

Red-green color discrimination as a function of stimulus field size in peripheral vision

Allen L. Nagy and Jeffrey A. Doyal

Wright State University, Dayton, Ohio 45435

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Red-green color-discrimination thresholds were measured at eccentricities of 10 and 25 deg in the nasal retina. Thresholds were measured as a function of stimulus field size both during the cone plateau and after dark adaptation. During the cone plateau, threshold decreased with increasing field size, but the effect of field size was dependent on the color of the test stimulus. The decrease in threshold was greater for yellow and orange test stimuli than for red and green tests. Two factors, summation and opponent-mechanism adaptation, appear to affect the relation between threshold and field size. An equation suggested by Boynton and Kambe in 1980 [Color Res. Appl. 5, 13 (1980)] provides a good description of the variation in thresholds with field size and eccentricity. After dark adaptation, thresholds increased for all test colors, suggesting that rod signals reduce discrimination. The dark-adapted thresholds could be described well by the addition of a rod term to the Boynton-Kambe equation.

1. INTRODUCTION

Before 1977 it was generally believed that color discrimination for stimuli presented to the peripheral retina was quite poor compared with foveal color discrimination. In that year Gordon and Abramov¹ published the results of color-naming experiments that suggested that peripheral color discrimination might be nearly as acute as foveal discrimination if large stimulus fields were presented to the periphery. Subsequent measures of discrimination thresholds by Noorlander *et al.*² and by Van Esch *et al.*³ confirmed that thresholds were approximately the same size in the fovea and in the periphery if the peripheral stimulus field was sufficiently large. Recently the similarity of foveal and peripheral color vision was supported by the hue and saturation scaling experiments of Abramov *et al.*⁴ The results of these experiments show that the perceived saturation of stimuli in the periphery is similar to that in the fovea if large stimulus fields are used in the periphery. However, Mullen⁵ found that the spatial resolution of color-coding mechanisms is clearly superior in the fovea and that peripheral hue-discrimination thresholds are larger than foveal thresholds even for the lowest spatial frequencies that were used.

It is clear that color discrimination is poor for small stimuli presented to the peripheral visual field and that wavelength discrimination functions for small peripheral stimuli differ in shape from foveal functions.^{6,7} Nagy and Wolf⁸ found that this difference could be characterized by changes in the parameters of the equation used by Boynton and Kambe⁹ to describe foveal thresholds or by a modified equation that included a rod term. Since rods were not excluded in their experiments, they could not discriminate between the two models.

The purpose of the experiments reported here is to determine how red-green color-discrimination thresholds vary as a function of field size. Thresholds were measured as a function of field size at eccentricities of 10 and 25 deg in the nasal retina. Measures were obtained dur-

ing the cone plateau after a bleach so that the rods could be prevented from contributing to the thresholds and also in the dark-adapted state at an eccentricity of 25 deg as an investigation of the effect that rod signals have on the threshold-versus-field-size function.

During the cone plateau, variations in red-green thresholds with field size could be characterized by changes in the Weber fraction (or Weber-Fechner fraction) and in the opponent coefficient of the Boynton-Kambe equation. After dark-adaptation, rod signals increased thresholds for all test wavelengths used, but the effect of the rod signal varied with both test wavelength and field size. A modified form of the Boynton-Kambe equation that included a rod term was used to describe thresholds in the dark-adapted state.

2. METHODS

A. Subjects, Apparatus, and Stimuli

Three observers between the ages of 23 and 43 years participated in the study. Rayleigh matches indicated that all three had normal color vision.

Stimuli were presented on a Barco color monitor (CDCT 5151). The monitor was driven by an AED 767 graphics processing unit, which was in turn driven by an Apple IIE computer. Approximately once every 6 s a circular stimulus field was presented in the center of the monitor screen. The hue of the field was one of the four standard test hues: green, yellow, orange, or red. After the stimulus field had been on for 500 ms, the hue was changed to the comparison color and then back to the standard color. The hue was changed gradually in a sinusoidal manner over a 1580-ms interval. Since the chromaticity of the field could not be varied continuously, the change was made in 20 discrete steps that approximated one-half cycle of a sine wave. The stimulus field then remained on at the standard test hue for another 500-ms interval before it was turned off. This stimulus presentation format was used to prevent the retinal fading (Troxler

effect) that occurs when stimuli are viewed continuously in the periphery. The gradual color change was used to avoid luminance artifacts that might occur when the color of a stimulus is changed rapidly on a CRT. Observers found it relatively easy to judge whether the stimulus field changed during the presentation interval even with peripheral viewing. Observers were instructed to respond yes if any change in the appearance of the stimulus occurred during the interval and no if the appearance of the stimulus did not change during the interval. They signaled a yes or no response by pushing one of two response buttons on a joy stick that was connected to the Apple computer. Responses were recorded by the Apple IIE, which then computed the size of the next hue change to be used according to the rules of a double random staircase procedure.

Five circular stimuli with diameters of 0.5, 1, 2, 4, and 8 deg were used at an eccentricity of 10 deg. At an eccentricity of 25 deg, fields with diameters of 1, 2, 4, 8, and 16 deg were used. The four standard colors used were red ($x = 0.584, y = 0.383$), orange ($x = 0.520, y = 0.398$), yellow ($x = 0.428, y = 0.471$), and green ($x = 0.300, y = 0.575$), with dominant wavelengths of 546, 573, 591, and 608 nm relative to an equal-energy illuminant. Thresholds were measured in the red direction for the green and the yellow test hues and in the green direction for the orange and the red test hues. The luminance of all stimuli was held constant at 17 cd/m². The colors of all stimuli were changed along a single line in the chromaticity diagram, which was chosen so that the excitation of the short-wavelength cones was held constant. Thus thresholds were determined only by changes in the excitation of the middle- and the long-wavelength cones. We assume that luminance is the sum of the excitations in the two long-wavelength cones.¹⁰ Therefore when the color of the stimulus was changed, the excitations of the long- and the middle-wavelength cones changed by the same amount but in opposite directions.

