How Temporal Cues Can Aid Colour Constancy

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Abstract: Colour constancy assessed by asymmetric simultaneous colour matching usually reveals limited levels of performance in the unadapted eye. Yet observers can readily discriminate illuminant changes on a scene from changes in the spectral reflectances of the surfaces making up the scene. This ability is probably based on judgments of relational colour constancy, in turn based on the physical stability of spatial ratios of cone excitations under illuminant changes. Evidence is presented suggesting that the ability to detect violations in relational colour constancy depends on temporal transient cues. Because colour constancy and relational colour constancy are closely connected, it should be possible to improve estimates of colour constancy by introducing similar transient cues into the matching task. To test this hypothesis, an experiment was performed in which observers made surface-colour matches between patterns presented in the same position in an alternating sequence with period 2 s or, as a control, presented simultaneously, side-by-side. The degree of constancy was significantly higher for sequential presentation, reaching 87% for matches averaged over 20 observers. Temporal cues may offer a useful source of information for making colour-constancy judgments. © 2000 John Wiley & Sons, Inc. Col Res Appl, 26, S180–S185, 2001

Key words: colour constancy; relational colour constancy; temporal transients; surface colour; spatial cone-excitation ratios

INTRODUCTION

Colour constancy is commonly interpreted as the invariant perception of the colours of surfaces under changes in illuminant, although there are other forms of colour constancy such as the invariant perception of the colours of surfaces under changes in object position (displacement colour constancy) and under changes in viewing medium (atmospheric colour constancy).[1-3] Relational colour constancy is similar to colour constancy, but refers to the invariant perception of the relations between the colours of surfaces under changes in illuminant,[4] or, by analogy with colour constancy, under changes in object position or viewing medium.

As has been made clear elsewhere,[5] illuminant colour constancy is usually assessed for two distinct adaptational conditions of the eye: one where the eye is allowed to become adapted to the differently illuminated scenes and another where little such adaptation takes place. This study is concerned with the latter condition and how the measurement of colour constancy by asymmetric colour matching might be improved by exploiting violations in relational colour constancy. To help explain the approach, results

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from previous studies, some unpublished, are first brought together, and some new experimental data on surface-colour matching are then described.

Unless otherwise indicated, all descriptions of stimuli refer to simulations of surfaces and illuminants on the screen of a computer-controlled colour monitor. A direct comparison of colour constancy for stimuli presented on a colour monitor and for stimuli consisting of physically illuminated matte coloured papers has suggested little difference between the two methods.[6]

MEASURING COLOUR CONSTANCY

A standard laboratory method of assessing the degree to which observers are colour constant is based on asymmetric simultaneous colour matching.[5,7] The observer matches a surface in one Mondrian-like pattern under one illuminant against the same surface in an identical pattern under another illuminant. The surfaces are viewed simultaneously, usually side-by-side. The match is asymmetric in that the mean retinal adaptation provided by the two sides of the viewing field are different. The observer moves his or her gaze repeatedly back and forth from one pattern to the other to avoid adapting to either.[8a]

The degree of colour constancy obtained depends on the particular experimental stimuli, the nature of the task, and the individual observer. With stimuli presented on a colour monitor and the observer instructed to make a "paper match", reported levels of simultaneous colour constancy have rarely exceeded 0.6–0.7, where 1.0 corresponds to perfect constancy.[7,8,11] Using illuminated reflecting surfaces as stimuli rather than their simulations on a computer monitor has yielded similar values.[12b] Why is measured performance not better? One reason may be that insufficient use is made of all the stimulus cues available.

