032)

[a] Colour-constancy indices for simultaneous and sequential presentation of Mondrian patterns with observer control of the chromaticity and luminance of the match illuminant and of just the chromaticity of the match illuminant. Indices were calculated for CIE 1976 (L^* u^* v^*) and CIE 1976 (u', v') spaces.

[b] SEs indicated in parentheses (see footnote b, Table 1).

calculated for individual patches were almost identical with those calculated for the corresponding illuminants.) When observers had control of both the chromaticity and luminance of the match illuminant, indices were calculated for three-dimensional CIE 1976 (L^* u^* v^*) colour space (Bäuml, 1999); the second illuminant, with correlated colour temperature 6700 K and luminance 50 cd m^{-2}, was taken as the nominally white light for this calculation (see e.g. Wyszecki & Stiles, 1982). When observers had control of just the chromaticity of the match illuminant, indices were calculated for two-dimensional CIE 1976 (u', v') colour space (Arend et al., 1991). Table 2 shows the indices averaged over the 20 observers for each of the two match conditions and for simultaneous and sequential presentation of the patterns.

With simultaneous presentation of the stimuli, the value of 0.60 for the mean colour-constancy index obtained with observer control of chromaticity and luminance (Table 2, first column of numbers, first row) is similar to previously reported values for asymmetric colour matching (e.g. Brainard et al., 1997, with nearly natural images), as is the value of 0.66 obtained with observer control of chromaticity (e.g. Arend et al., 1991). With sequential presentation of the stimuli, the mean value improved by 0.09 with control of both chromaticity and luminance of the match illuminant and by 0.09 with control of just the chromaticity of the match illuminant. These improvements in the index with change from simultaneous to sequential presentation were statistically significant, with and without observer control of luminance ($P < 0.01$, $P < 0.01$).

3.3. Variance versus bias in constancy index

The colour-constancy index suffers from the disadvantage that it confounds observer bias and variance; consequently, what appear to be departures from perfect colour constancy may in fact be the result of random errors. An indication of this confounding is given by the difference between (1) values of the colour-constancy index averaged over observers' matches and (2) values of the index for matches averaged over observers[7]. Table 2 shows the result of calculating (1). To calculate (2), observers' matches were averaged in (L^* u^* v^*) and (u', v') space (a legitimate operation because, as noted earlier, matches were expressed as illuminant settings), and the corresponding colour-constancy indices then obtained. Table 3 shows the result.

In all four conditions, the colour-constancy indices in Table 3 were larger than in Table 2, suggesting that the indices in Table 2 did indeed confound observer variance with bias. The advantage for sequential presentation remained statistically significant, with and without observer control of the luminance ($P < 0.05$, $P < 0.05$). The highest level of colour constancy was 0.87, obtained in the sequential condition with observers controlling just the chromaticity of the match illuminant. This value was also associated with the smallest standard error.

---

[7] More precisely, if $c(x, y)$ is the value of the colour-constancy index for an arbitrary match (x, y) and E is the operation of taking the mean, then $E(c(x, y)) \neq c(E(x, y))$.

4. Discussion

Fast illuminant changes can improve estimates of colour constancy in the unadapted eye. With sequential presentation of stimulus patterns, colour-constancy indices obtained by asymmetric colour matching increased by about 10% whether observers controlled both the chromaticity and luminance of the match illuminant or its chromaticity alone. This advantage held for both individual and group matching behaviour. In addition to improving colour constancy, sequential presentation reduced the variance of matches between observers by 25–30%.

4.1. Sources of variation

There was, however, considerable residual variance between observers, even in the best experimental condition. Between-observer variance, which has also been reported in other studies (Arend & Reeves, 1986; Arend et al., 1991; Troost & de Weert, 1991; Cornelissen & Brenner, 1995), has sometimes been attributed to the varying experience and knowledge of the observer. In the present work, all except one of the observers were untrained in the task, but each understood it sufficiently well to explain it back to the experimenter. There were also systematic differences in within-observer variance, which was correlated over experimental conditions (product-moment correlation coefficients r ranged between 0.70 and 0.83). Other stimulus-related sources of variation seem not to be significant; for example, a post-hoc analysis of the correlation between the degree of constancy and the chromaticity of the test patch showed little association ($r < 0.15$). As Arend and Reeves (1986) noted, in asymmetric colour matching the observer is presented with competing sources of information: the apparent colour of the test patch (hue, saturation, and brightness) versus the surface colour of the test patch. In general, the instructions given to the observer are intended to concentrate attention on one source of information or the other, but observers may attend in varying degrees to both. Adding transient cues to indicate the failure of a surface-colour match should reduce that ambiguity, which is consistent with what was found here. Even so, the present methodology remains imperfect in that observers still need to assess which of the two potentially uncertain cues to a surface-colour match they should prefer: the perceived goodness of the match itself or any transient cues to its failure.