The monitor was calibrated with a Minolta chromameter (CS 100). The luminance and the chromaticity of each phosphor were measured at 18 of the 256 levels available. The chromaticity of each phosphor did not vary significantly as a function of luminance level over the ranges used. Sixth-order polynomials fitted to the luminance data were used to establish tables of the luminance for each of the 256 levels of each phosphor. A program was used to compute the luminance levels of the phosphors that were required for production of a stimulus of given chromaticity and luminance. A least-squared-error criterion was used to obtain the nearest approximation to the desired stimulus.

A Kodak (AF-2) slide projector with half of a ping-pong ball mounted in front of the lens was used to produce a bright Ganzfeld for bleaching. The observer placed his eye in front of the hemisphere and viewed the bleaching field for 90 s. Pilot experiments showed that cones recovered from this bleach in approximately 3 min but that the cone plateau extended to approximately 9 or 10 min after the bleach.

B. Procedure

1. Luminance Equations

Before beginning the experiment, each observer was asked to equate the red, the green, and the blue phosphors

in luminance with a flicker photometric null. The green phosphor was fixed in luminance and alternated with either the red or the blue phosphor at 19 Hz. The luminance of the red or the blue phosphor was varied until flicker was minimized. Each observer made flicker photometric nulls for both foveal and eccentric viewing conditions on three different days before beginning the experiment. These data were used to scale the luminances of the red and the blue phosphors that were measured with the Minolta chromameter for each observer so that luminances of the stimuli used in the experiment could be equated for each individual observer.

2. Experiment

During the experimental sessions the observer sat in a dark room and viewed the monitor from a distance of 1 m. A chin rest was used to stabilize eye position. The stimuli were presented on a dark background approximately once every 6 s. A pair of staircases contained ~30–40 trials and took 3 or 4 min to complete. Staircases were run with the observer fully dark adapted and also during the cone-plateau period after exposure to a bright bleaching light. In order to bleach rods, the observer viewed the bright Ganzfeld for 90 s. To allow the cones to recover, he then waited 3 min before beginning the staircases. The staircases could easily be completed during the first 4 min of the cone plateau (7 min after the bleach).

One staircase began with the largest hue change that could be produced on the monitor, and the other began with no hue change. Trials were randomly chosen from one staircase or the other. Staircases continued until three reversals were made at the smallest step size. The mean of the last three reversals was taken as an estimate of the threshold for each staircase. In a typical session, thresholds were obtained for all five field sizes for a single standard hue. The order in which field sizes were run was randomized. When thresholds were run during the cone plateau, two standard hues typically were completed in a session lasting 2 h. When the observer was dark adapted, all four standard hues could be completed in a 2-h session. Thresholds were obtained for each test hue and field size on four different days, resulting in eight estimates of each threshold.

For peripheral thresholds, observers viewed a small fixation cross at the same distance as the monitor screen. The fixation cross could be moved so that the stimuli fell at eccentricities of either 10 or 25 deg in the nasal retina. All subjects used the left eye to make observations and wore an eye patch over the right eye. One eccentricity was used within an experimental session.

3. RESULTS

Threshold chromaticity differences in the MacLeod-Boynton¹⁰ chromaticity diagram are plotted as a function of field size for the 10-deg eccentricity in the upper panel of Fig. 1. Mean thresholds taken across observers are shown for each test color. The curves connecting the points were drawn by eye. For all four test colors, threshold falls rapidly with increases in field size up to a diameter of ~2 deg. The reduction in threshold is not proportional to the increasing area of the stimulus but is roughly proportional to the field diameter or the square root of the area between the two smallest field sizes.

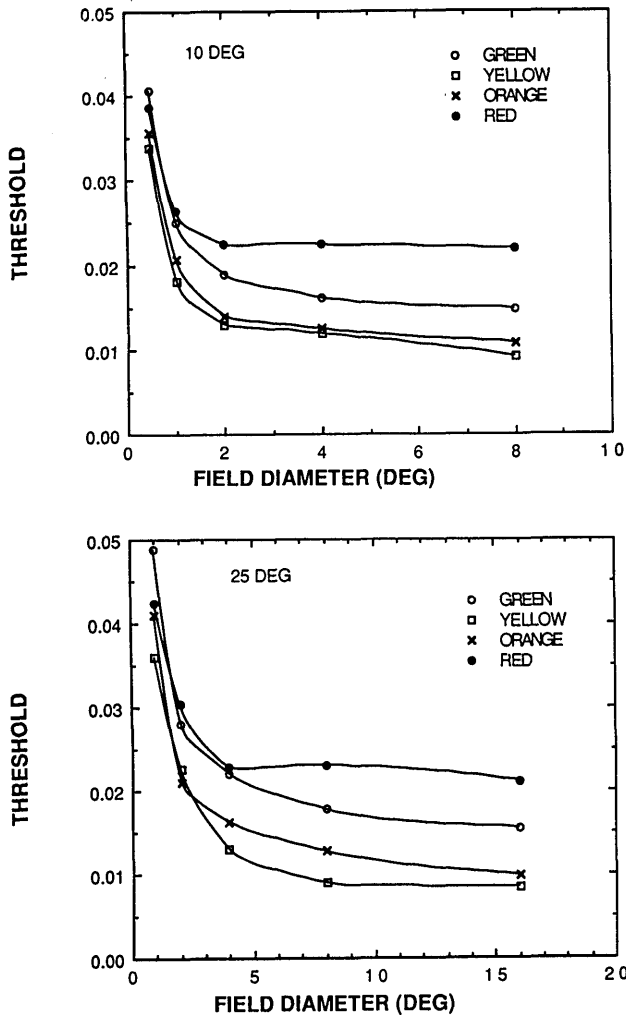


Fig. 1. Mean threshold plotted as a function of the diameter of the stimulus field for each of the four test wavelengths at eccentricities of 10 and 25 deg.

