Anomalous loss in blue–green wavelength discrimination with very brief monochromatic stimuli presented to the normal human eye

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The wavelength-discrimination curve of the normal human eye shows minima in discrimination thresholds at about 490 and 580 nm for viewing times of 1 s or longer. A reduction in viewing time was found to yield non-uniform increases in discrimination thresholds in the blue–green region of the spectrum, and these findings were quantified in objective, two-interval, forced-choice discrimination measurements. Monochromatic stimuli were presented foveally in a circular, horizontally oriented, bipartite field of 100 Td and angular subtense 2°. When viewing time was decreased to 3 ms there was a sharp increase in discrimination threshold over 490–520 nm, maximizing near 500 nm. In this region, the fields appeared markedly desaturated. The loss in discrimination was distinct from that exhibited by tritanopes, and a control experiment showed that the effect was not attributable to the reduced energy of the short flash.

One of the most significant characteristics of colour vision is the power to distinguish between the colour sensations evoked by different spectral radiations. If two patches of light are viewed foveally in a photometric field, say a 2° horizontal bipartite field, one illuminated by a radiation of wavelength λ and the other by a slightly different radiation, of wavelength $\lambda + \delta\lambda$, then as $\delta\lambda$ is increased the two halves of the field become just noticeably different in colour. (It is important that the brightnesses of the two patches be kept equal, to ensure that only the hue discrimination function is acting.) The value of $\delta\lambda$ will vary with λ and the resulting hue- or wavelength-discrimination curve shows minima in $\delta\lambda$, i.e. maxima in discrimination around 490 nm and 580 nm, the blue–green and yellow parts of the spectrum respectively (König and Dieterici, 1884; Wright and Pitt, 1934; Pitt, 1944; Bedford and Wyszecki, 1958). The shape of the wavelength-discrimination curve has been interpreted in terms of the absorption characteristics of the three classes of cone (Walraven and Bouman, 1966; Cavonius and Estévez, 1978; Boynton, 1979).

The wavelength-discrimination curve has classically been measured with long-duration exposures of the bipartite field (e.g. 1 s). The experiments reported here aim to quantify and expand earlier observations by Taylor (1983) who found that when brief flashes of light were used (3.75 ms), wavelength discrimination deteriorated at about 490 nm. In this region of the spectrum, the fields appeared colourless; but, when illuminated with other wavelengths, colour was clearly visible. The present report is primarily of empirical work; and, although a number of explanatory mechanisms are considered, no attempt is made at a detailed theoretical account.

Little other work has been done on wavelength discrimination under temporally restricted viewing conditions. Siegel (1965) found that discrimination deteriorated as exposure time decreased from 5 s to 20 ms. Data were reported, however, for only one wavelength (575 nm) and the exposure durations were much larger than those used in the present experiments. Kinney (1965) noted that as the exposure duration of coloured stimuli decreased from 400 ms to 50 ms, their colour changed, typically becoming less saturated. There appear to be no other reports in the literature of a much greater desaturation of blue–green stimuli at very short exposure durations.

A preliminary account of the work described here has been presented elsewhere (Foster *et al.*, 1986).

General methods

Apparatus and stimuli

A computer-controlled two-channel Maxwellian-view optical system was used (described essentially in Foster, 1981) with, as a light source, a single tungsten-halogen lamp run from a regulated d.c. power supply. Transmittances of the channels were controlled by compensated neutral density wedges and Wratten neutral density filters. Monochromatic stimuli for the channel producing the fixed reference wavelengths λ were obtained using narrow-band interference filters (Balzer B40) and stimuli in the other channel producing the variations $\delta\lambda$ in λ

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were produced with a high-radiance grating monochromator (Applied Photophysics M300). The interference filters were calibrated with a Pye Unicam spectrophotometer, in turn calibrated against a holmium-glass standard. The monochromator was calibrated with a helium-neon laser and a low-pressure mercury-vapour lamp. The average half-height full bandwidth of all the stimuli was 6.4 nm.

