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INFLUENCES OF VARIATION IN LENTICULAR AND MACULAR PIGMENTATION ON DICHROMATIC NEUTRAL POINTS

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ABSTRACT

Protanopic, deuteranopic and tritanopic neutral points were computed by determining the wavelength of light that produced the same quantal-catch ratio in the photopigments as that produced by a broad-band light of specified color temperature (range: 2 800–6 600 K). The Vos-Walraven primaries were used as photopigment absorption spectra that were screened by varying densities of ocular (0.5–2.5 at 400 nm) and macular (0.0–1.0 at 460 nm) pigmentation. The computations were carried out in 1 nm steps for the wavelength range of 380 to 720 nm. Most of the empirically determined mean, neutral-point loci in the literature were predicted from these computations to within 1–2 nm when average ocular and macular pigment densities were used. The neutral-point range associated with the extreme values of the prereceptoral screening pigments was up to 25 nm for protanopes and deuteranopes and up to 13 nm for tritanopes.

INTRODUCTION

If an individual can discriminate between a broad-band ('white') light and all monochromatic lights between 400 and 700 nm, independently of brightness, we can reject the hypothesis that this individual is a monochromat or a dichromat. A monochromat fails in this discrimination task at every wavelength, while the dichromat fails to discriminate only at specific wavelengths. This latter narrow-band of discrimination failure represents the dichromat's neutral point. The dichromat's neutral point is the wavelength that can be metamerically matched to a broad-band standard, i.e. the wavelength that produces the same quantal-catch ratio in the photopigments as that produced by a broad-band illuminant. Thus, the neutral point for the different dichromacies can be calculated from the absorption spectra of the dichromat's photopigments, the density of the prereceptoral screening pigments and the quantal distribution of the broad-band standard.

Because the presence of a neutral point in an individual allows one to definitively reject the hypothesis of trichromatic vision, it is useful not only as a test for congenital color vision defects but also as a means to assess the

color vision of human infants, the aged, and in individuals with acquired color vision defects. However, the locus of the average neutral point is likely to vary for groups of different ages because of developmental changes in the prereceptoral screening pigments. Age-correlated changes in ocular density are well documented, resulting in a differential attenuation at 400 nm of a factor of about 24 between birth and 70 years (Boettner and Wolter, 1962; Said and Weale, 1959; Werner, 1982). Developmental changes in the macular pigment density spectrum are not as well documented. Indirect assessments of macular pigment absorption based on spectral sensitivity and color matching have not revealed age-correlated changes (Stiles and Burch, 1959; Ruddock, 1965; Verriest, 1974). On the other hand, the direct investigations of Schultze (1866) and Hering (1885) clearly support the possibility of age-correlated increases in macular pigment absorption. Schultze (1866) wrote:

> The yellow pigment develops in the human during the second year of life according to *Ammon*, *Michaelis* and *Arnold*. At least it becomes more intensive around this time. To establish whether it is completely absent prior to this would require further research. In the fresh eyes of a mature infant that died during birth, a microscopic examination of the place of direct vision revealed already a slight yellow tinge, (Authors' trans., p. 5)

On the same topic, Hering (1885) wrote:

> Of the macula of infants (whose age was never more than 4 weeks) I noticed only sometimes a hint of color. Perhaps it was covered by a clouding of the retina, because *Max Schultze* thought under the microsope he saw a tinge of yellow in the retina of a mature baby that died during birth . . . Similar observations were made on the lenses of a 3-year old boy ten hours after his death. The macula was quite noticeable and in its center pronouncedly yellow . . . (p. 183 f.)
>
> Thus, macula and lens act in the same way . . . there are also qualitative individual differences in the macular pigment . . . Already Max Schultze emphasized the large individual differences of the macula and attempted to define and explain differences in the color sense from that. (Authors' trans., p. 184 f.)

It thus seems likely that there are significant age-correlated changes in both ocular and macular pigment absorption as well as significant individual differences for observers of the same age.

It is therefore important to consider variation in prereceptoral pigmentation when diagnosing color vision defects with a neutral-point test since this variation alters the quantal distribution of the broad-band reference stimulus. As a consequence, the wavelength that is metameric to the broad-band light is correspondingly shifted. We modeled the shifts for broad-band illuminants of different color temperatures to quantitatively map the relations between neutral-point loci and prereceptoral screening.

