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47. Fast determination of the spectral modulation sensitivity function: a comparison between trichromats and deuteranopes

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Abstract

Using drifting comb-filtered spectra, rapid determinations of the spectral modulation sensitivity function (SMSF) were performed in two normal trichromats and two deuteranopes. Detection thresholds were measured for comb-frequencies (f) varying from 0.5 to 3.5 cycles/300 nm with a constant temporal frequency (1 Hz). The dichromatic SMSF shows a corner frequency at near 1.2 cycles/300 nm, whereas the corner frequency of the trichromatic SMSF is near 1.7 cycles/300 nm. The impairment of sensitivity of deuteranopes at high frequencies is explained by the loss of the red–green opponent-colour channel with its triphasic characteristic on the wavelength axis.

Introduction

In 1982, Barlow proposed that the modulation transfer function (MTF) of the chromatic system could be estimated by measuring threshold sensitivity to comb-filtered spectra. Such stimuli are produced by a sinusoidal modulation of the radiant energy over the visible spectrum (400–700 nm) and are defined by their frequency (cycles/300 nm), phase (degrees) and amplitude (Fig. 1).

In a previous study, discrimination thresholds for comb-filtered spectra were measured for one normal trichromat for various frequencies over the full range of phases (Bonnardel *et al.*, 1996). As was suggested by early studies using different kinds of periodic spectral modulation (Barlow *et al.*, 1983; Bonnardel and Varela, 1991), or more recently by computations from classical discrimination data (Romero *et al.*, 1995a), the chromatic system shows a large phase dependence. The spectral modulation sensitivity function (SMSF) was defined as sensitivity measured for the optimal phase (i.e. the phase which reveals the highest sensitivity). In the present study, drifting comb-filtered spectra provide faster determination of the SMSF, since for each frequency only one measurement is obtained, which necessarily corresponds to the optimal phase. Measurements of the SMSF in two normal trichromats and two deuteranopes are presented.

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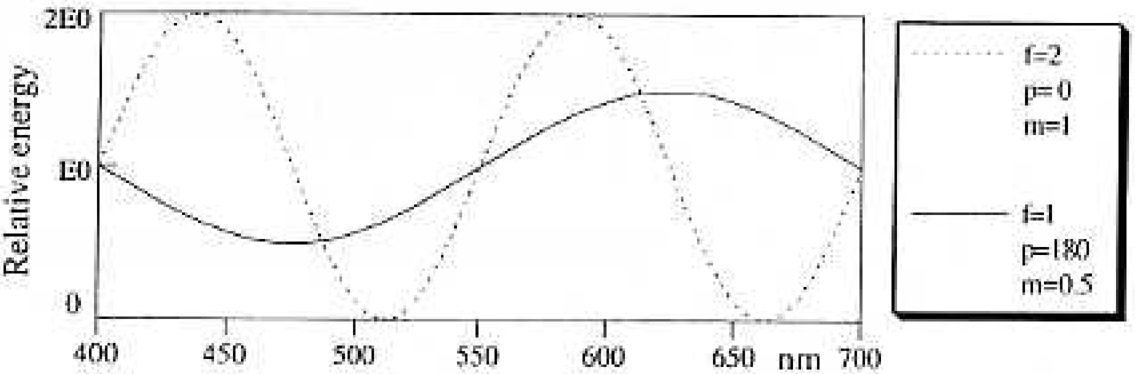

Fig. 1. Comb-filtered spectra are illuminants whose spectral power distributions are sinusoidal modulations over wavelength, expressed by:

$$E(\lambda) = E_0(\lambda)[1 + m \sin(fp(\lambda) + p_0)] \qquad 400 < \lambda < 700 \qquad [1]$$

where $E_0(\lambda)$ is the DC level of energy; m is the amplitude of the modulation varying from 0 to 1; and f is the frequency expressed in cycles/300 nm, hereinafter denoted c. p_0 is the initial phase (degree). $p(\lambda) = (1.2\lambda - 480)$ transforms the 300 nm interval into 360°.