Flashes of light were produced by the fast movement of a balsa-wood vane which was mounted on a low-inertia stepping motor, and which interrupted the optical system where the two channels were combined and the beams were of small (under 3 mm) diameter. This arrangement ensured that the flashes of each half field were of equal duration and synchronous. The duration of the whole-field flash was measured at the exit pupil with a fast photodiode connected to a calibrated oscilloscope. Two flash durations were used, the one of long duration, with half-height width 1 s and the other of short duration with half-height width 3 ms. Rise and fall times in both cases were less than 0.5 ms. These durations and time courses of the stimuli were highly repeatable. The geometry of the stimuli was defined by photographic masks inserted in the channels. The resulting circular bipartite field had horizontal division and subtended 2°. There was no background or surround field to this stimulus. Details of the procedure used to set the luminances of the half-fields are given later.

The stimuli were viewed through a 2 mm artificial pupil with an achromatizing lens and additional correcting lenses for non-emmetropic subjects. Head position was stabilized with the aid of a dental bite-bar. In all the experiments the subjects fixated the stimuli foveally with the right eye. Further details of the apparatus and its calibration are given in Foster (1981).

Subjects

Two male subjects served as observers. DHF (co-author) had normal colour vision, corrected Snellen acuity of 6/4, and was aged 41 years. MOS (co-author) had normal colour vision, corrected Snellen acuity of 6/5, and was aged 23 years. Both subjects were experienced psychophysical observers.

Procedure

The experiment was under computer control with subjects initiating each trial and signalling their responses with a push-button box connected to the computer. Wavelength-discrimination thresholds were determined by an adaptive two-interval forced-choice procedure (Hall, 1981) which yielded a psychometric function. At each reference wavelength λ, one hundred trials were performed. Each trial comprised two intervals, the one containing a flash with identical half-fields of wavelength λ, the other a flash with different half-fields of wavelengths λ and $\lambda + \delta\lambda$. The temporal ordering of the intervals was chosen pseudo-randomly. The subject indicated which of the two intervals contained the different half-fields. No feedback on correctness of response was given. The interval between the two flashes in each trial was approximately 2 s and that between each trial approximately 6 s. The size of the increment $\delta\lambda$ and the number of trials performed with that increment were determined by a modified PEST routine (Taylor and Creelman, 1967; Hall, 1981). After each set of 100 trials, which lasted 10–15 min, the subject rested and the room lights were turned on for at least 5 min.

The data derived at each reference wavelength were fitted by a logistic function that maximized the likelihood (Foster, 1986). Threshold was defined as the value of the increment $\delta\lambda$ corresponding to a performance level of 75% correct. The standard deviation of this threshold value was estimated by an incremental technique (Foster, 1986).

Experiment 1: Effects of flash duration and direction of wavelength change

As a preliminary measure, relative luminous efficiency functions were determined for each subject under the two conditions of stimulus exposure. These data were then used to set the equal brightness of the stimuli across the spectrum in the subsequent wavelength-discrimination measurements. The method used was heterochromatic brightness matching. Subjects viewed foveally a 2°, horizontally oriented bipartite field (the same as that used in the discrimination experiments). The top half was illuminated with light of wavelength 582 nm and retinal illuminance 100 Td. The wavelength of the bottom half was varied, and at each wavelength a brightness match was made between the two halves using a method of adjustment. Presentation of the field was under push-button control. One relative luminous efficiency curve was determined at field duration 1 s and another at field duration 3 ms.

Results are shown in *Figure 1*. Data for subject DHF show no differences in shape of the spectral luminosity function for the two flash durations (1 s and 3 ms); both functions maximize at about 560 nm. For subject MOS, there was a shift in the maximum of the luminosity function from 550 nm to about 520 nm with reduction in flash duration, possibly reflecting rod-intrusion, although the field size was 2°.