With increases in diameter beyond 2 deg, thresholds decline only slightly or not at all, depending on wavelength. For all field sizes, thresholds are highest for the green and the red test colors and lowest for the yellow and the orange test colors.

Mean thresholds measured at an eccentricity of 25 deg are shown in the lower panel of Fig. 1. Thresholds decline rapidly with increasing field size up to a diameter of ~4 deg at this eccentricity. Again the decrease is roughly proportional to the field diameter or the square root of the area only for the two smallest field sizes. As the diameter is increased beyond 4 deg, there is little or no decrease in threshold. Again thresholds are highest for the green and the red test colors and lowest for the yellow and the orange test colors at all field sizes.

Thresholds plotted as a function of the chromaticity of the test color are shown for individual observers in Figs. 2 and 3. The mean chromaticity difference at the threshold is plotted on the ordinate as a function of the chromaticity of the test color on the abscissa. Results from the three observers are shown with field size as a parameter within each panel. Thresholds obtained at an eccentricity of 10 deg are shown in Fig. 2, and those obtained at an eccentricity of 25 deg are shown in Fig. 3. The decline in

threshold with increasing field diameter is apparent for each observer. However, another aspect of the results is apparent in the plots of Figs. 2 and 3. The thresholds for the largest field sizes clearly describe a U-shaped function, but thresholds obtained with smaller fields tend to be flatter functions of test chromaticity. The solid curves in each figure represent the best fit of the Boynton-Kambe⁹ equation to each set of data.

The equation that Boynton and Kambe⁹ used to describe foveal red-green thresholds has the following form:

$$\tilde{\Delta}L = k[L + M + c|L - aM|].$$

$\tilde{\Delta}L$ represents the change in excitation of the L cones that is required for threshold. L and M represent the cone excitations generated by the test color, and k , c , and a are coefficients that were adjusted to fit the data. The Smith-Pokorny¹¹ fundamentals were used to represent the cone sensitivities. A least-squares-fitting procedure was used to fit the equation to the data at each field size and eccentricity for each observer. The two parameters in this equation, the Weber fraction, k , and the opponent coefficient, c , were varied to produce the best fit. An increase in the value of the Weber fraction, k , increases the size of all the predicted thresholds. An increase in the opponent coefficient, c , makes the predicted function more U shaped, increasing the predicted threshold for red and green test stimuli while leaving the predicted threshold for unique yellow stimuli unchanged. The effect of varying one of the coefficients while the other is held constant is illustrated in Fig. 4. In their experiments, Boynton and Kambe fixed the weighting coefficient, a , for the M cones in the opponent term at a value of 2. In fitting the equation to our data we found that better fits could be achieved for observers JAD and ALN if the value of this coefficient was varied. Therefore the value of the M-cone weight also was varied to achieve good fits.

Mean rms errors, expressed as a percentage of the mean threshold for each fit, are given in Table 1 for each observer. Overall the fits were quite good, with overall mean rms errors of 8.6% for the 10-deg data and 8.1% for the 25-deg data. The standard error of the mean for the measured thresholds tended to increase in proportion to the mean. That is, the variance of the measured threshold increased as the threshold increased. However, the standard error of the mean expressed as a percentage of the mean threshold is approximately constant and also is shown in Table 1 for each fit. The standard errors were typically 9–12% of the mean. Thus the threshold estimated from the fitted curve was typically within one standard error of the mean of the measured threshold.

Values of k and c for fits to the measured thresholds are shown in Figs. 5 and 6, respectively. In each figure, values for the 10-deg data are shown in the upper panel and values for the 25-deg data are shown in the lower panel. In Fig. 5 the decline in the Weber fraction with increasing field diameter is similar for all three observers. At both 10 and 25 deg, k declines with increasing diameter over the entire range, showing little evidence of flattening out even at the largest field sizes. The decrease in $\log k$ is approximately a linear function of \log field diameter. The fit of the straight lines to the data points provides an excellent description of the results with correlation coeffi-

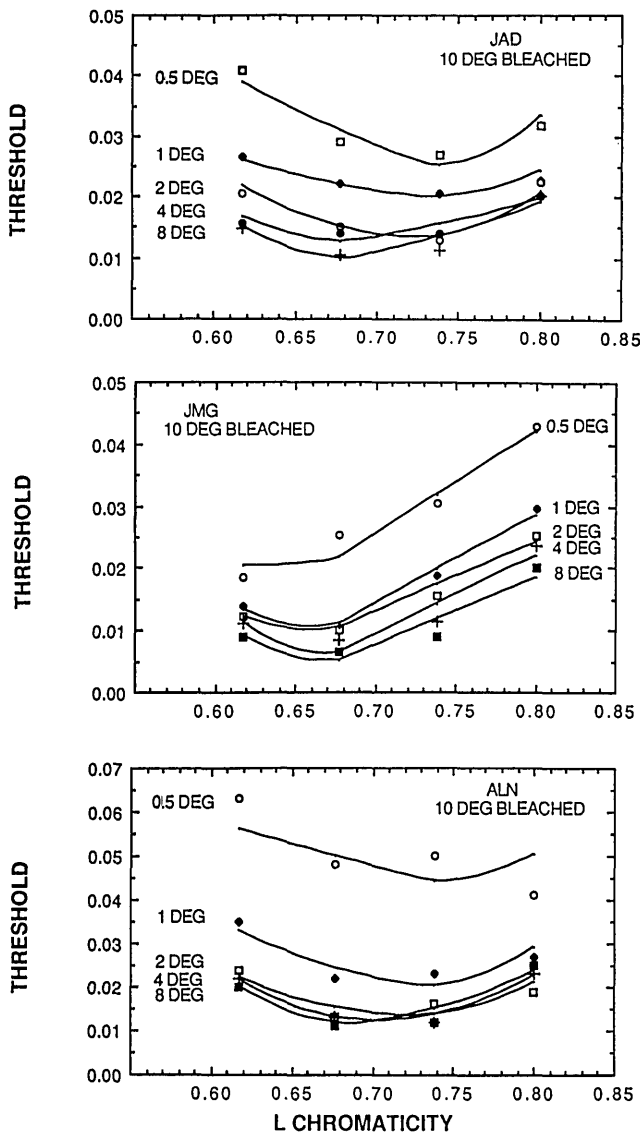


Fig. 2. Mean thresholds for observers JAD, JMG, and ALN plotted as a function of chromaticity for each field size. Data were obtained during the cone plateau at an eccentricity of 10 deg. Standard errors of the mean are ~10% of the threshold (see Table 1 below).