Materials and methods

The stimulator

Comb-filtered spectra were produced by a stimulator based on an interference wedge and a liquid crystal display (LCD) (Fig. 2). The LCD screen is of double super-twisted nematic type with a contrast ratio of 15:1. The screen is a passive-matrix addressing system of 640 × 480 pixels on which sinusoids are drawn in a rectangle whose size fits that of the continuous spectrum formed by the interference wedge. The software application, developed for Macintosh computers, allows us to display sinusoidal profiles of any frequency and phase, the level of modulation being set by the number of pixels corresponding to the width of the interference wedge at each wavelength.

It is worth noting that temporal modulation of the three primaries of a CRT display would provide relative absorption rates in the three types of cones equivalent to most of the drifting comb-filtered spectra by an appropriate setting of the relative intensity of the three phosphors. However, the advantage of comb-filtered spectra is that a direct measurement of the visual system sensitivity is obtained without a prior knowledge of the fundamentals or even of their number.

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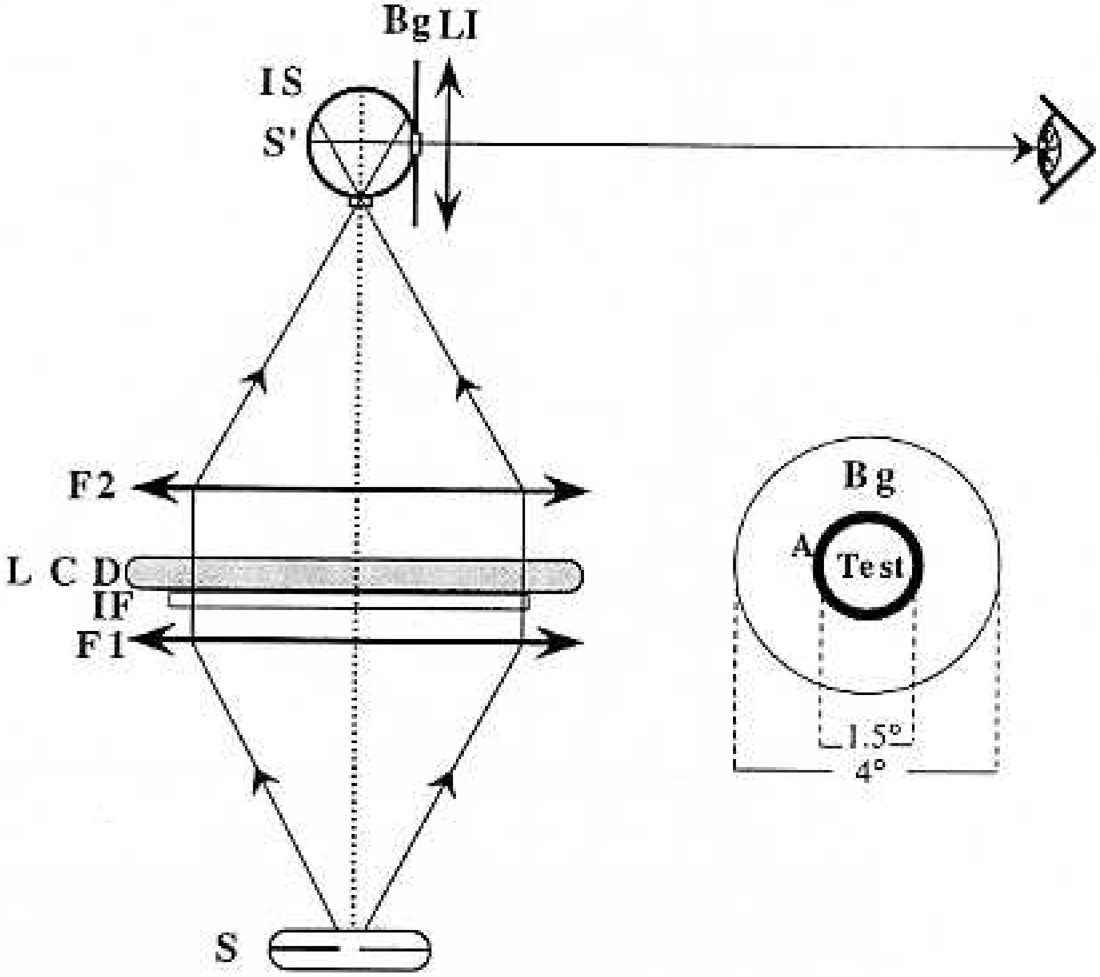