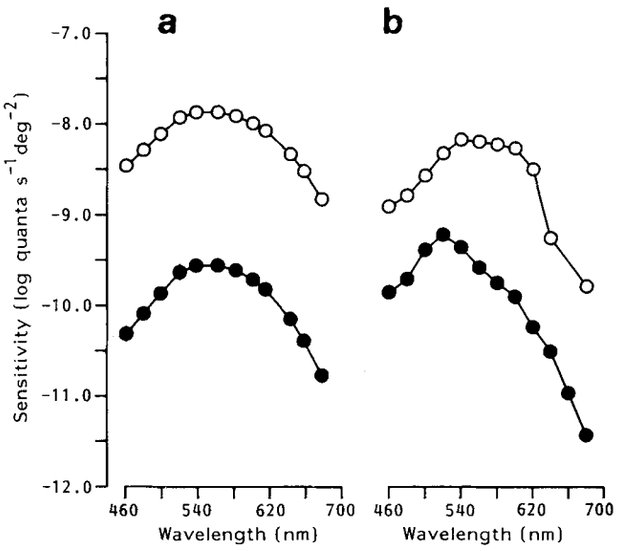

Figure 1 (*a*) Relative luminous efficiency functions obtained by heterochromatic brightness matching. Each point is the mean of six readings and the vertical bars show ±1 SE where this is sufficiently large. The two curves are for different durations, 1 s (○——○) and 3 ms (●——●), of the 2° bipartite stimulus field. The 3 ms curve is displaced downwards by 1.5 log unit. Subject DHF. (*b*) As in (*a*), subject MOS

Wavelength discrimination was first measured for the 1 s flash. Only positive increments $\delta\lambda$ were tested, i.e. the test wavelength probing towards wavelengths longer than the reference. Wavelength discrimination for the 3 ms flash was then measured for both positive and negative values of $\delta\lambda$. The reference wavelength was varied from 461 to 615 nm for subject DHF and from 461 to 658 nm for subject MOS.

Results and discussion

Wavelength-discrimination curves for the 1 s flash are shown for the two subjects in *Figure 2*(*a*, *b*) by the open circles. The curves are similar to those reported previously (e.g. König and Dieterici, 1884; Wright and Pitt, 1934), showing areas of good discrimination around 490 nm and around 580 nm (in the blue–green and yellow) where discrimination threshold is of the order of 1 nm, with poorer discrimination in other regions of the spectrum. Wavelength-discrimination curves for the 3 ms flash for positive values of $\delta\lambda$ are shown by the filled squares. There was a sharp increase in discrimination threshold over 490–520 nm, maximizing near 500 nm, where the fields appeared to both observers to be desaturated.

The data for 3 ms exposure were compared with those for 1 s using the generalized linear interactive modelling technique GLIM (Baker and Nelder, 1978) to test formally whether the 3 ms data could be represented as a scaled version of the 1 s data (compare Thomson and Trezona, 1951). The difference in shape of the curves was highly significant (for subject DHF $\chi^2_9 = 3007$, $p \ll 0.001$; for subject MOS $\chi^2_{11} = 4010$, $p \ll 0.001$). The 3 ms curve could not be obtained as a linear transform of the 1 s curve, which suggests that the effect was not attributable to a general decrease in performance. Indeed, the area of the spectrum where performance was poorest at 3 ms (490–520 nm) was an area of good performance at 1 s.

