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RESEARCH REPORT

SOURCES OF INDIVIDUAL DIFFERENCES IN ANOMALOSCOPE EQUATIONS FOR TRITAN DEFECTS*

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Abstract—The optimal blue-green equation for detecting tritan color defects was ascertained by systematically examining the effects of inert ocular pigments. Observers matched a test wavelength (410–470 nm) plus 500 nm to a mixture pair of 480 plus 580 nm for two field sizes: 2 and 8°. This technique was used to separate the sources of variation contributed by lens and macular pigment in the Moreland equation. The results of the experiment supported a formal analysis that showed that the wavelength of narrowest distribution must minimize a weighted sum of the sample variances in concentrations of lens and macular pigment.

Key words—Tritan defects; blue-green equations; macular pigment; lens; individual differences.

INTRODUCTION

A number of anomaloscope equations have been proposed for the detection of tritan defects, (Engelking, 1926; Trendelenburg, 1941; Richter, 1957; Speranskaya, 1960; Moreland, 1971; Moreland and Kerr, 1978, 1979). In the equations proposed by Speranskaya and Moreland, a "Cyan" test with fixed desaturant is matched to a mixture of "Blue" and "Green" primaries.

$$\underset{\text{(Test)}}{\text{Cyan}} \oplus \underset{\text{(Desaturant)}}{\text{Yellow}} \equiv \text{Blue} \underset{\text{(Mixture)}}{\oplus} \text{Green}. \qquad (1)$$

A major problem with such equations is that the distribution of the blue–green ratio in normal observers is appreciably broader than occurs in the Rayleigh match. Moreland (1971) showed that the increased variance is due to variation in the inert pigments of the eye, i.e. the lens and the macular pigment. Once the systematic age effects of the lens had been identified, Moreland suggested that an equation with a pair of mixture primaries that are both absorbed equally by the macular pigment would minimize the variance in the log blue–green ratio for normals. Moreland and Kerr (1978, 1979) explicitly tried to find the optimal equation by fixing the test field and varying the wavelength of the "Blue" primary:

$$\lambda \oplus 500\ \text{nm} \equiv 480 \oplus 580\ \text{nm}. \qquad (2)$$

They varied λ to find the equation that gave the smallest interobserver spread. This wavelength was 440 nm, in agreement with Ruddock's (1963) published density spectrum for macular pigment. However, the spectra compiled by Wyszecki and Stiles (1982) and by Vos (1972) differ considerably from Ruddock's. These spectra predict an equal macular pigment density for a wavelength between 415 and 420 nm and 500 nm. A possible interpretation of Moreland and Kerr's data is that their procedure minimized the variation contributed by both lens and macular pigment. In this paper our aim was to reassess the Moreland equation. We repeated Moreland and Kerr's experiment for two field sizes: 2 and 8°. Since the lens contribution is the same for both field sizes, this comparison of 2 and 8° matches allows us to separate the sources of variation contributed by lens and macular pigment in the Moreland equation.

THEORY

If the blue–green mixture ratio for the Moreland equation for an observer with no prereceptoral light losses is B/G, then the actual ratio for each observer will be B/G corrected for absorption by the lens and macular pigment:

$$B/G_{\text{Observer}} = (B/G) \times (T_{LG}/T_{LB}) \times (T_{MG}/T_{MB}); \qquad (3)$$

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*Portions of this work were presented at the *1982 Annual Meeting of the Optical Society of America.*

where T_{LG}, T_{LB} and T_{MG}, T_{MB} are the lens and macular pigment transmittances at the primary wavelengths G and B. By Lambert's Law, $T_\lambda = 10^{-pa_\lambda}$, where p is the optical pathlength independent of wavelength and a_λ is the decadic absorptivity at wavelength λ characteristic of the pigment. For a normal trichomat, the log of the measured ratio will be:

$$\log B/G_{\text{Observer}} = \log(B/G) + p_L(a_{LB} - a_{LG}) + p_M(a_{MB} - a_{MG}). \quad (4)$$

