VARIABILITY OF COLOR MIXTURE DATA—II. THE EFFECT OF VIEWING FIELD SIZE ON THE UNIT COORDINATES

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Abstract—Theoretical sources of variation of published color mixture data with variation in field size were considered. The differences in unit coordinates for 2° and 10° fields may be explained by postulating that the effective optical density of the cone photopigments decreases as field size increases. 1.33° tritanopic coefficients and small-field (artificial) tritanopic coefficients are shown to be consistent with the density hypothesis. Effective optical density decreases exponentially as the centrally fixated field of view increases. Similar changes occur for fields placed at eccentric positions.

Color mixture functions depend on the size of the viewing field. This observation is the basis for the CIE's decision to establish a 2° observer as representative of data for field sizes of 1° and 4° in extent, and a 10° observer for field sizes greater than 4° (Wyszecki, 1969). However, Fridrikh (1957) found 1° color mixture functions did not conform to CIE 2° data. Other reports (Hering, 1893; Horner and Purslow, 1947, 1948) suggest that color matching functions change as a function of field size.

If the changes reflected solely differences in inert visual pigments, the unit coordinates in a WDW system would be identical. However, the coordinates are not identical (Stiles, 1955a) and imply variation in the shape or spectral position of receptor sensitivities as a function of field size.

Previously (Smith, Pokorny and Starr, 1976), we discussed some possible models of inter-observer receptoral variability. In this paper, we consider models of variation of receptor sensitivity for different sizes of the viewing field. The models of inter-observer variability are relevant to the variable of field size. In the peripheral retina, the cones are "cone-shaped" and of reduced length. We could expect optical density to decrease and waveguide effects to vary with increasing eccentricity. The visual photopigments themselves may perturbate in \( \lambda_{\text{max}} \) if the microenvironment of the chromophore is changing. Stiles (1955b) and Stiles and Wyszecki (1974) have noted that macular pigment affects the 10° data in effective density about half that for the 2° data. Thus we may ask if the spectral filter required to explain the 2° inter-observer variability is required also to predict average unit coordinates and variance for the 10° observer.

PROCEDURE

The procedure described previously (Smith et al., 1976) defined a set of three basic spectra (S, M and L), that had the characteristics of visual photopigments. These spectra according to principles of changing optical density, or pigment shift, and variation of SF were examined as described previously. The resulting sets of tritanopic coefficients were examined at 250 cm\(^{-1}\) steps between \( P_2 \) and 14,000 cm\(^{-1}\) to determine those which would predict the coefficients for Wright's 7 tritanopes measured with a 1° 20' field (Wright, 1952) and those which would predict the small field tritanopic coefficients measured on Wright's eye for a 15° field viewed either with foveal fixation or with fixation at 20' or 40' from the fovea (Thomson and Wright, 1947).

RESULTS AND DISCUSSION

Trichromatic unit coordinates for average 10° observer

The 10° unit coordinates may be represented by reduced cone photopigment density combined with SF screening L. A comparison of the difference between the Stiles and Burch (1959) 10° (corrected for rod intrusion) and 2° P\(_2\) unit coordinates and the predicted differences under the assumption that the 10° data are characterized by photopigments in reduced concentration is shown in Fig. 1. The observed and theoretical differences closely fit from 25,000 to 17,500 cm\(^{-1}\). Between 17,500 cm\(^{-1}\) and 15,500 cm\(^{-1}\) the differences observed by Stiles and Burch (1959) perturbate unpredictably while the theoretical differences change smoothly through a negative lobe. The Stiles and Burch (1959) average 10° unit coordinates between 17,250 and 14,000 cm\(^{-1}\) are not observed values. In this spectral region, they noted rod intrusion, and corrected the average
on the spread of density pairs in Fig. 2, making it almost impossible to describe the scatter statistically. Panel (b) shows an example of a statistic assuming that the optical density of the pigments is distributed as a normal variable with parameters: $\mu_{OD_L} = 0.25$, $\mu_{OD_M} = 0.15$, $\sigma_{OD_L} = \sigma_{OD_M} = 0.05$, $\rho = 0.60$. The extreme values predicted by the statistic and falling within the 0.999 ellipse are shown in Fig. 3. This analysis must be considered preliminary until a set of 10° data free of rod intrusion is available.

Given the assumption that the 10° data are characterized by visual pigments in reduced density, it would also be possible to describe the interobserver variability by means of pigment shifts and a spectral filter.

The tritanopic coefficients

Earlier we found (Smith and Pokorny, 1975) it necessary for SF to be in density of 0.12 if the basic spectra, L, M were to predict Wright's tritanopic data (Wright, 1952). This result is incompatible with the trichromatic data presented in Paper I where SF is 0.05 and could imply that tritanopia is not a reduction form of normal trichromacy. However, Wright (1952) obtained the tritanopic data with a field size of 1° 20' rather than 2°, leading us to question if this field size difference could account for the discrepancy.