Wavelength-discrimination curves for the 3 ms flash for negative values of $\delta\lambda$ are shown in *Figure 2* by the filled diamonds. These curves are similar to those obtained with positive values of $\delta\lambda$ (filled squares in *Figure 2*) in that there was a marked decrease in performance in the blue–green region of the spectrum, although the peak in discrimination loss was shifted to slightly longer wavelengths (538 nm for subject DHF and 520 nm for subject MOS). This effect was anticipated. If the region of poor discrimination was close to, say, 520 nm, then by probing a test wavelength from a standard wavelength shorter than 520 nm, a peak loss would be obtained at a wavelength shorter than the 'true' area of poor discrimination, i.e. there would be a bias of the peak towards shorter wavelengths. The converse would be true for a probe from a standard wavelength longer than 520 nm, i.e. there would be a bias towards longer wavelengths. Of course, these biases would not be detectable if the magnitude of the discrimination threshold was always small in relation to its rate of change with reference wavelength, as was the case for the 1 s flash.

Deterioration in discrimination performance around 500 nm with the 3 ms flash might be ascribed to a loss in response of short-wavelength sensitive receptors resulting from their greater integration times (compare data of Weitzman and Kinney (1967) and Kaiser (1968) who examined colour naming of small, brief stimuli). The pattern of discrimination is, however, different from that shown by tritanopes viewing steady fields, where discrimination is poorest at rather shorter wavelengths, 450–470 nm (Wright, 1952). The discrimination loss is also different from that shown by protanopes or deuteranopes (Pitt, 1935, 1944).

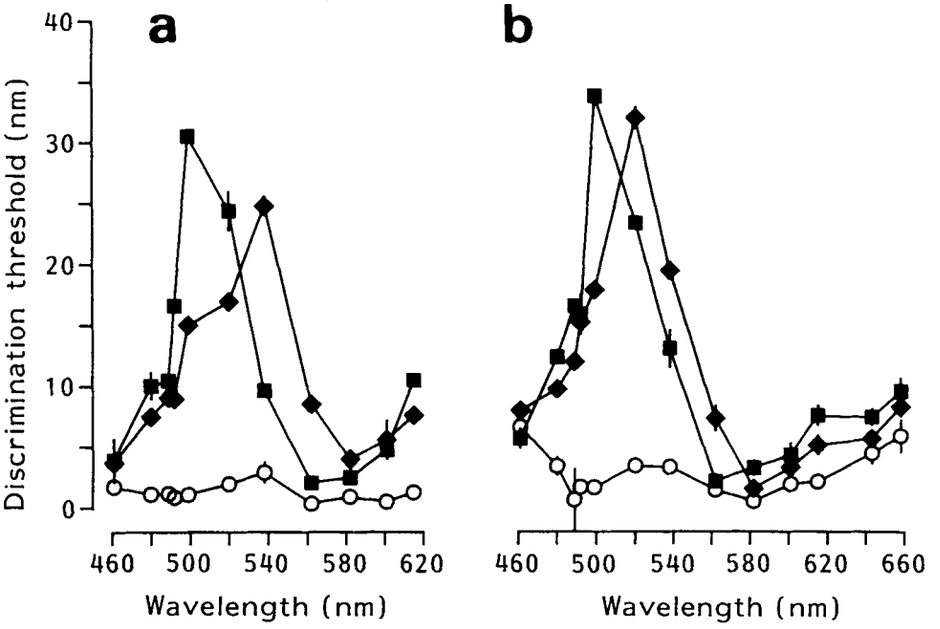

Figure 2 (*a*) Wavelength-discrimination curves obtained for a 1s flash (○—○), a 3 ms flash with discrimination thresholds being measured probing towards wavelengths longer than the comparison (■—■), and a 3 ms flash with discrimination thresholds being measured probing towards wavelengths shorter than the comparison (◆—◆). Discrimination threshold is plotted against wavelength of the comparison field. The vertical bars show ±1 SD where this is sufficiently large. Subject DHF. (*b*) As in (*a*), subject MOS