Fig. 2. The light from the source (S, short-arc xenon bulb equipped with UV and IR filters) located at the focal point of a Fresnel lens (F1) is focused by a second lens (F2) to form a real image S' of S at the aperture of the integrating sphere (IS). The liquid crystal display (LCD) is mounted in the collimated beam directly after the interference wedge (IF) which gives a continuous linear spectrum from 400 to 700 nm. The output of the integrating sphere (IS), viewed though a lens (LI), produces a homogeneous field 1.5° in diameter. A narrow dark annulus (A) delimits the test spot from a 4° background (Bg) of the same luminance (5 cd/m^2). In the absence of modulation ($E(\lambda) = E_0(\lambda)$), the chromaticity coordinates of the test spot are $x_0 = 0.275$ $y_0 = 0.358$. The chromaticity coordinates of the background are $x_0 = 0.355$, $y_0 = 0.427$.

Psychophysical procedure

The observer sat in a darkened enclosure and was adapted to the luminance of the test spot and uniform surround. His head was supported on a chin rest while he viewed monocularly with his dominant eye a 1.5° test spot of the required spectral composition on a 4° luminous background adjusted to match the unmodulated test spot in luminance and to approximate it in colour. In a

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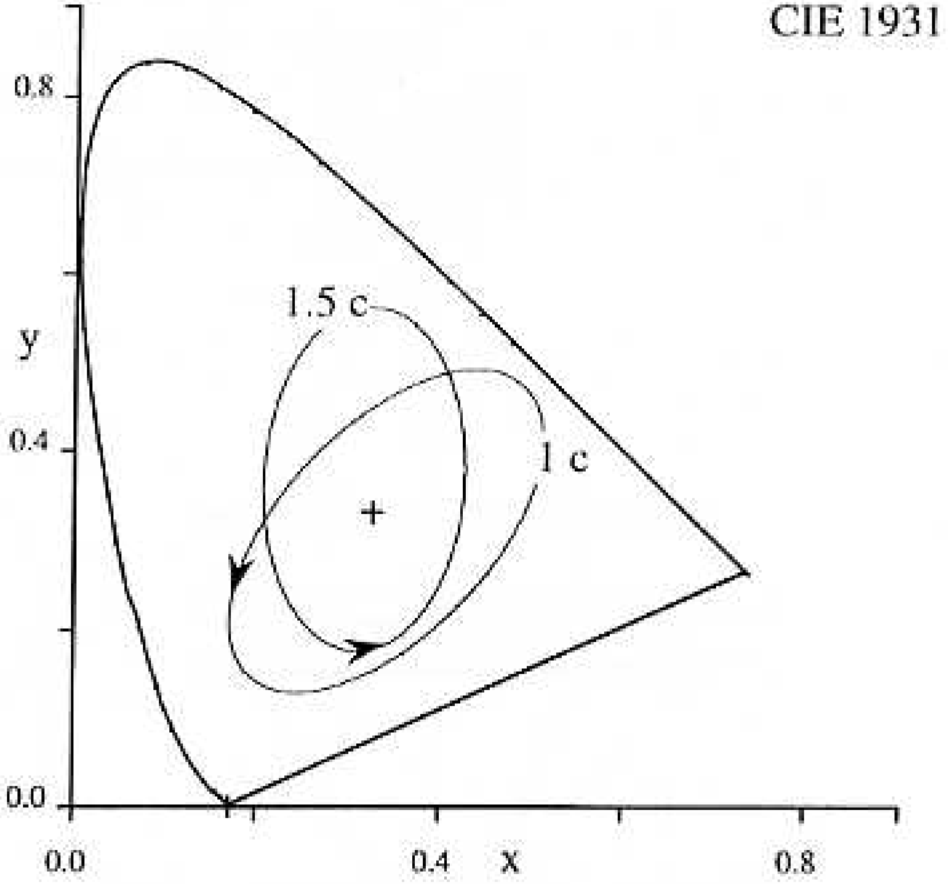