For this analysis it is assumed that observers differ only in the amount of lens and macular pigments, i.e. the decadic absorptivities of lens and macular pigments are identical for all observers, but the optical pathlengths of the pigments vary across observers. Stiles and Burch (1958) plotted estimated macular pigment density for their observers against estimated density of observers' lenticular pigment, and failed to find any appreciable correlation implying that the optical pathlengths for lens and macular pigment, are independently distributed. For a sample of observers the variance of the log of the observed ratio will be:

$$V(\log B/G) = (a_{LB} - a_{LG})^2 V(p_L) + (a_{MB} - a_{MG})^2 V(p_M). \quad (5)$$

$V(p_L)$ and $V(p_M)$ are the sample variances of optical pathlengths for the lens and macular pigment respectively. An equation that minimizes $V(\log B/G)$ for the population of observers is an optimal equation. From published tabulations of the density spectra of lens and macular pigment (Wyszecki and Stiles, 1982), it is obvious that there is no possible blue-green combination that will simultaneously set both $(a_{LB} - a_{LG})$ and $(a_{MB} - a_{MG})$ equal to zero. For a fixed wavelength G, $(a_{LB} - a_{LG})$ decreases monotonically as B gets closer to G, whereas $(a_{MB} - a_{MG})$ has an inverted U-shape. Therefore, $V(p_L)$ and $V(p_M)$ have to be considered in the minimization of the interobserver variation. Moreland and Kerr's assertion that an optimal equation should set $(a_{MB} - a_{MG})$ equal to zero is valid only if $V(p_L)$ is very much smaller than $V(p_M)$. In fact, their observed point of minimum interobserver variability is shifted toward 500 nm from the point where $(a_{MB} - a_{MG})$ is zero for the tabulation in Wyszecki and Stiles (1982), because presumably, $V(p_L)$ is a significant factor in their sample (Zaidi *et al.*, 1982; Moreland, 1984).* The implication for blue-green anomaloscope equations is that determining the optimal stimulus on these consideration necessitates obtaining good estimates of $V(p_L)$ and $V(p_M)$ for the target population.

EXPERIMENT

We tested our assertion by finding the wavelength that minimizes the variance in log (B/G) and also measuring the wavelength where a_{MB} is equal to a_{MG} for each of our observers. The spread in log (B/G) in the Moreland match was estimated from 8 observers with a 2° field. The density spectrum for macular pigment was estimated by comparing log (B/G) in Moreland matches on a 2 and an 8° field as a function of wavelength.

The logic of using two field sizes is as follows: the macular pigment optical pathlength decreases substantially from the 2 to the 8° perimeter of the field (Williams *et al.*, 1981; Vienot, 1983; Moreland and Bhatt, 1984). Other possible sources of differences in 2 and 8° fields include optical path-length of the lens, optical density of the cone photopigments and rod intrusion. Pflibsen *et al.* (1988) show that the aperture of the lens through which the light passes does not have an effect on retinal illumination for field sizes from 0 to 10 deg visual angle. The sensitivity curves of the long and middle wave sensitive photoreceptors have shallow slopes in this region so that a change in optical density with field size will not have an appreciable effect on the matches. Pokorny *et al.* (1981) show that rod intrusion in these matches will not alter the hue balance. This assertion was supported by the results of a pilot experiment, where one observer made 8° matches on the cone plateau after a 90,000 scot. td, 5 min bleach. There was no change in the blue–green ratio with rods bleached, so we can rule out the participation of rods in these color matches. The difference between 2 and 8° matches is thus primarily due to the difference in macular pigment absorbance in the two field sizes. For each observer:

$$(B/G)_8 = (B/G)_2 \times 10^{(p_2 - p_8)(a_{MB} - a_{MG})}; \quad (6)$$

where p_2 and p_8 are the optical pathlengths for macular pigment for the 2 and 8° field.

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*A number of studies suggest that the lens transmission function has multiple components (see Pokorny *et al.*, 1987). In the analysis above, multiple lens components would lead to multiple variance contributions due to inter-observer variance in the lens components. However, this would not change the main analytic conclusion, nor the interpretation of the empirical results.