OPERATIONAL APPROACH

Consider the following operational approach to surface-colour perception based on a simple discrimination task. In experiments described elsewhere,[16,17] observers were presented with Mondrian patterns undergoing either (1) an illuminant change or (2) an illuminant change with an additional material (spectral-reflectance) change. Illuminants were drawn from the daylight locus. The illuminant change was spatially uniform and the material change was simulated by applying a spatially nonuniform illuminant change (half of the patches in the pattern, selected at random, were subjected to a locally uniform illuminant change in one direction along the daylight locus, and the remaining half were subjected to a locally uniform illuminant change in the opposite direction). As the latter change could not be obtained by a spatially uniform (or spatially slowly varying) change in illuminant, it had the parsimonious interpretation that it was due to a change in materials. In this way, the stimuli were parameterized so that the magnitudes of the illuminant and material changes were commensurable. Observers were able to discriminate between illuminant and material changes quickly, effortlessly, and reliably, and required little or no training.[16,17]

How is this performance achieved? One possibility is that instead of attempting to estimate the illuminant or extract an illuminant-invariant estimate of surface colour[18,19] to make the required discriminations, observers simply assessed whether the perceived relations between the colours of surfaces were preserved, that is, whether relational colour constancy held.[c] Discriminating between illuminant changes and material changes partitions colour signals (the cone inputs from each surface in the scene) into classes that correspond one-to-one with constant colour percepts.[4] And discriminating illuminant changes from material changes also corresponds to discriminating whether the relations between surface colours are unchanged.

These spatial colour relations could be coded physically by the ratios of cone excitations—or ratios of some related quantities such as opponent-colour signals—generated in response to light reflected from different illuminated surfaces. Notice that these ratios refer to excitations within rather than between cone classes. Thus, suppose that $q_i(a)$ and $q_i(b)$ are the excitations in cone class i (where $i = 1, 2, 3$, corresponding to short-, medium-, and long-wavelength-sensitive cones) produced by light reflected from surfaces a and b under some illuminant e. Let r_i be the quotient $q_i(a)/q_i(b)$. Then it can be shown by computational simulation[4] that, for a large class of pigmented surfaces (the full Munsell set) and for classes of surfaces with spectral reflectances that are random functions of wavelength, these ratios r_i are, on average, almost invariant under changes in the illuminant e, whether e is drawn randomly from the sun and sky (correlated colour temperatures 4300–25,000 K) or from a Planckian radiator (2000–100,000 K). This stability is preserved and possibly improved when computed for natural scenes.[20] Taking, instead, spatial ratios of combinations of opponent and nonopponent cone excitations[21,22] may produce only modest improvements in stability.[23,29]

To summarize, relational colour constancy has a natural physical substrate: the almost-invariant ratio between activ-

[a] Adaptation is, of course, allowed to become complete in the dichoptic version of asymmetric simultaneous colour matching, where one Mondrian pattern is presented to one eye and the other pattern is presented to the other eye. Under these steady differential adaptation conditions, von Kries mechanisms dominate.[9,10]

[b] Making achromatic judgments about neutral surfaces in a physically illuminated coloured scene has yielded higher levels of colour constancy,[13,14] but the connection between these achromatic judgments and chromatic judgments is not fully resolved.[3,15]

[c] In this context, relational colour constancy may be regarded formally as a weaker notion than colour constancy,[3] but given a sufficient gamut of illuminants, it is possible to generate an illuminant-invariant percept.[4] Relational colour constancy is sometimes invoked implicitly in standard asymmetric colour matching: observers are asked to attend to the colour relations in a Mondrian pattern in an attempt to improve surface-colour matches.[5,7,8]

ity levels in a cone class for a given pair of surfaces under illuminant changes.

DO SPATIAL CONE-EXCITATION RATIOS PROVIDE THE CUE?

As already indicated, the invariance of spatial cone-excitation ratios for natural surfaces and illuminants is almost but not quite complete; the extent of the failure is a few percent.[4,20] If observers do indeed use spatial cone-excitation ratios to make inferences about relational colour constancy, then deviations of these ratios under an illuminant change, if visually detectable, should be misinterpreted as being due to surfaces undergoing a spectral-reflectance change.