Experiment 2: Apparent brightness and wavelength discrimination

The 3 ms flash of light appeared much less bright than the 1 s flash. It was therefore possible that the decrease in performance around 500 nm could be due simply to the lower energy content of the stimulus, for hue-discrimination performance is known to decrease as the luminance level decreases (Thomson and Trezona, 1951; Brown, 1951). In energy terms the 3 ms flash contained $1000/3 = 2.52$ log unit less energy than the 1 s flash, although only the first 50–100 ms of the latter would presumably be effective in determining brightness. As a preliminary to testing the effect of reduced stimulus brightness on discrimination, a brightness matching task was undertaken. The stimulus field was a foveal, spatially uniform, circular, 2° monochromatic field. Each trial consisted of the presentation of a 3 ms flash of the same retinal illuminance (100 Td) as that used in the discrimination experiment followed, 1.5 s later, by a 1 s flash of the same wavelength. The task of the subject was to judge whether the brightness of the 1 s flash was more or less than that of the 3 ms flash. On the basis of the subject's response, the retinal illuminance of the 1 s flash was increased or decreased by a staircase procedure. It was found that an equality of brightnesses was usually reached after 10 trials and the difference in illuminance at this equilibrium was calculated by taking the mean of the last 10 levels used. Twenty-five trials were performed at each wavelength, the latter ranging from 461 to 658 nm. The same two subjects took part in this experiment (DHF and MOS).

Results of this matching experiment were as follows. The 3 ms flash appeared equally bright as the 1 s flash when the retinal illuminance of the latter was decreased by 1.53 log unit for subject DHF and 1.20 log unit for MOS. The apparent difference in retinal illuminance was approximately constant across the spectrum (SD for DHF 0.095 log unit; SD for MOS 0.092 log unit). Although there were differences between subjects, the luminances of their brightness-matched 1 s flashes were approximately the same, a consequence of subject DHF performing the 3 ms discrimination measurements at slightly higher luminance. It was noticed by both subjects in these brightness-matching measurements that, in the region of the spectrum about 500 nm, the 3 ms flash appeared almost neutral but the 1 s flash of the same brightness did appear blue–green, an observation which gives further support to the hypothesis that it was the short exposure and not the energy that was the critical factor in reducing discrimination around 500 nm. In all other parts of the spectrum under investigation, the flashes of light appeared coloured (both at 3 ms duration and at 1 s with low luminance).

Following this preliminary calibration, wavelength discrimination was measured with a 1 s flash of reduced luminance but brightness equal to that of the 3 ms flash used in Experiment 1. The experiment was thus identical with Experiment 1 apart from flash duration and flash luminance. (It would have been desirable to perform a control experiment in which the brightness of the 3 ms flash was increased until it matched that of the 1 s flash, and discrimination then measured with the brighter 3 ms flash. Because of the very short flash duration and relatively narrow spectral width, insufficient light was available from the apparatus.)

Results and discussion

Figure 3 shows the results for low-luminance wavelength discrimination (filled circles). Wavelength-discrimination performance was similar to that for 1 s at 100 Td (open circles, replotted from *Figure 2*). For subject DHF, the RMS difference was 1.12 nm; for subject MOS, the RMS difference was 2.23 nm, with a slight deterioration in performance between 500 and 520 nm and an improvement in performance near 460 nm. Similar effects have been reported previously (McCree, 1960; Siegel and Siegel, 1972). These differences in threshold due to reduction in luminance were, however, small in relation to the very large increase in threshold around 500 nm obtained with the 3 ms flash (*see Figure 2*). The hypothesis that the latter loss in discrimination was due to a lower brightness of the stimulus relative to the 1 s 100 Td flash was therefore rejected.