By taking logs and rearranging terms, we obtain the equation:

$$\log(B/G)_2 - \log(B/G)_8 = (p_2 - p_8)(a_{MB} - a_{MG}). \quad (7)$$

The difference between the log ratios for the two field sizes, is proportional to the difference in the macular pigment absorptivity for wavelengths B and G, and the pathlength difference. If macular pigment absorption is equal for wavelengths B and G then the difference will be zero. We therefore set G equal to 500 nm, and B was varied from 410 to 470 nm to obtain an estimate of the absorption spectrum of macular pigment for each observer. By definition this procedure sets the macular pigment density at 500 nm equal to zero. The actual density spectrum for each observer will be translated up by the true density at 500 nm and multiplied by the difference in path length from the 2 to the 8° field. These transformations will not alter the wavelength with density equal to that at 500 nm, nor the wavelength corresponding to peak density.

METHODS

Equipment

A modified Moreland Universal Anomaloscope (Moreland and Kerr, 1978; Pokorny and Smith, 1976) was used to to present a bipartite field through circular field stops of 2 and 8° visual angle. The field was presented in Maxwellian view with the natural pupil providing the limiting aperture. The anomaloscope is designed so that the instrument's exit pupil is larger than the natural pupil, permitting small head movements for clinical observers. The variation in retinal illumination across observers does not affect color matches. The light source was a 500 W tungsten halogen lamp run at 120 V from a voltage regulator. Spectral lights were obtained by means of three-cavity interference filters with a half-height band pass of less than 10 nm. The test field was the mixture of a cyan "C" and a desaturating yellow "Y" channel and could be varied by two knobs: "C/Y" (saturation) and "$C + Y$" (brightness). The matching field was a mixture of a blue "B" and a green "G" channel and could be varied by two knobs: "G" (green only) and "B/G" (blue–green ratio). Each filter was calibrated for peak wavelength and band pass characteristics in the anomaloscope, using a laboratory built spectroradiometer and a microammeter. The sensitivity of the spectrodiometer was referenced to a standard lamp of known color temperature. Each knob had a digital read-out and was calibrated separately using the spectroradiometer. All the color matches in this study were made in the linear range of the knobs. Ambient illumination in the room was 900 lx with a correlated color temperature of 6200K (Verilux daylight F_{15}T8VLX lamps).

Observers

Eight observers with normal visual acuity and normal color vision participated in this experiment.

PROCEDURE

The test field wavelength (C) was 480 nm. It was desaturated by mixing with yellow light (Y) of wavelength 580 nm. The matching field primaries were G equal to 500 nm and B equal to 410, 420, 430, 440, 450, 460 or 470 nm. The order in which B was presented was determined by a pseudo-random sequence for each observer. Each B–G pair was presented at two field sizes, 2 and 8°. Each size-pair combination was presented five times for each subject, and the order for the field size was determined by a pseudo-random sequence for each pair of primaries. All the measurements for each observer were made on the same day in two sessions.

Observers made matches by adjusting the B/G knob to obtain a hue balance and the $C + Y$ knob to obtain a brightness match. The knob controlling the G channel was set so that the hue match was near the midpoint of the B/G knob. The C/Y test field saturation knob was set at a representative location for each mixture wavelength. Observers were allowed to choose a preferred eye, adapt to the ambient room illumination, and were told to glance back and forth from the stimulus to minimize change in color appearance with continuous viewing. They were instructed to ignore minor saturation differences and Maxwell's spot. A pilot experiment corroborated Moreland and Kerr's (1979) finding that it was possible to match in the presence of a representative saturation difference, and that this match had the same blue–green ratio as one made with that difference reduced to zero. The absence of a saturation effect is expected for color normal observers, because in the CIE 2° chromaticity diagram, the 480 plus 580 nm mixture line is tangential to the curved locus of constant hue in the region of the match, so that small changes in saturation