This hypothesis was tested[23] in an experiment with Mondrian patterns containing either 49 or two surfaces subjected to either (1) an illuminant change or (2) the same illuminant change, but for which the images were corrected so that spatial cone-excitation ratios were preserved exactly. The surfaces were drawn randomly from the Munsell set, and the illuminants randomly from the set of Planckian radiators. The extent of the deviation of the ratios in the uncorrected images (1) was varied systematically by sampling repeatedly from the population of surfaces and illuminants. A separate computational simulation showed that the particular corrected images (2) corresponded to highly improbable natural events. Nevertheless, observers systematically misidentified the corrected images as containing the illuminant changes, the probability of error increasing as the size of the deviations in the ratios increased. For the range of surfaces and illuminants tested, the sensitivity to deviations in ratios was found to depend on cone class. It was greatest for long-wavelength-sensitive cones and least for short-wavelength-sensitive cones, and in proportions similar to those underlying the photopic luminance-sensitivity function. (It may be relevant that other measurements of asymmetric colour matching have reported failures in colour constancy attributable mainly to short-wavelength-sensitive cone signals.[24]) As shown later, however, the observed distribution of sensitivities over the three cone classes does not mean that the ability to discriminate between illuminant and material changes is a consequence of processing solely within a luminance channel.

EFFECTS OF OMITTING A CONE CLASS

If, as suggested, relational colour constancy involves computations within cone classes (or possibly within post-receptoral channels), the loss of one cone class might result in only a modest loss in the ability to discriminate illuminant from material changes, providing that there was no significant loss in coverage of the spectrum. This hypothesis was tested in an experiment with two protanopes and two deuteranopes[25] (subsequently with three protanopes and three deuteranopes[26]). Their task, as for normal controls, was to discriminate illuminant changes from material changes in Mondrian patterns. The changes in illuminant were drawn from the daylight locus.

These dichromats were able to make the required discriminations about as well as normal observers could over the same conditions. It is possible, however, that red-green dichromats might have been less disadvantaged than expected, because their confusion loci are almost perpendicular to the daylight locus. Changes in daylight would, therefore, have produced detectable changes in chromaticity, which might have been used in some way to make illuminant-material-change discriminations.

As a test of this potential cue, the experiment was repeated with unnatural illuminants generated from the same spectral basis functions underlying the daylights, but constrained to vary along a protanopic or deuteranopic confusion line. A deuteranope and a protanope were examined. The deuteranope was still able to make the required discriminations, but the protanope performed poorly, possibly owing to his reduced spectral coverage at one spectral extreme.[25]

In an independent study of colour constancy using an achromatic matching task,[27] red-green colour-deficient observers were also found to produce almost normal levels of performance; their matches were as variable along a blue-yellow axis as along a red-green axis.[28]

LIGHTNESS CONSTANCY?

In that relational colour constancy appears to depend on the spatial ratios of cone excitations computed within rather than between cone pathways and in proportions related to the photopic luminance-sensitivity function, it might be argued that this constancy is based solely on relative luminance processing. This hypothesis was examined in an experiment[29] in which the discriminability of illuminant and material changes was measured in three types of Mondrian-pattern images: (1) isoluminant images, which, therefore, contained no luminance cues; (2) achromatic images, which, therefore, contained no chromatic cues; and (3) unmodified images. If relational colour constancy depended solely on relative luminance processing, performance should be indistinguishable for (2) and (3), but fall to chance levels for (1). In fact, observers were able to make reliable discriminations with all three types of images, with broadly similar levels of performance, implying that relational colour constancy is not based on processing within either luminance or chromaticity pathways alone.

To test more precisely whether spatial cone-excitation ratios could account for observed performance, a model was constructed that used a signal proportional to the size of the deviations in spatial cone-excitation ratios.[29] The model predictions accounted well for the variance in the data over all three image types. A model using a signal proportional to the size of the deviations in spatial ratios of opponent and nonopponent combinations of cone excitations produced slightly poorer fits.[29]

WHERE ARE RATIOS COMPUTED?