cients ≥ 0.91 . The slopes of these lines vary from -0.35 to -0.56 at 10 deg and from -0.60 to -0.80 at 25 deg.

The value of the opponent coefficient, c , increases with field size for all three observers, as shown in Fig. 6. The values of this coefficient were quite similar for observers ALN and JAD but were much larger at all field sizes for observer JMG. The value of c increases nearly linearly with field diameters as large as 4 deg at an eccentricity of 10 deg and is nearly constant for field diameters larger than 4 deg. At an eccentricity of 25 deg, c increases approximately linearly with field diameter over the entire range for observers JAD and ALN. For JMG the value of c increases approximately linearly up to a diameter of 8 deg and is then nearly constant. Straight lines indicate best fits of a linear equation.

In order to compare the peripheral thresholds with foveal thresholds, we obtained foveal thresholds from all three observers with the same procedures that we used to

obtain the peripheral thresholds. A stimulus field 1 deg in diameter was used. The foveal thresholds are shown in Fig. 7. Solid curves again indicate the best fit of the Boynton-Kambe⁹ equation. Values of k and c are given in Table 1 along with rms errors. Results obtained in the fovea are quite similar to the peripheral results for the largest field sizes for observers JAD and ALN. For observer JMG the value of k is somewhat larger, and the value of c is much smaller in the fovea than it is for large fields in the periphery. However, for all three observers foveal thresholds are approximately the same size as thresholds for large fields in the periphery.

Thresholds obtained in the dark-adapted state at an eccentricity of 25 deg are shown in Fig. 8. Results from each observer are again shown in separate panels with field size as a parameter. Dark-adapted thresholds were elevated with respect to thresholds obtained during the cone plateau for all test colors and field sizes. The mean

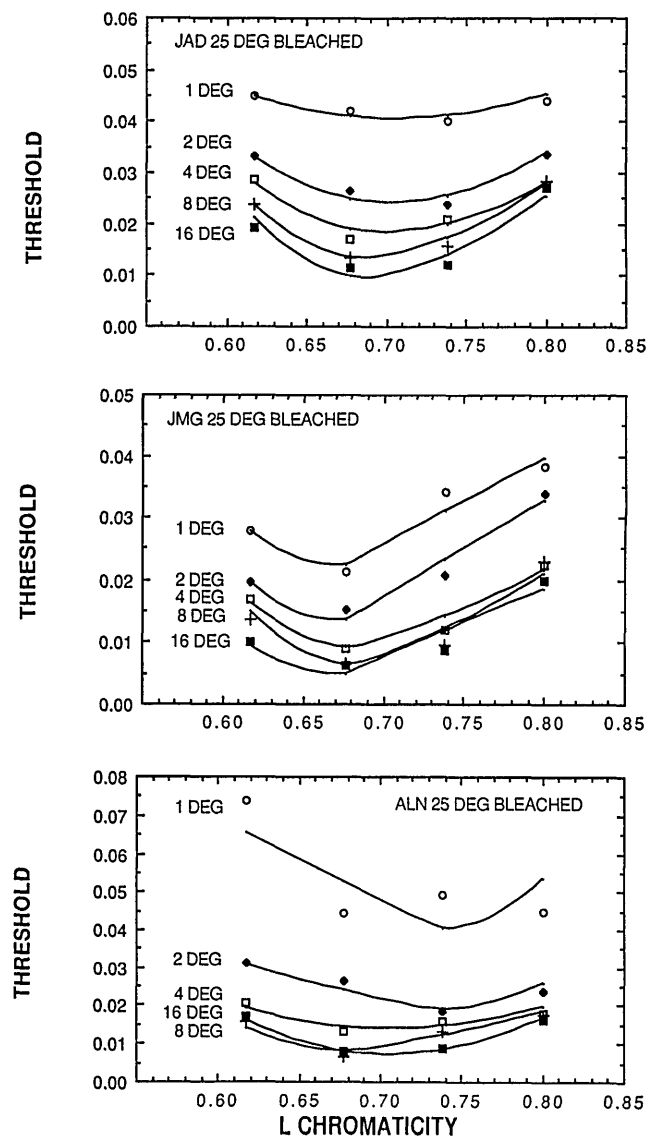


Fig. 3. Mean thresholds for observers JAD, JMG, and ALN plotted as a function of chromaticity for each field size. Data were obtained during the cone plateau at an eccentricity of 25 deg. Standard errors of the mean are ~10% of the threshold (see Table 1 below).

