

CHAPTER 22

TRITANOPIC COLOUR CONSTANCY UNDER DAYLIGHT CHANGES?

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Introduction

Thomas Young (1807) encapsulated the phenomenon of illuminant colour constancy by observing that a piece of writing paper retained its whiteness in a room illuminated either by the yellow light of a candle or by the red light of a fire. In the natural environment, the most common illuminant changes on surfaces are due to changes in daylight. How, then, do colour-constancy judgements vary under daylight changes?

To address this question, an experiment was performed to estimate the distributional properties of colour-constancy judgements. An operational approach was adopted in which observers were required to distinguish illuminant changes on a scene from changes in the reflecting properties of the surfaces comprising it (Craven and Foster 1992; cf. Rüttiger *et al.* 2001)¹. Thus, observers with normal colour vision were presented with computer simulations of a Mondrian-like pattern undergoing a change in daylight illuminant, and, at the same time as this illuminant change, the reflectance spectrum of the centre patch of the pattern also changed, its magnitude and colour direction varying from trial to trial. The frequency of “illuminant-change” responses was plotted against an equivalent illuminant change in the CIE 1976 (u' , v') chromaticity diagram (cf. Bramwell and Hurlbert 1996). To determine whether an anisotropy in this distribution was related to a diminished contribution from short-wavelength-sensitive cones, the same measurements were undertaken by two tritan observers, and, to provide a theoretical reference, performance of both colour-normal and tritan observers was modelled computationally using the information available from long-, medium-, and short-wavelength-sensitive cones.

1 Making these discriminations is equivalent to partitioning colour signals—the cone inputs from each surface in the scene—into classes that correspond one-to-one with constant colour percepts (Foster and Nascimento 1994, appendix I).

Methods

Stimuli and apparatus

The stimulus 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, drawn randomly from 1269 samples in the Munsell Book of Color (Munsell Color Corporation 1976). The random sampling producing each pattern was repeated, if necessary, to eliminate any accidental similarities between pairs of surfaces. Fresh random samples were drawn in each trial. Patterns were presented in a dark surround and were viewed binocularly at 100 cm.

One pattern was presented under a fixed, spatially uniform daylight of correlated colour temperature 25000 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 square where the 6700 K daylight was replaced by a spatially uniform local illuminant constructed from a linear combination of the daylight spectral basis functions due to Judd *et al.* (1964). The chromaticity of this local illuminant was sampled randomly in each trial from a large convex gamut in the (u', v') diagram comprising 56 points (shown by the small solid points in Fig. 22.2). Its luminance was sampled randomly from three values: 41, 50, and 59 cd/m^2 . Varying the chromaticity and luminance of this local illuminant is closely related (but not equivalent) to varying the chromaticity and luminance of the centre patch, but this parameterization in terms of an illuminant had the advantage that it was independent of the spectral reflectance of the centre surface (Foster *et al.* 2001).

Stimuli were generated on the screen of a 20-in., 1024×768 pixels, RGB colour display monitor (Trinitron, model GDM-20SE2T5; Sony, Tokyo, Japan), controlled by a computer with a raster-graphics card (VSG2/3F; Cambridge Research Systems, Rochester, UK) providing a nominal 15-bit intensity resolution per gun. Only the central 11 cm (4 in.) of the screen was used for stimuli. The screen refresh rate was approx. 100 Hz. A telespectroradiometer (PhotoResearch Inc., SpectraColorimeter PR-650, Chatsworth, CA, USA), calibrated by the National Physical Laboratory, was used for regular calibration of the display system. 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 per cent in Y (<5 per cent at low light levels).

Procedure

In each trial, the two patterns appeared sequentially in the same position, each for 1 s, with no interval. The task of the observer was to decide whether the surfaces in the successive patterns were the same, that is, whether the change was a pure illuminant change. Responses were made on a joystick connected to the computer. Fresh patterns were generated in each trial. Each observer performed in all about 20 trials at each of the 168 (56×3) sample points of the local illuminant, but in random order; that is, in

each trial, each combination of chromaticity and luminance of the local illuminant was drawn randomly without replacement from about 3360 values.

Subjects

Colour vision was classified with clinical methods, e.g. Ishihara pseudo-isochromatic plates, Farnsworth-Munsell 100-Hue test, Rayleigh and Moreland anomaloscopy (Interzeag Color Vision Meter 712, Schlieren, Switzerland), and luminance matching and increment thresholds on a white background. All observers had normal visual acuity in each eye, verified optometrically. There were 20 observers with normal colour vision, 9 male and 11 female, aged 21–36 years; and two tritanopic observers, both male and aged 52 and 56 years. Although these two observers' colour deficiency was consistent with it being inherited, the possibility cannot be excluded that they may have possessed short-wavelength-sensitive cones that were undetected in the present measurements. As shown later, however, their discriminations of illuminant changes from reflectance changes were not better than expected from predictions of model based on their having no short-wavelength-sensitive cones.