4.2. Simultaneous colour constancy

The present measurements of simultaneous colour constancy differ in detail from those in some previous studies. Thus, with regard to stimuli, there were no grey boundaries to the patterns being compared, which might have provided a normalizing reference; the large number of test surfaces for which matches were recorded were randomly drawn from the Munsell set subject only to the constraint that they could be displayed on the colour monitor; and accidental similarities between test and surrounding surfaces in each pattern were eliminated. With regard to observers, a larger number than usual were tested; they were not instructed to adopt a particular matching strategy, other than to make a paper match; and their results were not rated. The degree of colour constancy obtained by simultaneous colour matching was, however, almost the same as that recorded by simultaneous colour matching with nearly natural images, about 0.6 (Brainard et al., 1997).

Higher indices were reported by Bäuml (1999) in measurements of simultaneous colour constancy with Mondrian patterns on a colour monitor: averaged over four observers, a colour-constancy index of 0.79 in (L^* u^* v^*) space was obtained. The reasons for this improved performance are unclear: it seems unlikely (Bäuml, 1999, personal communication) that observers exploited accidental similarities between the test and surrounding patches within the patterns; alternatively, it may have been simply that this group of observers, all having performed three practice sessions, were unusually competent; for comparison, in the present study, six of the 20 observers tested obtained (L^* u^* v^*) constancy indices of 0.79 or greater in the equivalent experimental condition.

4.3. Underlying mechanisms

It has been assumed here that temporal transient cues underlie the observed improvement in colour constancy with sequential pattern presentation. Although the improvement was limited, it should be considered in relation to the prediction from the time course of adaptation that constancy should be worse, not better, with sequential presentation. Conversely, it might be argued that sequential presentation should produce better constancy because it involves little or no memory load and the information that the observer needs to perform the task is immediately available, whereas simultaneous pattern presentation requires eye movements and must involve some memory load. Yet, as has been shown elsewhere (Linnell & Foster, 1996; Foster et al., 2000), the advantage of sequential presentation depends on the sharpness of the change from one image to the next: smoother changes, with rates less than 5 s^{-1}, produce poorer performance, even though no eye movements are required.

If temporal transient cues do underlie improved colour constancy, they are probably derived from a low-level signal based on spatial ratios of cone excitations or of combinations of cone excitations arising from light reflected from pairs of surfaces in the image. Under illuminant changes these ratios are preserved almost exactly for Munsell surfaces, and for surfaces with random spectral reflectances (Foster & Nascimento, 1994) and for those drawn from natural pastoral scenes (Nascimento et al., 1999). Moreover, deviations in these ratios are interpreted by observers as being due to changes in surface reflectance even when they are actually due to changes in illuminant (Nascimento & Foster, 1997). Such signals, which do not require adaptation to the illuminated scene nor knowledge of the illuminant (D'Zmura & Iverson, 1994), could be generated early in the visual pathway, perhaps within the eye itself (Cornelissen & Brenner, 1995; Rüttiger et al., 1999), but as illuminant changes can be discriminated moderately well from non-illuminant changes in dichoptically viewed images (Nascimento & Foster, 1998), cone-excitation ratios might also be computed more centrally, as part of a multi-stage analysis of surface colour (Walsh, 1999). They cannot of course account for the whole of colour constancy, for the colour percept associated with any particular surface requires a spectral reference to anchor cone-ratio information (Land, 1959; Gilchrist et al., 1999). Nevertheless, from the evidence presented here, cone-excitation ratios may play a significant role in the detection of violations of colour constancy.