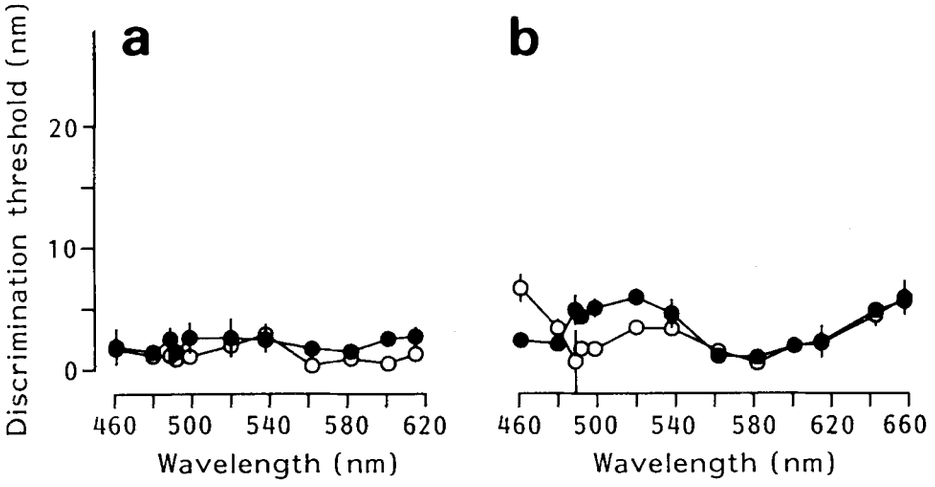

Figure 3 (*a*) Wavelength-discrimination curves obtained for a 1 s flash of retinal illuminance 100 Td (○—○, replotted from *Figure 2*) and for a 1 s flash of lower illuminance such that its brightness matched that of a 3 ms 100 Td flash (●—●). Subject DHF. Other details as in *Figure 2*(*a*). (*b*) As in (*a*), subject MOS

General discussion

There would seem to be an anomalous loss in wavelength discrimination in the blue–green region of the spectrum for very short flashes of light. The explanation for the loss is not immediately apparent. It cannot be modelled on the impaired discrimination shown by congenital colour defectives, nor is it due to the low brightness of a very short flash, although low luminance may introduce a small decrease in discrimination performance.

The region of discrimination loss corresponds to the peak sensitivity of the rod system, but it is not clear that rod-intrusion could explain the effect. The stimulus was foveal and the luminosity function for subject DHF was unchanged for short durations, although for subject MOS there was a shift towards shorter wavelengths. Even if there were significant rod involvement, leading to the introduction of an achromatic signal around 500 nm, it is not obvious how the addition of an extra receptor system could cause a deterioration in performance in any part of the spectrum. The shape of the wavelength discrimination functions for 3 ms flashes were closely similar for the two observers, even though there were apparently different levels of rod activity. The simplest interpretation is that rod excitation (in subject MOS) was irrelevant in producing the wavelength discrimination loss.

Measurements of colour appearance and wavelength discrimination in the peripheral retina do show losses in performance relative to the fovea (Weale, 1951, 1953; Moreland and Cruz, 1959) that are somewhat analogous to those found here, except that they are more spectrally extended and bear their closest similarity to the present findings only at large eccentricities (e.g. 25°).

One other possible analogy (Farnsworth, 1955; Weitzman and Kinney, 1967) comes from wavelength-discrimination measurements made with very small light sources (Willmer and Wright, 1945, Bedford and Wyszecki, 1958; McCree, 1960). Losses were found variously in the region 430–550 nm, overlapping the losses reported here. The present findings would not be inconsistent with the notion that the alterations in wavelength discrimination observed with very small and with very short flashes have a common underlying mechanism.

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References

Baker, R. J. and Nelder, J. A. (1978) *The GLIM System* Oxford, Numerical Algorithms Group.

Bedford, R. E. and Wyszecki, G. W. (1958) Wavelength discrimination for point sources. *J. Opt. Soc. Am.* **48**, 129–135.

Boynton, R. M. (1979) *Human Color Vision*, pp. 251–295. New York, Holt, Rinehart and Winston.

Brown, W. R. J. (1951) The influence of luminance level on visual sensitivity to color difference. *J. Opt. Soc. Am.* **41**, 684–688.

Cavonius, C. R. and Estévez, O. (1978) π-mechanisms and cone fundamentals. In *Visual Psychophysics and Physiology* (eds Armington, J. C., Krauskopf, J. and Wooten, B. R.), pp. 221–231. London, Academic Press.