Because ratios involve the comparison of signals from pairs of surfaces, it might be assumed that these computations are performed spatially locally and retinally.[8,27,30] Yet, in principle, they could be computed at some higher level in the visual system.[d] To test whether ratios could be computed across the two eyes, the following experiment was performed.[31] In a two-interval design, observers were presented with pairs of abutting Munsell surfaces undergoing two types of colorimetric changes: in one interval, an illuminant change included a small change in spatial cone-excitation ratios; in the other, a similar change took place, but cone-excitation ratios were constant. The observer's task was to identify the interval containing the illuminant change. The experiment had two conditions: in one, the surfaces were viewed binocularly; in the other, one surface was viewed by one eye and the other was viewed by the other eye. Observers reliably discriminated between the two intervals in both viewing conditions, although less well in the dichoptic condition. This result does not, of course, imply that there is no retinal contribution to the computation of spatial cone-excitation ratios, but it does establish the possibility of a similar computation taking place centrally.

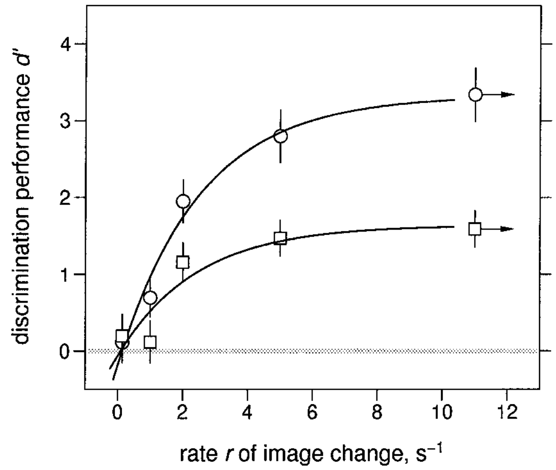

FIG. 1. Discrimination performance d' as a function of the rate r of image change for two observers (indicated by circles and squares). The two data points with arrows show asymptotic values of d' for the shortest transition interval of 0 ms. The smooth curves are best-fitting saturating functions of the form $1 - \exp(-r/\rho)$, where ρ is the rate constant. Further experimental details are given elsewhere.[32]

RATE OF ILLUMINANT CHANGE

Does the cue provided by deviations in spatial cone-excitation ratios take the form of a transient or more sustained signal? This question was addressed in an experiment in which illuminant and material changes were applied to Mondrian patterns at different rates.[32] The transition from one image to the next was ramped over intervals whose durations was drawn from the range 0, 200, 500, 1000, and 7000 ms (where 0 ms corresponds to a change within one frame refresh of the monitor, i.e., 16.7 ms). Thus, the first image was displayed for 1 s; it was transformed over the selected interval; and then the second image was displayed for 1 s. The observer's task was the same as in earlier experiments, namely, to discriminate between an illuminant change and a material change. (An additional control experiment showed that increasing the total display duration by increasing the transition interval did not significantly affect performance.)

The results shown in Fig. 1 have been replotted from the original data to show discrimination performance (discrimination index d' from signal-detection theory[33]) as a function of the rate r of image change (reciprocal of the transition interval measured in s) for two observers. The two data points with arrows show the asymptotic values of d' for the shortest transition interval of 0 ms. The smooth curves are best-fitting saturating functions of the form $1 - \exp(-r/\rho)$, where ρ is the rate constant. Despite the differences in absolute levels of performance by the two observers, their optimum rate constants ρ were very similar: 2.4 and 2.5 s^{-1}.