Acknowledgements

This work was supported by the Biotechnology and Biological Sciences Research Council (grant no. S08656), the Centro de Física da Universidade do Minho, Braga, Portugal, and the British Council. We thank V. S. Isham for advice. A partial account of the data presented here was abstracted in Foster et al. (2000). We thank J. P. S. Parkkinen, J. Hallikainen, and T. Jaaskelainen for providing data for the spectral reflectances of the Munsell papers.

References

Arend, L., & Reeves, A. (1986). Simultaneous color constancy. *J. Opt. Soc. Am. A*, *3*, 1743–1751.

Arend, L. E. (1993). How much does illuminant color affect unattributed colors? *J. Opt. Soc. Am. A*, *10*, 2134–2147.

Arend, L. E., Reeves, A., Schirillo, J., & Goldstein, R. (1991). Simultaneous color constancy: papers with diverse Munsell values. *J. Opt. Soc. Am. A*, *8*, 661–672.

Bäuml, K.-H. (1999). Simultaneous color constancy: how surface color perception varies with the illuminant. *Vision Res.*, *39*, 1531–1550.

Brainard, D. H. (1998). Color constancy in the nearly natural image. 2. Achromatic loci. *J. Opt. Soc. Am. A*, *15*, 307–325.

Brainard, D. H., Brunt, W. A., & Speigle, J. M. (1997). Color constancy in the nearly natural image. 1. Asymmetric matches. *J. Opt. Soc. Am. A*, *14*, 2091–2110.

Brainard, D. H., & Wandell, B. A. (1992). Asymmetric color matching: how color appearance depends on the illuminant. *J. Opt. Soc. Am. A*, *9*, 1433–1448.

Bramwell, D. I., & Hurlbert, A. C. (1996). Measurements of colour constancy by using a forced-choice technique. *Perception*, *25*, 229–241.

Brown, R. O., & MacLeod, D. I. A. (1997). Color appearance depends on the variance of surround colors. *Curr. Biol.*, *7*, 844–849.

Cataliotti, J., & Gilchrist, A. (1995). Local and global processes in surface lightness perception. *Percept. Psychophys.*, *57*, 125–135.

Cleveland, W. S. (1994). *The elements of graphing data*. Summit, N.J: Hobart Press.

Cornelissen, F. W., & Brenner, E. (1995). Simultaneous colour constancy revisited: an analysis of viewing strategies. *Vision Res.*, *35*, 2431–2448.

Craven, B. J., & Foster, D. H. (1992). An operational approach to colour constancy. *Vision Res.*, *32*, 1359–1366.

D'Zmura, M., & Iverson, G. (1994). Color constancy. III. General linear recovery of spectral descriptions for lights and surfaces. *J. Opt. Soc. Am. A*, *11*, 2389–2400.

Efron, B., & Tibshirani, R. J. (1993). *An introduction to the bootstrap*. New York.: Chapman & Hall.

Fairchild, M. D., & Lennie, P. (1992). Chromatic adaptation to natural and incandescent illuminants. *Vision Res.*, *32*, 2077–2085.

Fairchild, M. D., & Reniff, L. (1995). Time-course of chromatic adaptation for color-appearance judgments. *J. Opt. Soc. Am. A*, *12*, 824–833.

Foster, D. H., Amano, K., & Nascimento, S. M. C. (2000). How temporal cues can aid colour constancy, *Col. Res. Appl.*, in press.

Foster, D. H., Craven, B. J., & Sale, E. R. H. (1992). Immediate colour constancy. *Ophthal. Physiol. Opt.*, *12*, 157–160.

Foster, D. H., & Nascimento, S. M. C. (1994). Relational colour constancy from invariant cone-excitation ratios. *Proc. R. Soc. Lond. B*, *257*, 115–121.

Gilchrist, A., Kossyfidis, C., Bonato, F., Agostini, T., Cataliotti, J., Li, X. J., Spehar, B., Annan, V., & Economou, E. (1999). An anchoring theory of lightness perception. *Psychol. Rev.*, *106*, 795–834.

Jaaskelainen, T., Parkkinen, J., & Toyooka, S. (1990). Vector-subspace model for color representation. *J. Opt. Soc. Am. A*, *7*, 725–730.

Jin, E. W., & Shevell, S. K. (1996). Color memory and color constancy. *J. Opt. Soc. Am. A*, *13*, 1981–1991.