Results and discussion

The frequency of “illuminant-change” responses was calculated as a function of the chromaticity of the local illuminant in the (u', v') chromaticity diagram collapsed over luminance levels of the local illuminant. A three-dimensional perspective plot of the distribution is shown in Fig. 22.1 for pooled data from the 20 observers with normal colour vision. Each plot point was based on 1650 trials.

Despite the approximate uniformity of the (u', v') chromaticity diagram in this region of the colour space, the distribution of responses was anisotropic: observers were less able to detect spectral reflectance changes in one direction than in another (an analogous result was obtained by Rüttiger *et al.* (2001) in an achromatic matching task). The long axis of the distribution is shown more clearly in the contour plot of Fig. 22.2(a), where the darker the contour, the higher the frequency of “illuminant-change” responses. Also shown in the figure are the points corresponding to the first and second illuminants (open square and circle, respectively), the curve corresponding to the daylight locus (L), and the protanopic, deuteranopic, and tritanopic confusion lines (P , D , and T , respectively) passing through the chromaticity coordinates of the second illuminant. If perfect colour constancy had obtained, then the response contours would have been centred on the coordinates of the second illuminant, but the peak of the distribution is shifted towards the first illuminant (open square) (Bramwell and Hurlbert 1996; Foster *et al.* 2001).

The long axis of the distribution is close to the tritanopic confusion line (T), although biased towards the daylight locus (L) (Rüttiger *et al.* 2001). Is the anisotropy therefore a consequence of the failure of short-wavelength-sensitive cones to contribute fully towards the discrimination task? Some support for this hypothesis comes from an experiment

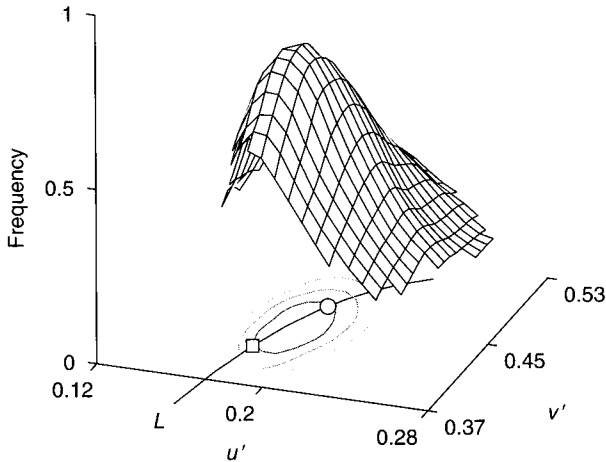


Figure 22.1 Detectability of changes in surface colour during illuminant changes for observers with normal colour vision. The three-dimensional perspective plot based on the 1976 CIE (u' , v') chromaticity diagram shows the frequency of "illuminant-change" responses as a function of the colour of the local illuminant (simulating a reflectance change) on the centre patch of a Mondrian-like pattern. The daylight locus is indicated (L).

where observers viewed images in which the ratios of cone-specific excitations arising from light reflected from pairs of surfaces were altered (Nascimento and Foster 1997). In that experiment, observers had to discriminate between a natural illuminant change on a pattern in which ratios were almost but not exactly preserved (Foster and Nascimento 1994) and the same illuminant change in which the image was corrected so that ratios were preserved exactly. Sensitivity to deviations in these ratios was found to be almost absent for short-wavelength-sensitive cones. Other measurements based on asymmetric colour matching have also pointed to failures in colour constancy associated with short-wavelength-sensitive cones (Bäumel 1999).

To test this hypothesis here, the distribution of the detectability of reflectance changes (Fig. 22.1) was determined for two tritan observers. If short-wavelength-sensitive cones contribute little to the task, then the distribution of responses should be similar to that for normal controls. The pooled contour plot for tritan observers is shown in Fig. 22.2(b). Although based on fewer trials per point (120 versus 1650 in Fig. 22.2(a)), the distribution is more elongated than for normal controls, and its long axis, defined more clearly at lower response frequencies, is close to the tritanopic confusion line (T), although, rather as with normal observers, biased slightly towards the daylight locus (L).

