

## CHAPTER 23

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# RED-GREEN COLOUR DEFICIENCY AND COLOUR CONSTANCY UNDER ORTHOGONAL-DAYLIGHT CHANGES

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### Introduction

Several distinct processing stages are thought to underlie the constant perception of surface colour under change in illuminant (Kraft and Brainard 1999; Walsh 1999). Colour constancy depends, in particular, on preserving spatial ratios of cone-specific excitations arising from light reflected from pairs of surfaces in a scene (Foster and Nascimento 1994; Nascimento and Foster 1997), and deviations in these ratios may account for the rapid, parallel detection of violations in colour constancy (Foster *et al.* 2001). If such detection involves comparisons of activity within cone classes, then the loss of one cone class might have little effect, providing that there was no significant reduction in coverage of the spectrum and that the remaining cone classes were sensitive to the underlying changes in the colour signal.

This hypothesis was tested operationally in a previous study with computer-simulated surfaces and illuminants (Foster and Linnell 1995). Under illuminants drawn from the daylight locus, red-green dichromats were able to detect simultaneous changes in surface spectral reflectance whose colour directions were along the daylight locus. Their levels of performance were about as good as those for observers with normal colour vision. Under illuminants with chromaticities lying along a line approximately perpendicular to the daylight locus, a deuteranope was still able to perform the corresponding task, but a protanope performed more poorly. In an achromatic-matching task (Rüttiger *et al.* 2001), red-green dichromats also obtained levels of performance close to those of normal controls for illuminant changes along the daylight locus, but performed more poorly in the approximately orthogonal direction.

In an attempt to further explore the limits on surface-colour perception in red-green colour deficiency, an analogue of the experiment described in Foster *et al.* (Chapter 22, this volume) was performed to estimate the distributional properties of these discriminations in affected individuals (cf. Rüttiger *et al.* 2001). Several protan and

deutan observers were presented with computer-simulations of a Mondrian-like pattern undergoing a change in illuminant. This illuminant change was constructed so that in the CIE 1976 ( $u'$ ,  $v'$ ) chromaticity diagram it defined an axis that was approximately perpendicular to the daylight locus and therefore close to a red–green dichromatic confusion line. At the same time as the 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 detectability of this spectral reflectance change was plotted against an equivalent illuminant change in the ( $u'$ ,  $v'$ ) chromaticity diagram. To provide a theoretical reference, performance of colour-normal, protanopic, and deuteranopic observers was modelled computationally using the information available from long-, medium-, and short-wavelength-sensitive cones.

## Methods

### Stimuli and apparatus

The stimulus patterns were square, of side  $7^\circ$  visual angle, and comprised an array of 49 ( $7 \times 7$ ) square Lambertian coloured surfaces of side  $1^\circ$  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.

As in Foster *et al.* (Chapter 22, this volume), the patterns were presented under two successive illuminants. The first illuminant was a fixed, spatially uniform, artificial daylight composed of a linear combination of the daylight spectral basis functions of Judd *et al.* (1964) so that in ( $u'$ ,  $v'$ ) space its chromaticity coordinates were located on the perpendicular to the tangent to the daylight locus at the chromaticity coordinates of the second illuminant, a fixed, spatially uniform daylight of correlated colour temperature 6700 K. The ( $u'$ ,  $v'$ ) coordinates of the first and second illuminants were (0.143, 0.484) and (0.197, 0.467), respectively. Their common luminance was  $50 \text{ cd/m}^2$ . On the centre square of the pattern, the 6700 K daylight was replaced by a spatially uniform local illuminant also constructed from a linear combination of the daylight spectral basis functions of Judd *et al.* (1964). Its chromaticity was sampled randomly in each trial from a large convex gamut in the ( $u'$ ,  $v'$ ) diagram comprising 57 points shown by the small solid points in Fig. 23.1. Its luminance was sampled randomly from three values: 41, 50, and  $59 \text{ cd/m}^2$ .

Stimuli were generated on the screen of a 20-in.,  $1024 \times 768$  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