Judd, D. B., MacAdam, D. L., & Wyszecki, G. (1964). Spectral distribution of typical daylight as a function of correlated color temperature. *J. Opt. Soc. Am.*, *54*, 1031–1040.

Kraft, J. M., & Brainard, D. H. (1999). Mechanisms of color constancy under nearly natural viewing. *Proc. Natl. Acad. Sci. USA*, *96*, 307–312.

von Kries, J. (1905). Die Gesichtsempfindungen. In W. Nagel, *Handbuch der physiologie des menschen (Physiologie der sinne vol. 3)*, (pp. 109–282). Braunschweig: Vieweg und Sohn.

Kuriki, I., & Uchikawa, K. (1996). Limitations of surface-color and apparent-color constancy. *J. Opt. Soc. Am. A*, *13*, 1622–1636.

Land, E. H. (1959). Color vision and the natural image. Part I. *Proc. Natl. Acad. Sci. USA*, *45*, 115–129.

Linnell, K. J., & Foster, D. H. (1996). Dependence of relational colour constancy on the extraction of a transient signal. *Perception*, *25*, 221–228.

Lucassen, M. P., & Walraven, J. (1993). Quantifying color constancy: evidence for nonlinear processing of cone-specific contrast. *Vision Res.*, *33*, 739–757.

Maloney, L. T. (1999). Physics-based approaches to modeling surface color perception. In K. R. Gegenfurtner, & L. T. Sharpe, *Color vision: from genes to perception* (pp. 387–416). Cambridge: Cambridge University Press.

Munsell Color Corporation (1976). *Munsell book of color — matte finish collection*. Baltimore, MD: Munsell Color Corporation.

Nascimento, S. M. C., Ferreira, F. P., & Foster, D. H. (1999). Statistics of natural surface reflectance functions by fast multispectral imaging. *Invest. Ophthalmol. Vis. Sci.*, *40*, S748.

Nascimento, S. M. C., & Foster, D. H. (1997). Detecting natural changes of cone-excitation ratios in simple and complex coloured images. *Proc. R. Soc. Lond. B*, *264*, 1395–1402.

Nascimento, S. M. C., & Foster, D. H. (1998). Detecting changes in dichoptic spatial cone-excitation ratios. *Invest. Ophthalmol. Vis. Sci.*, *39*, S615.

Parkkinen, J. P. S., Hallikainen, J., & Jaaskelainen, T. (1989). Characteristic spectra of Munsell colors. *J. Opt. Soc. Am. A*, *6*, 318–322.

Rinner, O., & Gegenfurtner, K. R. (2000). Time course of chromatic adaptation for color appearance and discrimination. *Vision Res.*, *40*, 1813–1826.

Rüttiger, L., Braun, D. I., Gegenfurtner, K. R., Petersen, D., Schönle, P., & Sharpe, L. T. (1999). Selective colour constancy deficits after circumscribed unilateral brain lesions. *J. Neurosci.*, *19*, 3094–3106.

Speigle, J. M., & Brainard, D. H. (1999). Predicting color from gray: the relationship between achromatic adjustment and asymmetric matching. *J. Opt. Soc. Am. A*, *16*, 2370–2376.

Troost, J. M., & de Weert, C. M. M. (1991). Naming versus matching in color constancy. *Percept. Psychophys.*, *50*, 591–602.

Valberg, A., & Lange-Malecki, B. (1990). "Colour constancy" in Mondrian patterns: a partial cancellation of physical chromaticity shifts by simultaneous contrast. *Vision Res.*, *30*, 371–380.

Walsh, V. (1999). How does the cortex construct color? *Proc. Natl. Acad. Sci. USA*, *96*, 13594–13596.

Webster, M. A., & Mollon, J. D. (1995). Colour constancy influenced by contrast adaptation. *Nature*, *Lond.*, *373*, 694–698.

Whittle, P. (1996). Perfect von Kries contrast colours. *Perception*, *Suppl.*, *25*, 16.

Wyszecki, G., & Stiles, W.S. (1982). *Color science: concepts and methods*, *quantitative data and formulae* (2nd ed.), New York: Wiley.

Zaidi, Q., Spehar, B., & DeBonet, J. (1997). Color constancy in variegated scenes: role of low-level mechanisms in discounting illumination changes. *J. Opt. Soc. Am. A*, *14*, 2608–2621.