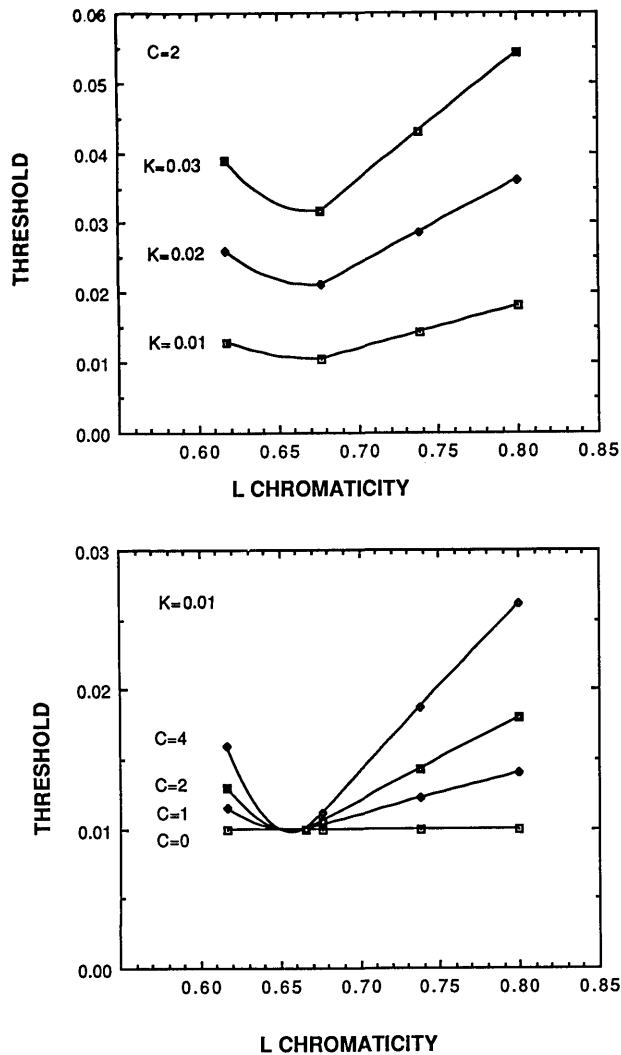


Fig. 4. Illustration of the effect of varying the coefficients *k* and *c* on predicted thresholds.

elevation is shown as a function of test color in Fig. 9. Threshold elevation was greatest for the green and the yellow test colors and least for the orange and the red test colors. Measures of the scotopic luminance level of the four test colors with a Pritchard Photometer (1980B) revealed that rod excitation was greatest for the green test color (35.8 scotopic cd/m²) and that rod excitation decreased linearly with increasing *L* chromaticity of the test color to a minimum (9.1 scotopic cd/m²) for the red test color.

A comparison of dark-adapted and cone-plateau results suggests that the rod signals generated by the test stimuli elevate the threshold roughly in proportion to the level of rod excitation generated by the test color, but the elevation of the threshold for the yellow test color is slightly greater than is predicted by this rule. We tried to describe the dark-adapted thresholds by adding a rod-excitation term, *R*, to the Boynton-Kambe equation:

$$\Delta L = k[L + M + b(R) + c[L - aM]].$$

The form of this equation is consistent with the slightly larger effect of rod signals on thresholds for test colors near unique yellow, as suggested by Fig. 9. The values of

the coefficients in the opponent term, *c* and *a*, were held fixed at the values required for fitting the cone-plateau data described above. The values of the Weber fraction, *k*, and the coefficient for the rod term, *b*, were varied so that the best fit was achieved. The curves in Fig. 8 represent the best fits of the equation. Mean rms error was 8.7%, approximately the same size as for fits to the cone-plateau data. Values of log *k* and log *b* are plotted as a function of field diameter in the upper and the lower panels, respectively, of Fig. 10. The value of log *k* decreases linearly with log field diameter, as it did for the bleached conditions. The slopes of the straight lines fitted to the data range from -0.65 to -0.74 and are similar to those obtained during the cone plateau. Values of the coefficient for the rod term, *b*, generally tend to increase with field diameter, which suggests a larger effect of rod signals with increasing field size. However, the functions for individual observers are rather irregular.

Table 1. Values of Coefficients, rms Errors, and Standard Errors of the Mean for Bleached Conditions^a

Location	Field Size	Observer	<i>k</i>	<i>c</i>	<i>a</i>	rms	Standard Error of the Mean
Foveal	1	JAD	0.008	2.6	2.4	7.4	8.1
		JMG	0.009	4.2	2.3	4.6	8.2
		ALN	0.009	4.1	2.0	6.5	7.8
10 deg	0.5	JAD	0.024	1.5	2.7	5.5	10.4
		JMG	0.016	3.7	1.8	7.6	14.6
		ALN	0.044	0.6	2.8	12.8	11.6
	1	JAD	0.019	1.0	2.6	3.6	10.3
		JMG	0.008	6.1	1.9	4.7	11.4
		ALN	0.018	2.2	2.6	8.8	7.0
	2	JAD	0.011	2.9	2.5	7.3	9.8
		JMG	0.008	4.8	1.9	6.6	10.7
		ALN	0.011	3.0	2.5	10.0	14.0
4	JAD	0.012	1.8	2.2	7.3	8.8	
	JMG	0.005	8.5	2.0	14.5	13.0	
	ALN	0.009	4.7	2.4	5.4	9.5	
8	JAD	0.009	3.1	2.2	9.0	9.5	
	JMG	0.004	9.0	2.0	15.6	10.2	
	ALN	0.009	4.8	2.3	10.1	9.9	
25 deg	1	JAD	0.039	0.5	2.4	2.4	10.5
		JMG	0.021	2.2	2.0	5.7	16.9
		ALN	0.040	1.4	2.8	16.1	12.6
	2	JAD	0.021	1.9	2.4	3.7	12.1
		JMG	0.012	4.3	2.0	7.0	16.4
		ALN	0.018	1.7	2.7	6.7	12.6
	4	JAD	0.015	2.8	2.4	6.1	11.1
		JMG	0.008	4.7	2.2	8.5	13.2
		ALN	0.012	2.0	2.4	8.4	12.2
	8	JAD	0.010	5.2	2.3	3.8	9.4
		JMG	0.005	8.8	2.2	14.1	11.2
		ALN	0.007	4.6	2.2	9.6	10.3
16	JAD	0.006	9.5	2.3	9.5	9.5	
	JMG	0.004	9.1	2.0	15.9	9.7	
	ALN	0.004	10.0	2.4	4.1	10.0	

^aThe rms and the standard error of the mean are expressed as percent-ages of mean threshold.