Fig. 3. The chromaticity coordinates of fully-modulated comb-filtered spectra (m = 1) were computed for two frequencies (1 and 1.5 cycles) for a continuous variation of phase (arrows indicate the starting phase p_0 and the direction of variation). When plotted in the CIE (1931) diagram they describe an ellipse. Variation in depth of modulation corresponds to movement along a line that joins the unmodulated spectrum (cross) to an elliptical contour in a given direction, i.e. phase.

detection task, the observer indicated whether or not a change occurred during the 2 sec test presentation of a drifting comb-filtered spectrum. A trial was initiated after the observer had given his response and began with a 1 sec presentation of a static comb-filtered spectrum. The test interval during which the comb-filtered spectrum scrolled was signalled by beeps. Between test presentations the unmodulated spectrum was displayed. Twelve comb frequencies from 0.5 to 3.5 cycles with a constant temporal frequency (1 Hz) were tested in three runs of four independent and interleaved staircase procedures. The four last measures of six reversals were used to compute the thresholds. The experimental data points correspond to the mean of three experimental sessions of about 45 min each.

Drifting comb-filtered spectra produce luminance modulations whose amplitude is greater at low comb frequencies. The size of the spot, the duration of the test presentation and the temporal frequency were, therefore, chosen to favour

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detection on the basis of chromatic cues, and a dark annulus around the test spot was added to mask the achromatic component (Mollon, 1982; Kulikowski and Walsh, 1991).

Observers

A vision scientist (ST) and one of the authors (VB) participated in the experiment as normal trichromat observers. Their colour vision was previously tested with the usual clinical tests. The dichromatic observers are two male adults of the same age as the trichromat observers and were classified as deuteranopes according to Ishihara, Farnworth-Munsell 100-hue, and the Nagel anomaloscope.

Results and discussion

Calibrations

The spectral power distribution of the test field was measured at the position of the observer's eye with a spectroradiometer (model PR-650, Photo Research). The parameters of the sinusoidal spectral modulation represented by the fraction $E(\lambda)/E_0(\lambda)$ (see equation [1] in legend Fig. 1) were estimated by mean of a fitting procedure (Kaleidagraph-Macintosh software). For 72 best-fitting sinusoids the mean correlation was 0.98. The linear relationship between the amplitude of the best-fitted sinusoid and the number of pixels in the width of the electronic mask was determined from these 72 fits and served to compute the amplitude for the rest of the threshold measures. The reciprocal of the amplitude was then plotted as a function of frequency.

Spectral modulation sensitivity functions

The mean SMSF of the two trichromat observers and the mean SMSF of the two dichromat observers are shown in Figure 4. The trichromatic SMSF shows a corner frequency near 1.7 cycles whereas the dichromatic SMSF starts to decrease at frequencies above 1.2 cycles. These results are consistent with previous measurements performed with a Michelson interferometer by Barlow *et al.* (1983) and Gemperlein *et al.* (1990), where the maximum sensitivity of a deuteranope observer is shifted toward low frequencies.