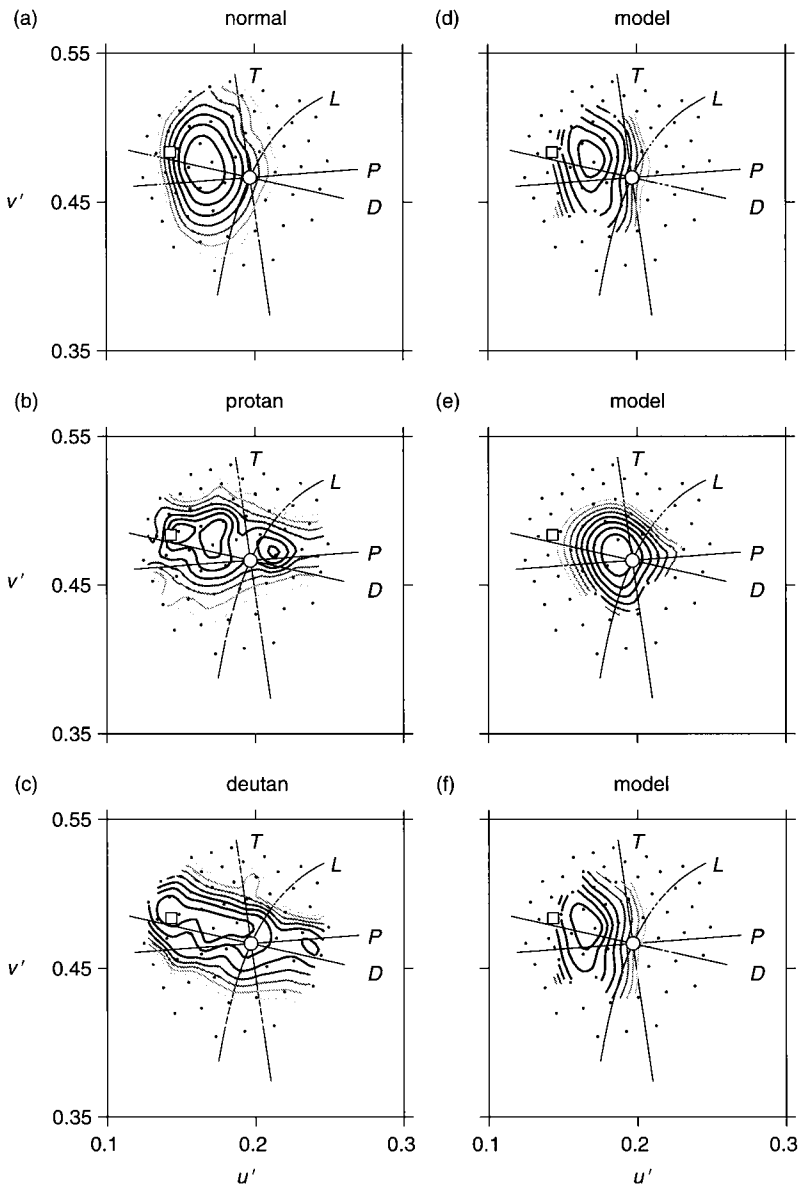
In each trial, the two patterns appeared sequentially in the same position, each for 1 s, with no interval. The task of the observer was to decide whether the surfaces in the successive patterns were the same, that is, whether the change was a pure illuminant change. Responses were made on a joypad connected to the computer. Fresh patterns were generated in each trial. Each observer performed, in all, 10–20 trials at each of the 171 ( $57 \times 3$ ) 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 at least 1710 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. All observers had normal visual acuity in each eye, verified optometrically. There were 10 observers with normal colour vision, 4 male and 6 female, aged 21–36 years; and five red–green colour-deficient observers, all male, comprising two protanopes and one protanomalous trichromat, aged 21–35 years, and two deuteranopes, aged 25 and 26 years.

## Results and discussion

The frequency of “illuminant-change” responses was plotted against the chromaticity of the local illuminant in the  $(u', v')$  chromaticity diagram collapsed over luminance levels of the local illuminant (as in Foster *et al.*, Chapter 22, this volume). The distribution of responses for the 10 observers with normal colour vision is summarized in the contour plot of Fig. 23.1(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 been obtained, then all the response contours would have been centred on the coordinates of the second illuminant (open circle), but the peak of the distribution is shifted towards the first illuminant (open square) (cf. Bramwell and Hurlbert 1996; Foster *et al.* 2001). Unlike the normal response distribution for illuminant changes along the daylight locus (Foster *et al.*, Chapter 22, this volume), here the distribution was almost isotropic.



**Figure 23.1** Detectability of changes in surface colour during orthogonal-daylight illuminant changes for observers with normal and red–green colour deficiency. Each contour represents a constant frequency of “illuminant-change” responses in the 1976 CIE ( $u'$ ,  $v'$ ) chromaticity diagram. Data in (a), (b), and (c) are for normal, protan, and deutan observers, respectively, and in (d), (e), and (f) 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, deuteranopic, and tritanopic confusion lines are indicated ( $L$ ,  $P$ ,  $D$ , and  $T$ , respectively).

Figure 23.1 (b and c) shows the corresponding contour plots for the protan and deutan observers, respectively. As anticipated from Rüttiger *et al.* (2001), these observers' distributions were more elongated than for normal controls in the directions of their confusion lines, suggesting that information about deviations in spatial cone-excitation ratios in the remaining medium-to-long-wavelength-sensitive cone class was not used as effectively as it might be. As with tritan observers (Foster *et al.*, Chapter 22, this volume), the fact that the discrimination contours cut the protanopic and deuteranopic confusion lines is not inconsistent with observers having the corresponding deficiencies: 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.

To provide a theoretical reference for these data, the performance of normal, protanopic, and deuteranopic observers was modelled computationally under the assumption that the discriminatory cue was generated by deviations in spatial cone-excitation ratios, as in Nascimento and Foster (2000) and Foster *et al.* (Chapter 22, this volume). Again, no attempt was made to model the discriminatory process in detail. The contributions from long-, medium-, and short-wavelength-sensitive cones were weighted according to their approximate average proportions in the normal eye (Curcio *et al.* 1991; Carroll *et al.* 2000; Kremers *et al.* 2000) but with the contribution from short-wavelength-sensitive cones reduced to one-sixth, as in Foster *et al.* (Chapter 22, this volume), that is, 2 : 1 : 0.03. For protanopes and deuteranopes, the respective contributions of long- and medium-wavelength-sensitive cones were assumed to be zero. The model contour plots for normal, protanopic, and deuteranopic observers are shown, respectively, in Fig. 23.1 (d, e, and f).

Although the plot for normal controls is similar to that observed, the large anisotropies found with the sample of protan and deutan observers were not reproduced by the corresponding dichromatic models, confirming that information about deviations in spatial cone-excitation ratios in the remaining medium-to-long-wavelength-sensitive cone class was indeed not used effectively.

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