METHODS

The neutral point for a given type of dichromat, for example the tritanopic neutral point, was obtained from the following equation (see also Wyszecki and Stiles, 1982):

$$\frac{\int_{380}^{720} Q(\lambda)\cdot\beta(\lambda)d\lambda}{\int_{380}^{720} Q(\lambda)\cdot\gamma(\lambda)d\lambda} = \frac{\beta(\lambda_{np})}{\gamma(\lambda_{np})}$$

where Q represents the relative number of quanta at a particular wavelength, λ, and β and γ are the absorption spectra corrected for ocular and macular pigment screening of the tritanope's short- and long-wave photopigments, respectively. The subscript np with λ denotes the neutral-point wavelength. For our calculations it was assumed that the tritanope's photopigments were identical to the middle- and long-wave photopigments of the normal trichromat. The deuteranopic neutral point was defined by the above equation except that the β terms were replaced by α, where α represents an absorption spectrum identical to the normal trichromat's short-wave photopigment. Similarly, the above equation for the protanopic neutral point was modified by replacing the γ terms with α.

For each of the three dichromacies we calculated neutral points by convoluting the broad-band quantal distribution of interest with the screened photopigment absorption spectra in 1 nm steps over the spectral range of 380 to 720 nm. The Vos-Walraven primaries, as tabled by Vos (1978), were used for the photopigment absorption spectra. In addition, we followed Vos in assuming that the average macular pigment density at 460 nm was 0.33 and the average density for the ocular media was 1.48 at 400 nm. After determining that these average values predicted empirically determined neutral points in the literature, we repeated the calculations to observe the shifts in the neutral points associated with variations in the density of the macular pigment from 0.0-to-1.0 (steps of 0.05) and the ocular media from 0.5-to-2.5 (steps of 0.05).

RESULTS AND DISCUSSION

Table 1 presents some of the mean neutral-point wavelengths for protanopes, deuteranopes and tritanopes in the literature. The tabled entries are arranged in order of increasing correlated color temperature; the neutral-point wavelength can be observed to decrease for all types of dichromats with increasing color temperature. With each empirical entry in Table 1, the calculated value is shown in parentheses. With the exception of the deuteranopes of Hecht and Shlaer (1936; to be discussed below), the computed values are close to the empirically determined values. Indeed, ignoring the data of Hecht and Shlaer, we see that the mean absolute deviation between the empirical and computed values is only 1 nm.

Figures 1, 2, and 3 present the neutral points that we calculated for broad-band lights with correlated color temperatures of 2 800, 5 000 and 6 600 K, respectively. Separate panels within each figure show the neutral points for tritanopes, deuteranopes and protanopes. Within each panel, we present the neutral point wavelengths associated with the macular pigment density specified on the axis of ordinates and the ocular media density

Table 1. Comparison of empirical and calculated neutral points.

Author(s)	Color temperature	Neutral-point wavelength (nm) empirical (calculated)		
		Protanope	Deuteranope	Tritanope
Fischer et al. (1951)	2 800 K	–	–	580 (*579*)
Fischer et al. (1951)	4 800 K	–	–	570 (*570*)
Wright (1952)	4 800 K	–	–	571 (*570*)
Pitt (1935)	4 800 K	496 (*496*)	500 (*503*)	–
Hecht and Shlaer (1936)	5 000 K	498 (*496*)	510 (*502*)	–
Sloan and Habel (1955)	6 500 K	493 (*493*)	–	–
Walls and Heath (1956)	6 500 K	492 (*493*)	498 (*499*)	–
Walls (1964)	6 500 K	–	–	568 (*567*)

specified on the axis of abscissae. The smooth contours represent boundaries between neutral point wavelengths. Thus, within each contoured area the various combinations of screening pigmentations produce the same neutral-point wavelength.