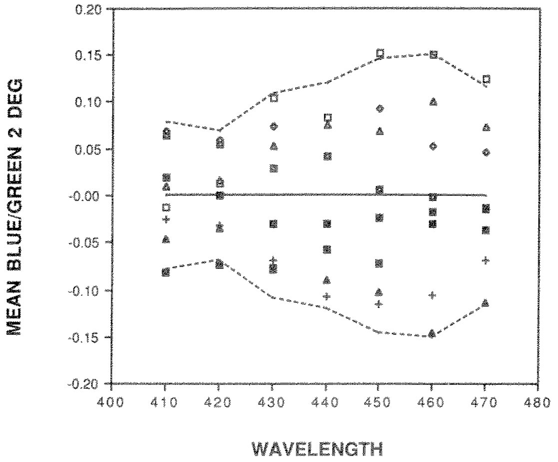

Fig. 1. The mean of log (B/G) for each observer is plotted against the B wavelength for 8 observers. The presence of less than 8 points for any test wavelength indicates that the mean ratio was identical for more than one observer. The observers' means are centred around the sample mean for each wavelength. The dashed lines are drawn through ($\pm$) 1.5 SD for each wavelength.

will not change the hue of the 480 plus 580 nm mixture appreciably. The B/G dial setting for each match was converted to the ratio of the radiances of the blue and green wavelengths. The log of the ratio of radiances will be referred to as log (B/G).

RESULTS

The scatter in mean log(B/G) for the 2° field is shown as a function of wavelength in Fig. 1. The minimum variance in our sample is for B equal to 410–430 nm, in agreement with Moreland and Kerr. Figure 2 shows 2 and 8° log ratios plotted against the B wavelengths for each observer. For each observer there is a wavelength at which the ratios for the two field sizes are equal to each other. As derived in equation (7), the difference between the log ratios for the two field sizes will be zero if the macular pigment absorption is equal for 500 nm and the B wavelength. The region of overlap between the ratios for the two field sizes is in the range 410–420 nm for each observer. To facilitate this comparison, we have simultaneously translated all the measurements for each observer for each B, to fit in the panel. This manipulation leaves the relationship between the ratio for the two field sizes unchanged. These two results from Fig. 1 and 2 are consistent with the mathematical result given before: the point of minimal interobserver variabilty in log B/G is at a longer wavelength than the wavelength that would minimize the variance due to macular pigment differences between observers. As shown algebraically in an earlier section, this must be due to sample variation in the amount of lens pigmentation.

By subtracting the mean of log $(B/G)_8$ from the mean of log $(B/G)_2$ for each B, we have derived an estimate of the optical density spectrum of macular pigment for each observer. These estimates are plotted in Fig. 3. Our estimate that the density of macular pigment is equal at 500 nm and in the wavelength range of 410–420 nm, is in general agreement with the Wyszecki and Stiles compiled curve. The peak for six of our observers is at 450 nm wheareas the Wyszecki and Stiles average curve peaks at