Farnsworth, D. (1955) Tritanomalous vision as a threshold function. *Die Farbe* **4**, 185–197.

Foster, D. H. (1981) Changes in field spectral sensitivities of red-, green- and blue-sensitive colour mechanisms obtained on small background fields. *Vision Res.* **21**, 1433–1455.

Foster, D. H. (1986) Estimating the variance of a critical stimulus level from sensory performance data. *Biol. Cybern.* **53**, 189–194.

Foster, D. H., Scase, M. O. and Taylor, S. P. (1986) Anomalous loss in blue–green hue discrimination in very brief monochromatic stimuli presented to the normal human eye. *J. Physiol.* **381**, 64P.

Hall, J. L. (1981) Hybrid adaptive procedure for estimation of psychometric functions. *J. Acoust. Soc. Am.* **69**, 1763–1769.

Kaiser, P. K. (1968) Color names of very small fields varying in duration and luminance. *J. Opt. Soc. Am.* **58**, 849–852.

Kinney, J. A. S. (1965) Changes in appearance of colored stimuli with exposure duration. *J. Opt. Soc. Am.* **55**, 738–739.

König, A. and Dieterici, C. (1884) Ueber die Empfindlichkeit des normalen Auges für Wellenlängenunterschiede des Lichtes. *Annalen der Physic und Chemie* **22**, 579–589.

McCree, K. J. (1960) Small-field tritanopia and the effects of voluntary fixation. *Opt. Acta* **7**, 317–323.

Moreland, J. D. and Cruz, A. (1959) Colour perception with the peripheral retina. *Opt. Acta* **6**, 117–151.

Pitt, F. H. G. (1935) Characteristics of dichromatic vision. *Medical Research Council: Reports of the Committee upon the Physiology of Vision, No. XIV.* London, HMSO.

Pitt, F. H. G. (1944) The nature of normal trichromatic and dichromatic vision. *Proc. R. Soc.* **B132**, 101–117.

Siegel, M. H. (1965) Color discrimination as a function of exposure time. *J. Opt. Soc. Am.* **55**, 566–568.

Siegel, M. H. and Siegel, A. B. (1972) Hue discrimination as a function of stimulus luminance. *Percept. Psychophys.* **12**, 295–299.

Taylor, M. M. and Creelman, C. D. (1967) PEST: Efficient estimates on probability functions. *J. Acoust. Soc. Am.* **41**, 782–787.

Taylor, S. P. (1983) *The Effect of Restricted Viewing Time on Colour Vision.* UWIST Cardiff, PhD thesis.

Thomson, L. C. and Trezona, P. W. (1951) The variations of hue discrimination with change of luminance level. *J. Physiol.* **114**, 98–106.

Walraven, P. L. and Bouman, M. A. (1966) Fluctuation theory of colour discrimination of normal trichromats. *Vision Res.* **6**, 567–586.

Weale, R. A. (1951) Hue-discrimination in para-central parts of the human retina measured at different luminance levels. *J. Physiol.* **113**, 115–122.

Weale, R. A. (1953) Spectral sensitivity and wave-length discrimination of the peripheral retina. *J. Physiol.* **119**, 170–190.

Weitzman, D. O. and Kinney, J. A. S. (1967) Appearance of color for small, brief, spectral stimuli, in the central fovea. *J. Opt. Soc. Am.* **57**, 665–670.

Willmer, E. N. and Wright, W. D. (1945) Colour sensitivity of the fovea centralis. *Nature* **156**, 119–121.

Wright, W. D. and Pitt, F. H. G. (1934) Hue-discrimination in normal colour-vision. *Proc. Phys. Soc. Lond.* **46**, 459–473.

Wright, W. D. (1952) The characteristics of tritanopia. *J. Opt. Soc. Am.* **42**, 509–521.