Fig. 2. (a) The density pairs (OD_L on the ordinate, OD_M on the abscissa) which yield unit coordinates falling within the extreme values of the Stiles and Burch 10° data. SF is set at 1/2 the difference in density of L and M and screens the denser pigment. Symbols: O, for density pairs for which unit coordinates fall within + 2 S.D. of the NPL observers; O, density pairs for which unit coordinates fall within the extreme values of the NPL observers. 2(b) A statistical description of the data in panel (a). A bivariate normal distribution of optical density for L and M is assumed with parameters $\mu_{OD_L} = 0.25$, $\mu_{OD_M} = 0.15$, $\sigma_{OD_L} = \sigma_{OD_M} = 0.05$, $\rho = 0.6$. The solid line ellipses enclose area of 0.50, 0.75, 0.95 and 0.99 under such a bivariate normal distribution.
Variability of color mixture data—II

We calculated tritanopic coefficients for a range of densities of L and M up to maximal densities of 1.0. SF was set (as in the trichromatic program) at 1/2 the difference in density of L and M and to screen the denser visual pigment. We examined sets of theoretical tritanopic coefficients for those which would predict the coefficients of the Wright (1952) tritanopes. In Fig. 4, the circles show the pairs of densities $OD_L$ and $OD_M$ which predict the tritanopic coefficients obtained for a 1° 20' field. The circles fall in the density range of 0.65 for L. and 0.55 for M. Thus the tritanopic data may be considered as a reduction form of normal trichromacy provided we assume a higher optical density for the visual pigment in a smaller field. Variation of the spectral position of L and M with SF less than or equal to 0.075 did not yield sets of unit coordinates agreeing with the average Wright (1952) data. However, as was true for the trichromatic data either variation of optical density or spectral position together with variation of SF produces comparable variation of the tritanopic unit coordinates.

Small-field tritanopic coefficients

Thomson and Wright (1947) measured small-field tritanopic coefficients on Wright’s eye with a 15’ field fixated foveally, at 20’ from the fovea, and at 40’ from the fovea. There are systematic differences in the sets of coefficients on which Thomson and Wright comment, pointing out that they must be of receptor origin. The foveally fixated set (as also the original set for a 20’ field published by Wilmer and Wright (1945)] fall outside the extreme values of the Wright (1952) tritanopes.

The symbol $W_0$ in Fig. 4 shows the densities of L and M which would predict the coefficients for these foveally fixated small (15’–20’) fields. The density pair falls at 1.0 for L, 0.9 for M. With fixation at 20’, the small-field tritanopic coefficients for Wright, shown by symbol $W_{20}$ in Fig. 4, coincides with the 1° 20’ tritanopic coefficients of tritanopes. With fixation at 40’, the density pair which would predict the coefficients, shown by symbol $W_{40}$ in Fig. 4, falls at 0.5 for L, 0.4 for M. The data for a trichromat are consistent with the concept of a continuous change in effective density across the retina.

Effective optical density as a function of field size

We have presented evidence that the differences in color mixture data for trichromats which occur for different field sizes can be viewed in terms of a continuous variation of effective optical density. Estimates of optical density of L as a function of field size are shown in Fig. 5. The error bars are for the 1° 20’ trichromatic and 1° 20’ tritanopic coefficients shown in Figs. 2 and 4. $W_0$ shows the position of

![Fig. 3. The extreme values of the $P_1$ unit coordinate predicted by the statistic of Fig. 2b for density pairs falling within the 0.999 ellipse. The Stiles and Burch extreme values are shown (crosses) for comparison.](image)

![Fig. 4. The density pairs ($OD_L$ on the ordinate, $OD_M$ on the abscissa) which yield tritanopic coefficients falling within the range of the Wright observers (circles). The dashed ellipse is the 0.999 ellipse for the 2° trichromatic observers (see Paper I). The symbols $W_0$, $W_{20}$, $W_{40}$ represent the density pairs which yield agreement with small-field tritanopic coefficients on Wright’s eye with fixation at 0, 20’ and 40’ from the fovea respectively.](image)

![Fig. 5. Estimates of optical density of the long-wavelength sensitive pigment as a function of field size. The error bars show the estimates derived in this paper from various color matching experiments. The squares are the estimates of optical density in deuteranopes obtained by Miller (1972) and Smith and Pokorny (1973). The solid line has the equation: $OD = 0.23 + 0.8825e^{-d}$. $d$ in deg visual angle.](image)
the Thomson and Wright foveally fixated data. The squares are estimates of optical density in deuteranopes made by Miller (1972) with a 1.6° field and Smith and Pokorny (1973) with a 2.5° field. Walraven and Bouman (1960) obtained an estimate of 0.7 for a 1° field in their analysis of the Stiles-Crawford color change. Effective optical density appears to decrease exponentially as field size is increased. The solid line passing near the squares and bars has the equation $OD = 0.25 + 0.8825 e^{-3.33x}$, $d$ in deg visual angle. The generality of this function must be considered preliminary since it hinges on data from different observers in a limited number of studies. We present color fields (Stiles, 1955b). It is of interest to consider the change. Effective optical density appears to decrease exponentially as field size is increased. The $\phi$ coefficients for Wright's eye (Thomson and Wright, 1947) at 20' from the fovea (W₂₀, Fig. 4) agree with the tritanopic coefficients of tritanopes (Wright, 1952) in a 1° 20' field whose perimeter would fall at 40'. The $W_{\phi\odot}$ coefficients fall outside the variability of the 1° 20' observers. Although based on only one observer, this result suggests that the color appearance is not determined at the perimeter of the field. An alternative approach may be constructed in terms of neural processing changes with eccentricity. Doorn, Koenderink and Bouman (1972), Hines (1976) and Wilson (1976) suggest that the area of the retina optimally sensitive to a given stimulus varies with spatial frequency. A given field foveally fixated may be optimally matched by a given set of receptive fields which will then determine the field appearance. As field size increases, coarser, more peripheral fields may in turn be optimised. A third approach might be that a weighted areal average is computed across the field. There is not yet sufficient evidence to distinguish between these possibilities.

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REFERENCES