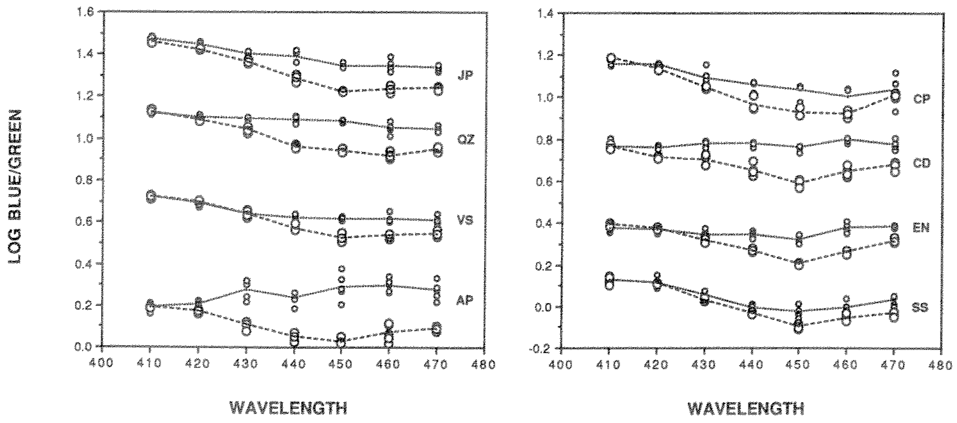

Fig. 2. The log (B/G) for 2° matches is plotted as ($\circ$) and for 8° matches as ($\bigcirc$) against the B wavelength for 8 observers. Five matches for each wavelength-field size pair are plotted for each observer. In case of overlap all points may not be visible. The dotted line connects the means of the 2° matches and the dashed line the means of the 8° matches. The measurements for different observers have been displaced up for clarity.

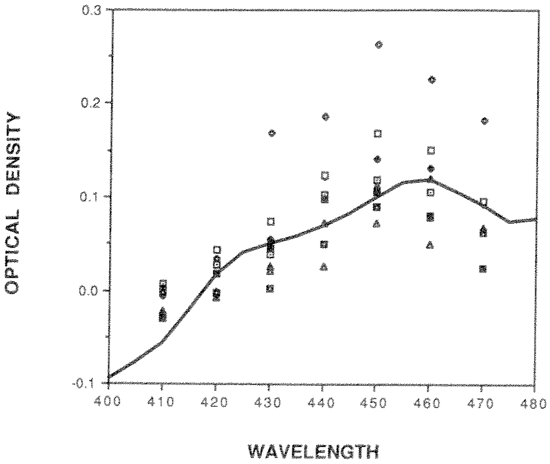

Fig. 3. The optical density of macular pigment derived from the color matches of 8 observers for 410–470 nm. The solid line is the macular pigment spectrum from Wyszecki and Stiles scaled to the average optical density difference (2–8°) of this sample of observers and vertically adjusted to coincide with the mean at 460 nm.

460 nm. The peaks for our other two observers are at 440 and 460 nm. It should be noted that the Wyszecki and Stiles curve is the average of very widely scattered data, and this discrepancy in the peak wavelength, may not be important.

DISCUSSION

To summarize, we have shown both formally and experimentallly that the wavelength of the narrowest distribution in the Moreland match depends on the characteristics of the sample of observers. This wavelength simultaneously minimizes sample variance in concentrations of lens and macular pigment. For both Moreland and Kerr's sample and our sample, the population variance of the log blue–green ratio for a 2° field is about the same for wavelengths 410–430 nm. Any of these wavelengths is suitable as a constituent of the mixture on the basis of this criterion.

Other considerations may be used to choose between these test wavelengths. First, an equation with shorter *B* wavelengths has greater variation across age groups due to the aging of the lens. Second, a tritan confusion mixture pair leads to procedural simplification. Once the "*G*" knob is set to equate the blue and green in luminance for the observer, changing the blue–green ratio varies only the quantum catch of the *S*-cones, and a two-adjustment match may be made (see Pokorny and Smith, 1984). A good choice for the Moreland equation is 430 nm (Pokorny *et al.*, 1981) since 430 and 500 nm are close to a tritanopic confusion line.* Tritan observers are presumed to differ from normal trichromats in *S*-cone spectral sensitivity, but not in *L*-cone and *M*-cone spectral sensitivities. In the absence of inert pigment differences, the color match made by a tritan observer lies on a tritan confusion line with the match made by a normal trichromat to the same test light. If the pair of lights on the mixture side lie on a tritan confusion line, the matching width can be used to differentiate incomplete from complete tritanopia. The existence of a color anomaly due to a shifted *S*-cone pigment has been questioned, but Pokorny *et al.* (1981) found that some older observers with autosomal-dominant tritan defects made matches shifted along a tritan confusion line from normal matches consistent with rods as an active third mechanism.

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*Moreland and Roth (1987) have analyzed the related question about the optimal tritan pair on the mixture side. The differences in standard deviations of the blue–green ratio between (436 and 490), (436 and 500) and (429 and 507), though statistically significant, do not seem excessive in practical terms.

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