In addition to the relative loss of sensitivity at high frequencies, the deuteranopes show a general impairment of sensitivity compared to normal observers: deuteranopes needed illuminants of higher purity in order to detect a change in the test. Without drawing any conclusion from four observers, it is interesting to note that in their study Regan *et al.* (1994) reported that dichromats, as a population, had higher thresholds than normal trichromats in the tritan direction. The test consisted of computer-controlled displays of

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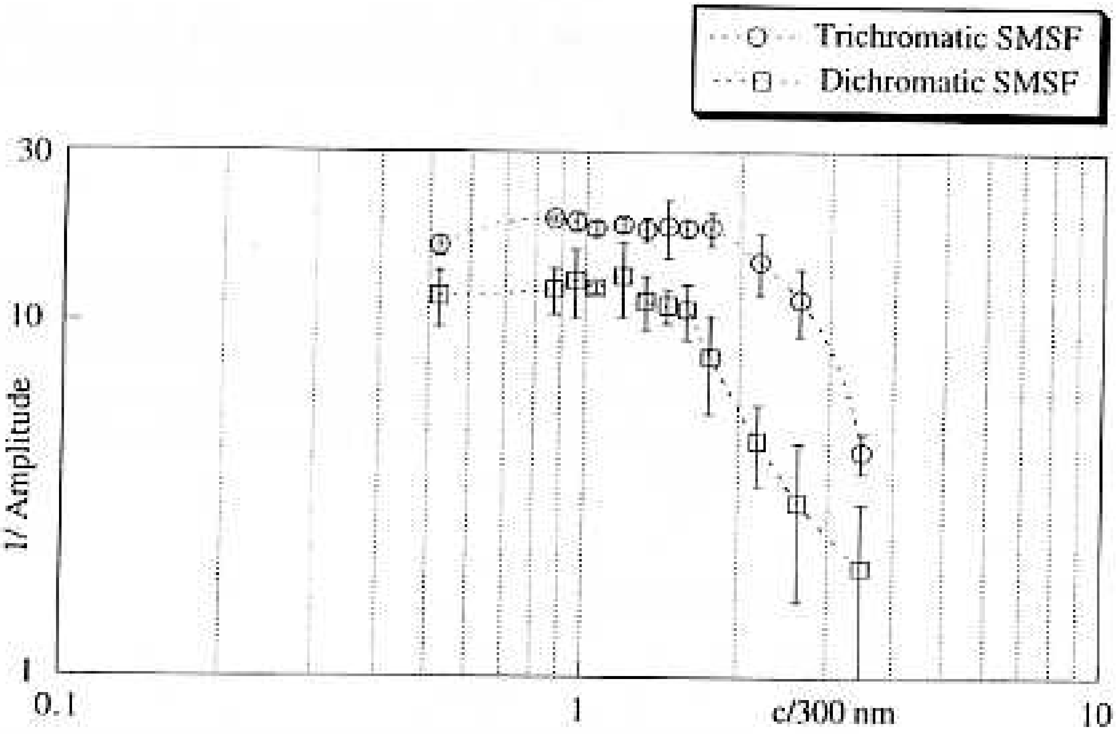

Fig. 4. Mean SMSF of the two trichromat observers (circles) compared with the mean SMSF of the two dichromat observers (squares). For each curve, the y-bars represent the difference between the threshold measurements of the two observers.

pseudoisochromatic plate patterns whose chromaticities vary discretely along different directions in the colour space. When the sensitivity was probed from the achromatic point, the measurements, as in our test, corresponded to saturation threshold.

Finally, it is not clear whether the high frequency cut-off, here estimated as being near 4 cycles for the two curves, occurs at lower frequencies in the case of dichromat observers.

Theory

Benzschawel *et al.* (1986) and more recently Romero *et al.* (1995b) used current opponent-colours models to predict the sensitivity of the whole visual system to comb-filtered spectra. In these models, the spectral opponency that is achieved by neural interaction between the three classes of receptors is expressed as the result of a linear combination of a set of cone fundamentals. In the Ingling and Tsou model (1977), Smith and Pokorny fundamentals (1975) are used to derive one achromatic and two opponent-colour mechanisms (Fig. 5).