Although increasing densities in the ocular media and macular pigment can each significantly shift the neutral point wavelength toward higher values, macular pigment variation is associated with greater neutral-point variation than ocular pigment variation. That is, a unit change in macular pigment density tends to shift deuteranopic and protanopic neutral points by about 12 to 14 nm, while a unit change in ocular media density shifts deuteranopic and protanopic neutral points by about 4 to 5 nm. For the tritanope, the neutral point shifts are 5 to 9 nm and 2 nm with a unit density increase in macular and ocular pigmentation, respectively.

Comparison of Figs. 1–3 indicates that the neutral-point range is approximately the same for protanopes and deuteranopes with broad-band lights from 2 800 to 6 600 K (i.e., approximately 22 to 25 nm). In contrast, the tritanopic neutral-point range is increased with increasing color temperature (i.e., from about 7 nm to 13 nm). Thus, the effect of variation in prereceptoral screening pigments on tritanopic neutral points can be minimized with broad-band standards of lower color temperature.

Hecht and Shlaer's mean deuteranopic wavelength is not only longer than predicted, it is also substantially longer than the average value obtained by Pitt (1935) with a broad-band light of nearly the same color temperature. To explain the high wavelength obtained by Hecht and Shlaer, it was asserted by Walls and Mathews (1952) that: 'Something was seriously wrong with their apparatus . . . Either their wavelength scale had slipped or else their comparison field was not receiving anything like 5 000 K light . . .' (pp. 80–81). However, the problem with this assertion, as Walls and Mathews pointed out, is that it still does not explain the large range of individual subject variation that was obtained by Hecht and Shlaer. Large variations between subjects can, however, be attributable to variations in macular and ocular pigment density. This is clearly seen in Fig. 2 for the standard used by Hecht

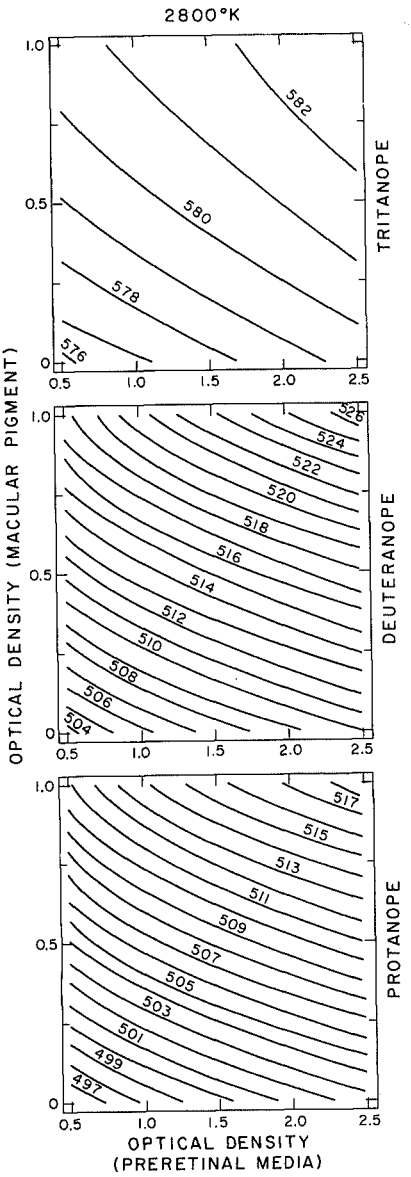

Fig. 1. Calculated neutral points for tritanopes, deutranopes and protanopes are presented in separate panels. The computations refer to a broad-band standard with a correlated color temperature of 2 800 K. Within each panel, macular pigment density is plotted on the axis of ordinates and ocular density is plotted on the axis of abscissae. The smooth curves represent boundaries between areas of the same neutral-point wavelength.