Performance improved smoothly as the rate r of image change increased. It was close to chance levels at rates of 1 s^{-1} or less and was best at the highest rates of change, that is, greater than 5.0 s^{-1}. Phenomenologically, high rates of image change produced a "pop-out" effect with material changes, but little or none with illuminant changes. It seems that the cue for detecting deviations in cone-excitation ratios is predominantly a transient one, although the temporal resolution of the display system used in the experiment was not sufficiently fine to determine the detailed time course of the underlying signal.

SEQUENTIAL SURFACE-COLOUR MATCHING

Given (1) the close connection between colour constancy and relational colour constancy, (2) the operational interpretation of relational colour constancy in terms of discriminating illuminant changes from material changes, and (3) the sensitivity of this task to temporal transient cues, is it possible to improve standard measures of colour constancy by introducing similar transient cues? To answer this question, an experiment[34] was undertaken in which colour constancy was estimated by asymmetric colour matching across two Mondrian patterns that were presented in rapid temporal sequence, in the same position. To provide a matched control, the experiment was repeated with the Mondrian patterns presented steadily, side-by-side, in the usual way.

One Mondrian pattern was presented under a fixed daylight of colour temperature 25,000 K and luminance approx. 50 cd m^{-2}; the other Mondrian pattern, made of the same materials in the same positions, was presented under a fixed daylight of colour temperature 6700 K and of the same luminance, except for the center patch of the pattern, where the 6700 K daylight was replaced by an adjustable local illuminant constructed from the daylight spectral basis functions of Judd *et al*.[35] with variable coefficients. By adjusting these coefficients with a computer joy-pad, the observer could vary the colour of the local illuminant over a large convex region of colour space around the point correspond-

[d] A suggestion made by A. Hurlbert, at Trieste, 1995.

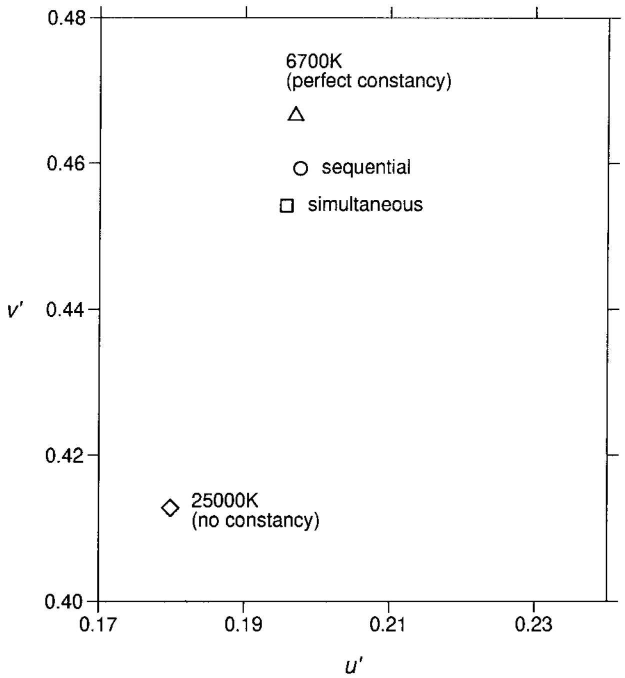

FIG. 2. Average local-illuminant settings for surface-colour matches made by 20 observers controlling just the chromaticity of stimuli presented simultaneously (open square) and sequentially (open circle).

ing to 6700 K. Fresh Mondrian patterns were generated in each trial. Each observer made paper matches in each of four experimental conditions (simultaneous and sequential stimulus presentation; with both chromatic and luminance control of the local illuminant[12] and with just chromatic control[5]). The instructions to observers concerning surface-colour matches were similar to those given in studies by Arend and Reeves.[5,7] With simultaneous stimulus presentation, observers were expected to move their eyes from one pattern to the other[8]; with sequential stimulus presentation, however, there was, in principle, no need to move their eyes at all.