The achromatic channel (A) results from the positive combination of L and M cones. The r–g channel which receives its inputs from a positive combination of L and S cones opposed to M cones exhibits a triphasic spectral profile with

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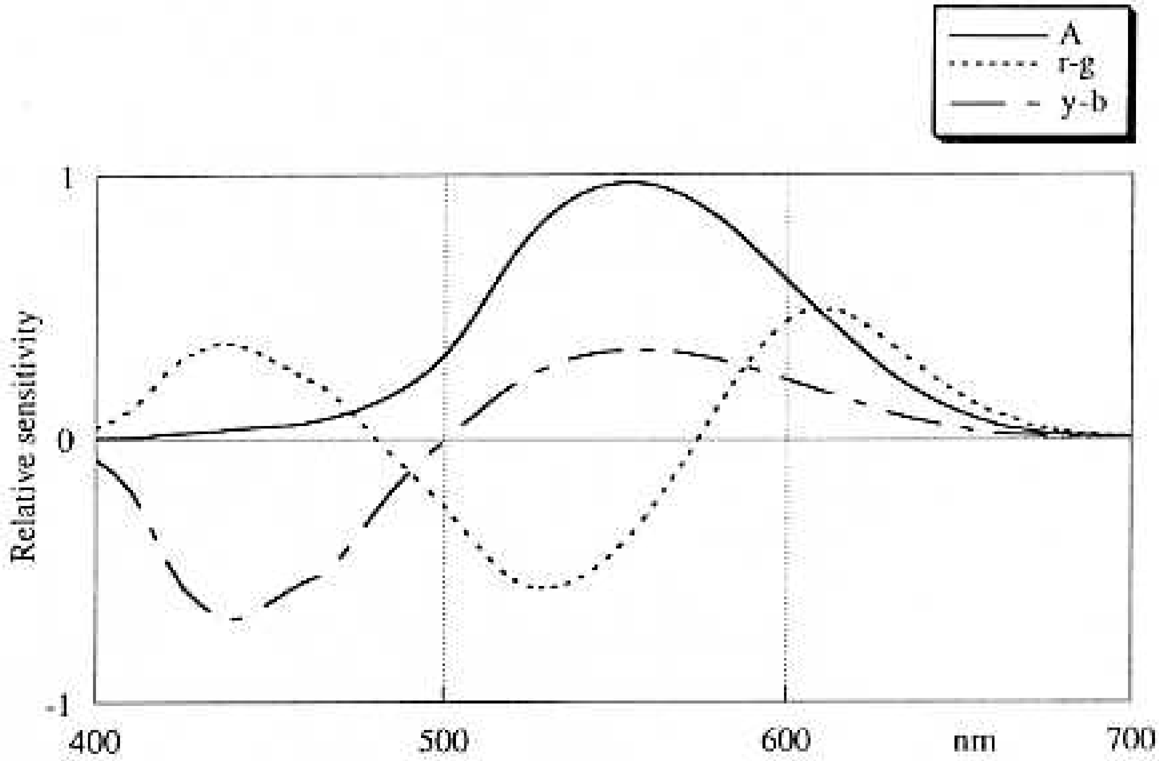

Fig. 5. Spectral sensitivity curves, A(λ) (solid line), r–g(λ) (dotted line) and y–b(λ) (dashed line), of the three mechanisms postulated in the Ingling and Tsou model (1977).

two zero-crossings (480 and 570 nm). The y–b channel corresponds to a positive combination of L and M cones opposed to S cones and shows a diphasic profile with a zero-crossing at 500 nm.

The individual response for a given frequency and a given phase, $S_A(f, p)$, $S_{r\text{-}g}$ (f, p) and $S_{y\text{-}b}$ (f, p), are then computed for a maximal modulation (m = 1) with frequencies varying from 0.1 to 5.9 cycles in steps of 0.1 cycles and p varying from 0 to 330° in steps of 30°.

Following Benzschawel *et al.* (1986):

$$S_A\,(f, p) = [(A_{f,\,p})^2 - (A_0)^2\,]^{1/2} \qquad [2]$$

with $A_{f,\,p} = \Sigma E(\lambda) \times A(\lambda)$ and $A_0 = \Sigma A(\lambda)$ for $400 < \lambda < 700$ and similarly for $S_{r\text{-}g}$ and $S_{y\text{-}b}$.