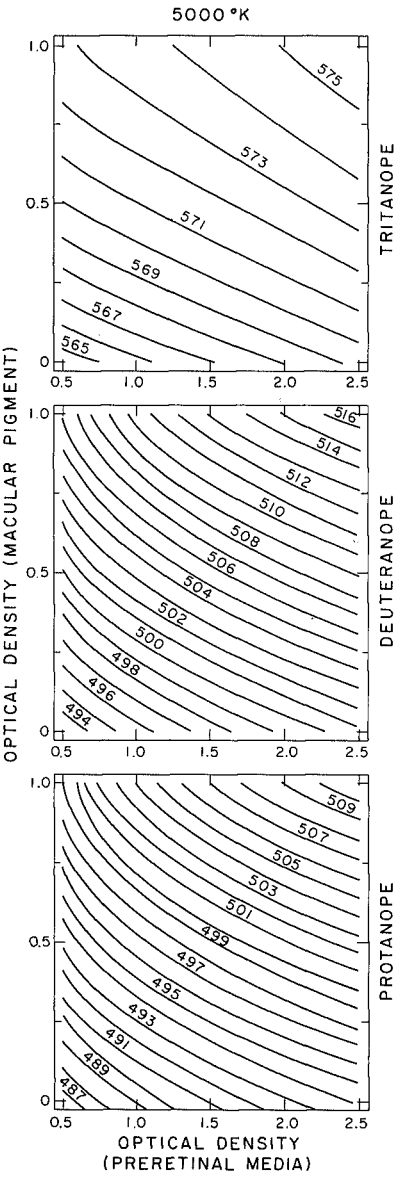

Fig. 2. Calculated neutral points for tritanopes, deuteranopes and protanopes are presented in separate panels. The computations refer to a broad-band standard with a correlated color temperature of 5 000 K. Within each panel, macular pigment density is plotted on the axis of ordinates and ocular density is plotted on the axis of abscissae. The smooth curves represent boundaries between areas of the same neutral-point wavelength.

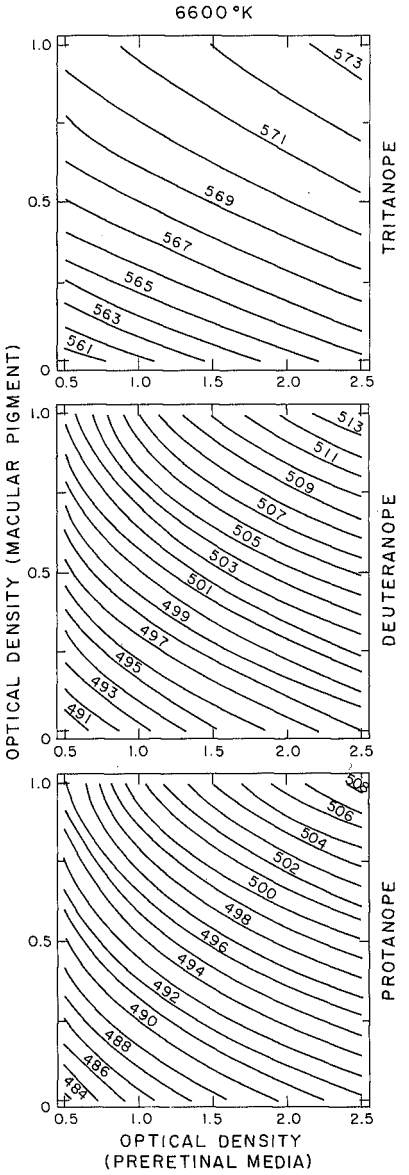

Fig. 3. Calculated neutral points for tritanopes, deuteranopes and protanopes are presented in separate panels. The computations refer to a broad-band standard with a correlated color temperature of 6 600 K. Within each panel, macular pigment density is plotted on the axis of ordinates and ocular density is plotted on the axis of abscissae. The smooth curves represent boundaries between areas of the same neutral-point wavelength.

and Shlaer (1936). Along similar lines, Judd, Plaza and Farnsworth (1950) reported a tritanopic neutral point at 586 nm for a standard of 2 900 K. Their calculated wavelength for an individual with normal ocular and macular pigmentation was, however, 578–579 nm, which perfectly agrees with our calculations. Their conclusion that this individual had 'abnormally heavy ocular pigmentation' is consistent with our computations.

It may be concluded from our computations, and consistent with data in the literature, that individual variation and age-correlated changes in macular and ocular pigmentation can significantly alter the locus of dichromatic neutral points. The quantitative mapping of neutral point contours presented in Figs. 1, 2 and 3 may be useful in predicting the range of wavelengths that should be tested for different color temperature standards with different groups such as infants and the elderly that are likely to have lower or higher prereceptoral pigmentation than a group of middle-aged adults.

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