Figure 2 shows, in CIE 1976 (u', v') colour space, local-illuminant settings for surface-colour matches averaged over 20 observers controlling just the chromaticity of stimuli presented simultaneously (open square) and sequentially (open circle). It can be seen that, with sequential presentation, matches were closer to the 6700 K illuminant, representing perfect colour constancy.

To quantify any improvement, Arend and Reeves' constancy index[7] was calculated for the local-illuminant settings[12] averaged over all observers.[e] Depending on whether observers controlled both chromaticity and luminance or just chromaticity, matches were expressed in CIE 1976 (L^* u^* v^*) space or (u', v') space, respectively. Thus, in each space, if a is the distance between the observer's setting and the 6700 K illuminant and b is the distance between the 25,000 K and 6700 K illuminants, then the constancy index is $1 - a/b$. Table I shows colour-constancy indices for the four experimental conditions.

TABLE I. Colour-constancy indices (±1 sem) for simultaneous and sequential presentation of Mondrian patterns. Observers controlled either both chromaticity and luminance or just the chromaticity of the match. Values shown are for matches averaged over 20 observers.

		Simultaneous	Sequential
Control variables	Chromaticity and luminance ($L^*u^*v^*$ metric)	0.70 (0.06)	0.77 (0.04)
	Chromaticity (u', v' metric)	0.78 (0.04)	0.87 (0.03)

Over the 20 observers, the difference between simultaneous and sequential stimulus presentation was significant, with and without observer control of the luminance ($p = 0.04$ and $p = 0.02$, respectively).

CONCLUSION

Abrupt changes in illuminant occur naturally in everyday life, for example, when a cloud passes over the sun, or when an incandescent lamp is switched on in a daylit room, or when someone moves in front of the light and casts a shadow. Relational colour constancy is generally preserved within the affected region, and observers are acutely sensitive to its failure.

The evidence presented here suggests that the ability to detect violations in relational colour constancy depends on temporal transient cues from changes in spatial ratios of cone excitations, or of some closely related quantities. These ratios may be computed centrally as well as retinally, and they need not be confined to a luminance channel. It was proposed that, because relational colour constancy and colour constancy are closely connected, it should be possible by introducing stronger transient cues to improve estimates of colour constancy based on surface-colour matching of illuminated Mondrian patterns. As anticipated, matching performance was found to be better by presenting images sequentially in the same position, where transient cues were strong, than by presenting images continuously in the same position, where these cues were weak or absent.[f] This advantage held whether observers controlled both the chromaticity and luminance or just the chromaticity of the match.[g]

[e] Indices calculated from local illuminant settings were almost the same as values calculated from individual surface matches.

[f] Weak transient cues could be generated with simultaneous images as the observer looked repeatedly back and forth from one side to the other,[8] but these cues are likely to be masked by the eye movements themselves.[36,37]

[g] It might be argued that the advantage for sequential presentation derives more from the fact that the images are in the same position, rather than from their alternation. Yet it was shown earlier (Fig. 1) that sequential presentation is not itself sufficient for good discrimination performance:

The method of surface-colour matching described here is a hybrid one, in the sense that there were at least two sources of information available to the observer: (1) transient cues from changes in spatial cone-excitation ratios indicating violations in relational colour constancy and (2) other more sustained cues used by observers to make colour-constant matches across steady images. It is not obvious what relative weight observers placed on these two information sources, which may have been competitive, because asymmetric colour matching with continuously presented images biased settings away from perfect colour constancy and towards hue-saturation-brightness matches. Estimates of colour constancy might, therefore, be improved further by devising a task that depends solely on transient cues.

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the image change must also be rapid. Despite the phenomenology, it might be argued that the advantage for sequential presentation comes from the different memory loads involved, but any estimate of the load for sequential presentation must include an effect of backward image masking, which would increase the effective interval between the stimuli. It is difficult to circumvent this problem, for using different spatial configurations of the sequentially presented surfaces would disrupt the spatial registration of the ratio signals across the two images, and consequently weaken the transient cues.

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