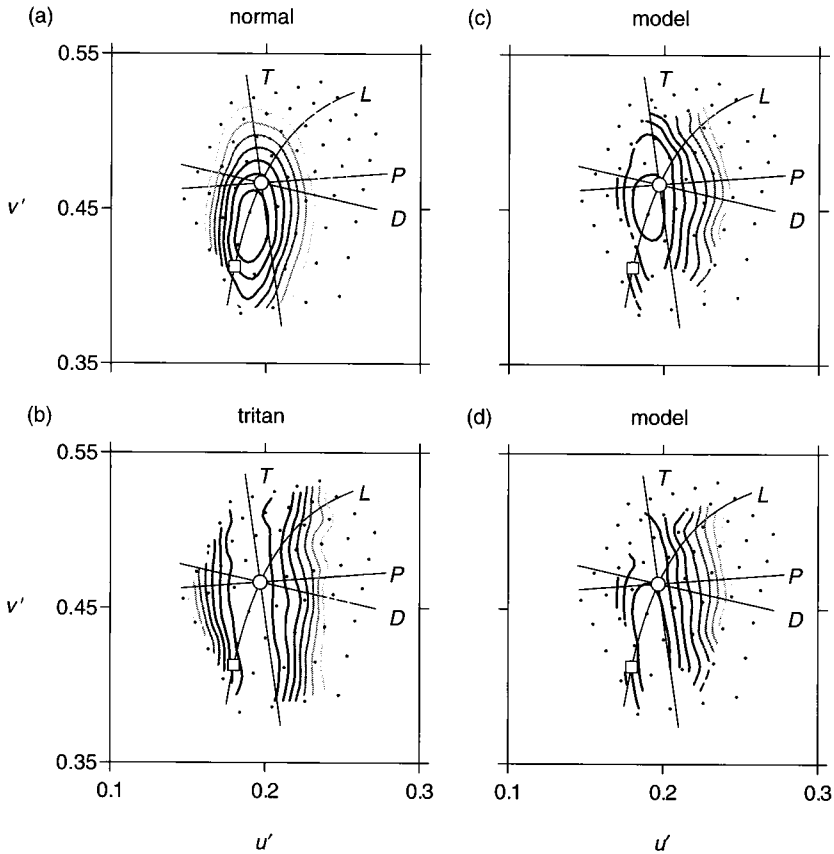


Figure 22.2 Contour plots derived from distributions of the kind shown in Fig. 22.1. Each contour represents a constant frequency of “illuminant-change” responses: the darker the contour, the higher the frequency. Data in (a) and (b) are for normal and tritan observers, respectively, and in (c) and (d) for the corresponding simulations based on deviations in spatial cone-excitation ratios. The open squares and circles show, respectively, the chromaticity coordinates of the first and the second illuminants on the pattern. The daylight locus and the protanopic, deutanopic, and tritanopic confusion lines are indicated (L , P , D , and T , respectively).

The different anisotropies for normal and tritan observers suggests that short-wavelength-sensitive cones may indeed make a contribution to the normal detection of reflectance changes under changes in daylight, particularly when deviations in spatial cone-excitation ratios are extreme (the lower parts of the contours in Fig. 22.2(a)). To provide an alternative, theoretical reference for these data, the performance of normal and tritanopic observers was modelled computationally under the assumption that the discriminatory cue was generated by deviations in spatial cone-excitation ratios, as described in a previous analysis of relational colour constancy in isoluminant and achromatic images (Nascimento and Foster 2000). No attempt was made to model

the discriminatory process in detail, and responses were again collapsed over luminance levels. With contributions from long-, medium-, and short-wavelength-sensitive cones weighted according to their approximate average proportions in the normal eye of 2:1:0.2 (Curcio *et al.* 1991; Carroll *et al.* 2000; Kremers *et al.* 2000), the predicted response distributions for normal controls showed little anisotropy, but reducing the contribution of short-wavelength-sensitive cones to about one sixth, giving weights of 2:1:0.03, proved more successful. For tritanopic observers, the contribution of short-wavelength-sensitive cones was assumed to be zero. Changing the balance of the contributions from long- and medium-wavelength-sensitive cones had relatively little effect. Figure 22.2(c) shows the normal model contour plot. It reproduces the anisotropy in the observed response distribution, although not exactly its location or the direction of the long axis, consistent with the degree of colour constancy being limited by a bias towards the first illuminant, as noted earlier. Figure 22.2(d) shows the tritanopic model contour plot. The direction of the long axis is similar to that observed, although the extent of the anisotropy is not correctly reproduced (the fact that some discrimination contours intersect the tritanopic confusion line is not inconsistent with tritanopia: although the direction of the illuminant shift may be along the confusion line, the direction of the product of illuminant and reflection spectra need not). For normal observers, it may be that the apparent failure of short-wavelength-sensitive cones to contribute fully is due to other factors, for example, the size of the cue in relation to the size of the mean illuminant shift. Nevertheless, short-wavelength-sensitive cones seem to make a disproportionately small contribution to the detection of colour-constancy failures under daylight changes.

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