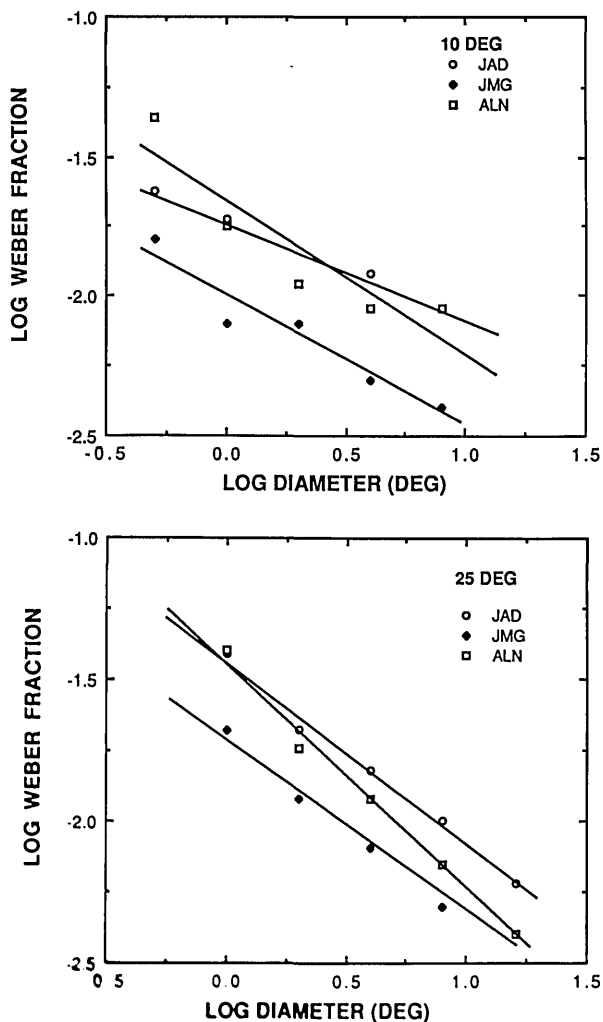


Fig. 5. Variation in the value of the Weber fraction, k , required for fitting the data for different field sizes at eccentricities of 10 and 25 deg.

It is important to note that the modified equation was fitted to data at one luminance level. As one of the reviewers of this paper pointed out, the equation implies that more rod intrusion would be expected at higher luminances and less at lower luminances. This prediction is contrary to expectations. The value of the coefficient, b , is probably dependent on luminance level as well as on field size, becoming smaller as luminance level is raised. Since all our data were obtained at one luminance level, we were not able to address this question here.

4. DISCUSSION

These experiments show that red-green color-discrimination thresholds in the peripheral visual field decrease with increasing field size and that they are quite similar to foveal thresholds when field size is large. This result is in good agreement with previous studies by Abramov *et al.*,⁴ Noorlander *et al.*,² and Van Esch *et al.*³ The results also suggest that threshold decreases very little for increases in field diameter greater than 2 deg at an eccentricity of 10 deg or increases in field diameter greater than 4 deg at an eccentricity of 25 deg. From estimates of the cortical magnification factor, Noorlander *et al.*² and Van Esch

*et al.*³ estimated that somewhat larger fields were required for fovealike discrimination. Van Esch *et al.* used circular fields 4 deg in diameter at an eccentricity of 8 deg and fields 10 deg in diameter at an eccentricity of 25 deg. The results of Noorlander *et al.* suggest that summation may occur over even larger areas for contrast-sensitivity measures with chromatic gratings at these two eccentricities. Our results suggest much smaller summation areas, as do the results of Abramov *et al.*,⁴ who used a color-naming method to estimate the field size required to produce maximally saturated chromatic stimuli in the periphery. Their estimates of these field sizes for red and green stimuli at eccentricities of 10 and 25 deg in the nasal retina are similar to the field sizes required for minimum threshold in this study.

It is difficult to compare our results with those from studies of summation areas for luminance in the periphery. Estimates of areas of linear summation for luminance vary considerably, depending on the conditions used in the study.¹² Summation areas for luminance thresholds clearly vary with the adaptation state of the observer.¹³ However, Wilson¹⁴ measured summation for increments on a white background field of 212 cd/m². At eccentricities

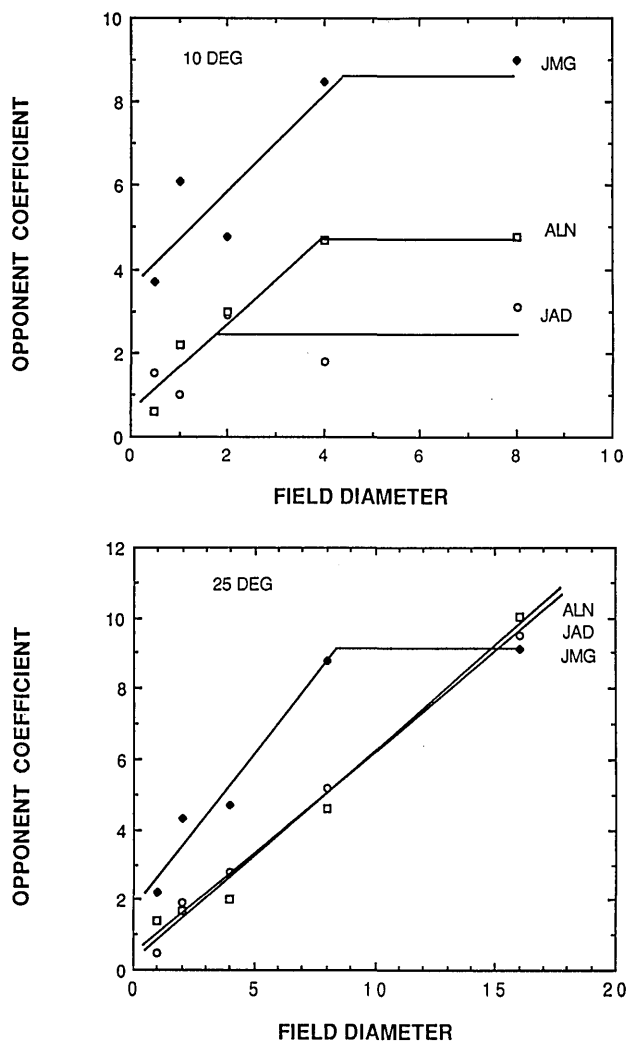


Fig. 6. Variation in the value of the opponent coefficient, c , required for fitting the data for different field sizes at eccentricities of 10 and 25 deg.