The maximal response computed over the 12 phases (i.e. response to the optimal phase, p_{opt}), is then plotted as a function of frequency (Fig. 6). The response of the achromatic channel is maximal for the lowest frequency (0.1 cycles) and decreases by 50% at 1.3 cycles, where it is equal to that of the two opponent-colour channels. The maximal response function of the two opponent-colour channels shows bandpass profiles with similar bandwidth and a centre frequency of 0.9 and 1.6 cycles, respectively, for the y–b and r–g channels.

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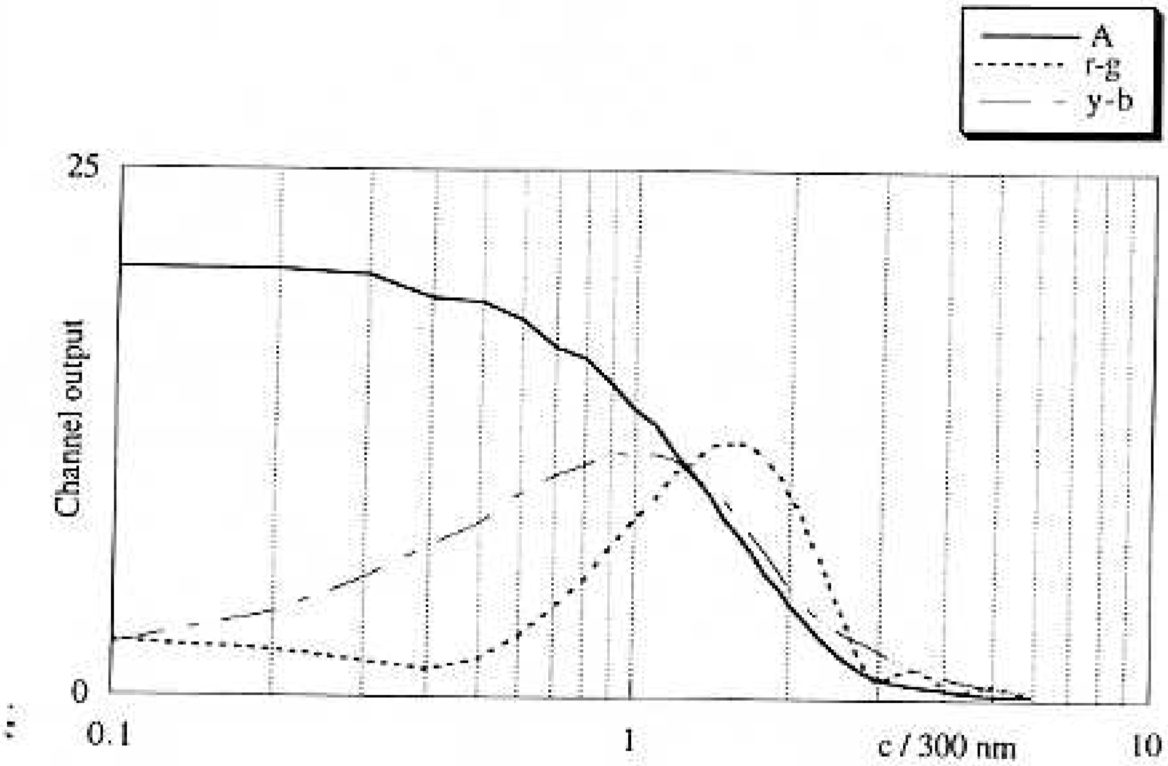

Fig. 6. The response of the three channels (A(λ), solid line; r–g(λ), dotted line; y–b(λ), dashed line) were computed for comb-filtered spectra with frequency varying from 0.1 to 5.9 cycles. Maximal response functions plotted on this graph correspond to the response of each channel to the optimal phase; S_A (f, p_{opt}), $S_{r\text{-}g}$(f, p_{opt}), $S_{y\text{-}b}$(f, p_{opt}).