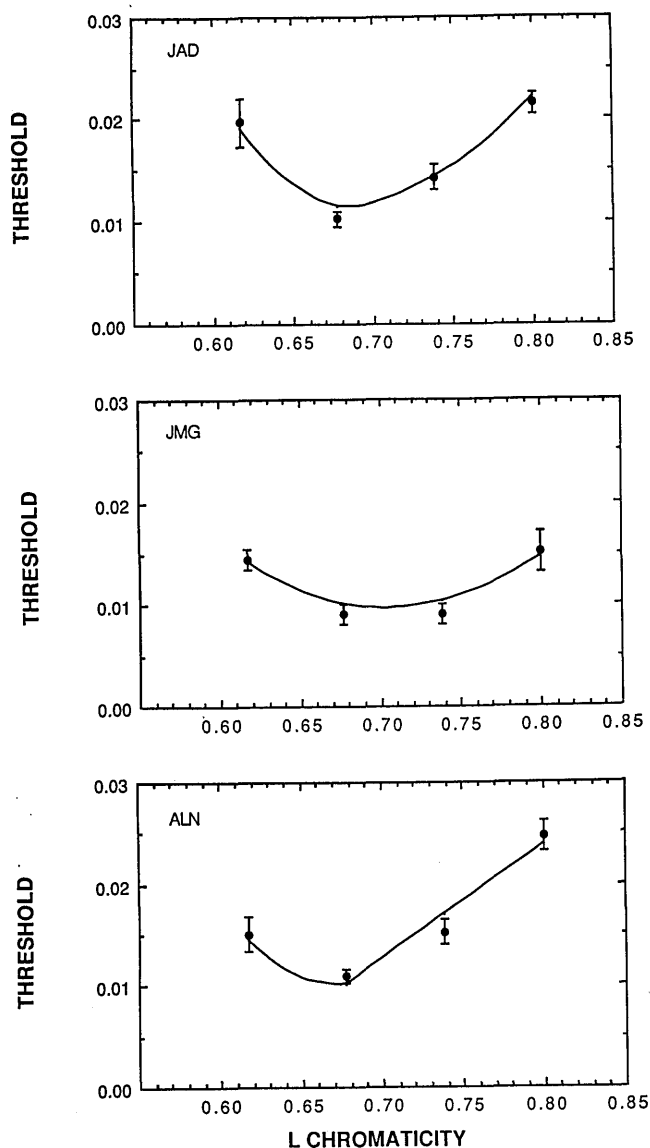


Fig. 7. Thresholds measured in the fovea for observers JAD, JMG, and ALN.

of 10 and 25 deg, threshold decreased linearly with stimulus area for field diameters up to ~8 and 20 min, respectively. These fields are smaller than the smallest fields used in the present study. However, luminance threshold continued to decrease roughly in proportion to the square root of the area with increases in diameter up to nearly 2 deg, the largest field used by Wilson. Our results for the two smallest field sizes used at each eccentricity are similar: the decrease in threshold is not proportional to the stimulus area but is roughly proportional to the square root of the area. In this respect the chromatic thresholds for the smallest fields are similar to the luminance thresholds measured by Wilson. However, the fact that the effect of field size interacts with the wavelength of the test stimulus makes the comparison with summation for luminance less meaningful. This interaction is discussed in Subsection 4.A.

A. Interaction of Field Size and Wavelength

The results clearly suggest that the color of the test stimulus influences the effect of field size on thresholds.

Thresholds for yellow and orange test stimuli decrease more with increasing field size than do thresholds for red and green test stimuli.

Foveal threshold versus wavelength functions are typically U shaped in the red-green portion of the spectrum (see Refs. 3 and 9), with a minimum in the yellow portion of the spectrum near 580 nm. Boynton and Kambe⁹ used the equation discussed in Section 3 to describe this U-shaped function for foveal data. The equation has two terms that correspond to luminance, or the sum of the L and M excitations ($L + M$), and to a red-green opponent channel ($L - 2M$). The opponent term is multiplied by a weighting constant, and the sum of the terms is multiplied by a Weber fraction. The magnitude of the Weber fraction sets the threshold at the bottom of the U, and the weight of the opponent term sets the steepness of the U-shaped function.

Threshold-versus-wavelength functions for large peripheral stimulus fields are similar to foveal functions