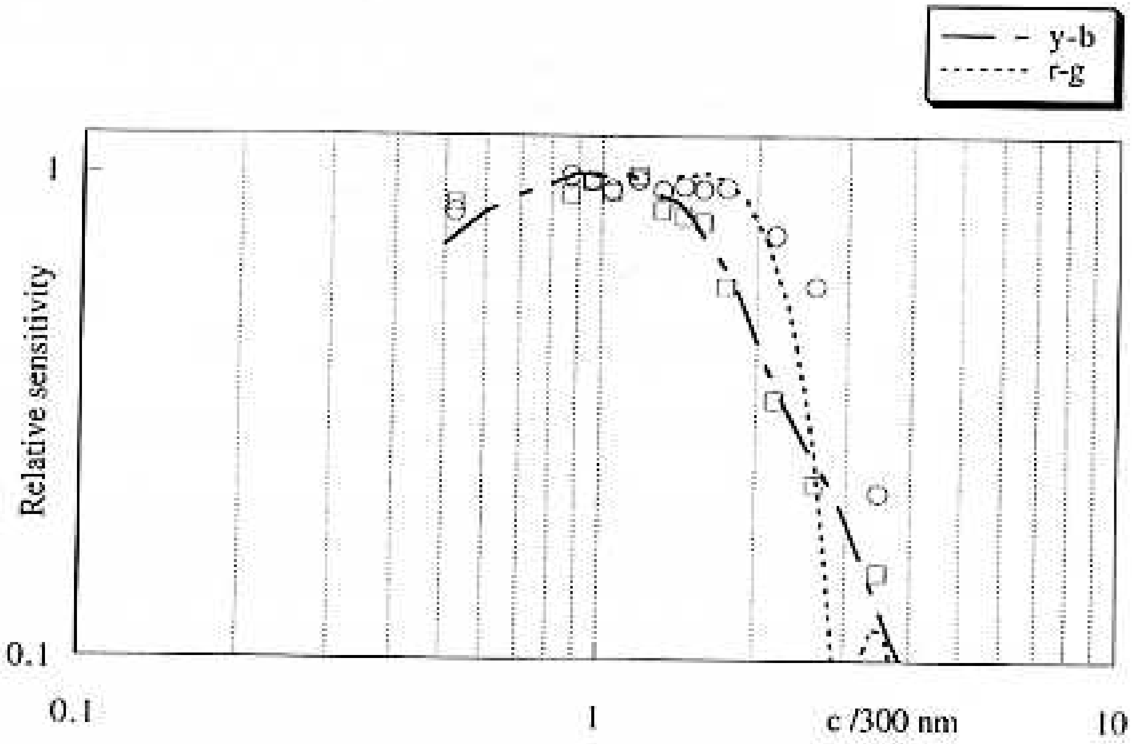

Fig. 7. The data points of the trichromatic (circles) and of the dichromatic (squares) SMSF are plotted with the maximal response function of r–g and y–b mechanisms in normalized ordinates

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Although there are noticeable differences in their response decay, after 5 cycles the response of the three channels is residual as shown in the studies of Benzchawel *et al.* (1986) and Romero *et al.* (1995b).

For comparison, the experimental data points of Figure 4 are plotted on the same graph as the maximal response functions of r–g and y–b channels on a linear normalized Y-axis (Fig. 7). Except for the measurement obtained at the lowest frequency (0.5 cycles), where the contribution of the luminance component is the strongest, the maximal response function of the y–b channel can account for both the span of the maximum of sensitivity and the descending slope of the deuteranopic SMSF. The response of the r–g channel accounts for the extension of the maximum of sensitivity to 1.7 cycles observed in the trichromat SMSF, but poorly predicts its descending slope, which is shallower. A full account of the trichromatic SMSF will need a rule of combination of the three channels.

Conclusion

This first determination of the SMSF in two deuteranope observers suggest that the colour system of red–green dichromats based on one diphasic opponent-colour channel suffers a loss of modulation sensitivity for high frequencies compared with a trichromatic system.

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