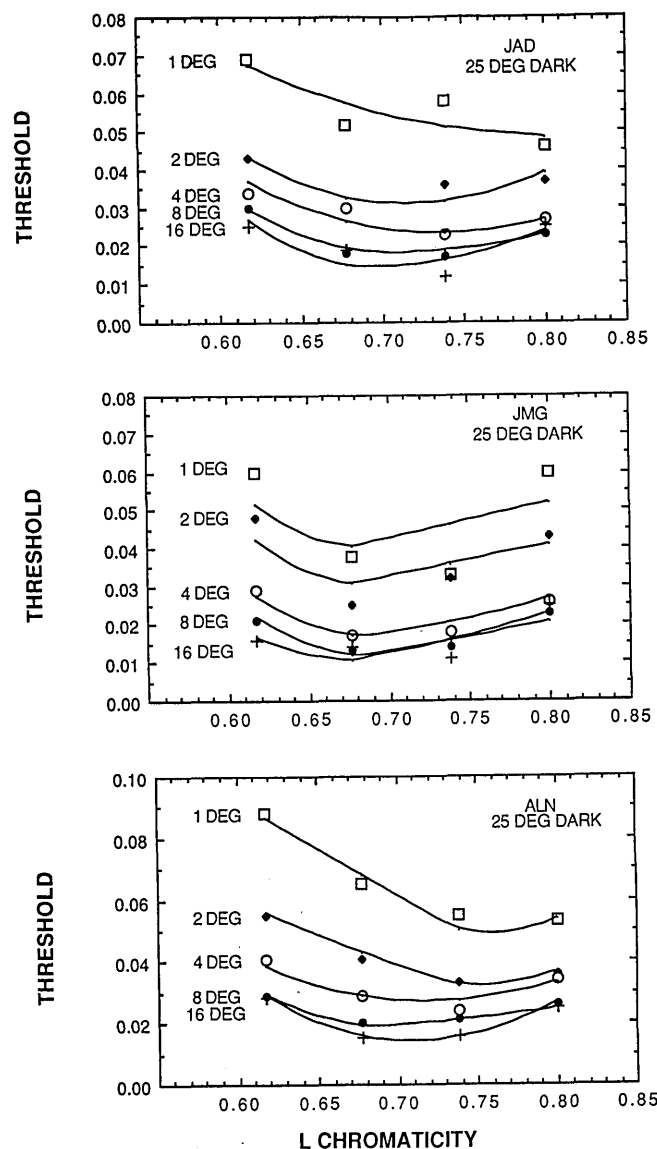


Fig. 8. Mean thresholds for observers JAD, JMG, and ALN plotted as a function of chromaticity in the dark-adapted state at an eccentricity of 25 deg. Standard errors of the mean are ~10% of the threshold (see Table 2).

Table 2. Values of Coefficients, rms Errors, and Standard Errors of the Mean for Dark-Adapted Conditions.^a

Location	Field Size	Observer	<i>k</i>	<i>b</i>	rms	Standard Error of the Mean
25 deg	1	JAD	0.036	0.35	8.0	9.9
		JMG	0.025	0.35	18.2	12.6
		ALN	0.034	0.44	4.5	8.6
	2	JAD	0.023	0.15	7.2	10.7
		JMG	0.013	0.78	11.9	8.4
		ALN	0.022	0.40	2.3	7.8
	4	JAD	0.012	0.59	7.8	8.5
		JMG	0.009	0.48	5.8	12.0
		ALN	0.019	0.20	7.0	8.9
8	JAD	0.007	0.90	4.3	7.7	
	JMG	0.005	0.70	7.6	9.1	
	ALN	0.006	0.80	4.1	8.5	
16	JAD	0.005	0.88	14.6	7.2	
	JMG	0.004	0.88	23.0	9.3	
	ALN	0.006	0.40	4.1	7.8	

^aThe rms and the standard error of the mean are expressed as percentages of mean threshold.

size reflects less sensitivity in small fields. Thus there appear to be two factors that influence the effect of stimulus-field size on color discrimination. As field size is increased, larger numbers of neural units in the retina are stimulated, resulting in greater sensitivity to chromatic differences. The increase in overall sensitivity is reflected by the decrease in the value of the Weber fraction. However, the larger stimulus fields also produce more excitation in red-green opponent-color mechanisms for stimuli that are not near the null point of the mechanism (yellow). The opponent-level excitation reduces sensitivity to chromatic differences and therefore works against the increase in sensitivity. Thus thresholds for red and for green stimuli do not decrease as much as those for yellow stimuli when field size is increased. Threshold-versus-field-size functions for reddish and greenish stimuli therefore reflect not only an increase in sensitivity but also adaptation at red-green opponent sites.^{15,16,17} Even if linear summation of signals occurred over fairly large retinal areas, it would not be evident in threshold-versus-field-size functions because of the effect of opponent-level adaptation, except, perhaps, for unique yellow stimuli that would be expected to produce little adaptation in red-green opponent mechanisms.

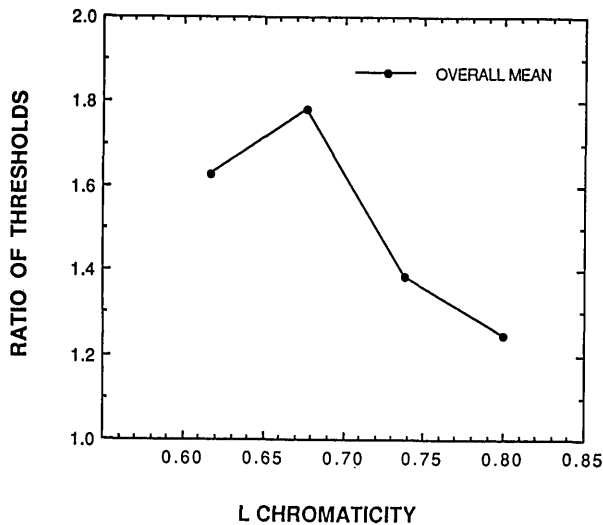


Fig. 9. Ratio of mean dark-adapted thresholds to bleached thresholds plotted as a function of chromaticity.

and can be described by the Boynton-Kambe equation. Values of the coefficients for fits of the equation to data obtained with large fields in the periphery are similar to values for fits to foveal data. Our analysis shows that threshold-versus-wavelength functions obtained with small peripheral stimulus fields can also be described by the Boynton-Kambe equation. However, the value of the Weber fraction increases as field size decreases, while the value of the opponent coefficient decreases with decreases in the field size and approaches zero. The fits to data obtained with small fields are nearly as good as fits to data obtained with large fields.

The decrease in the value of the opponent coefficient with field size suggests that small fields produce much less adaptation at the opponent-color coding mechanism, while the increase in the Weber fraction with decreasing field

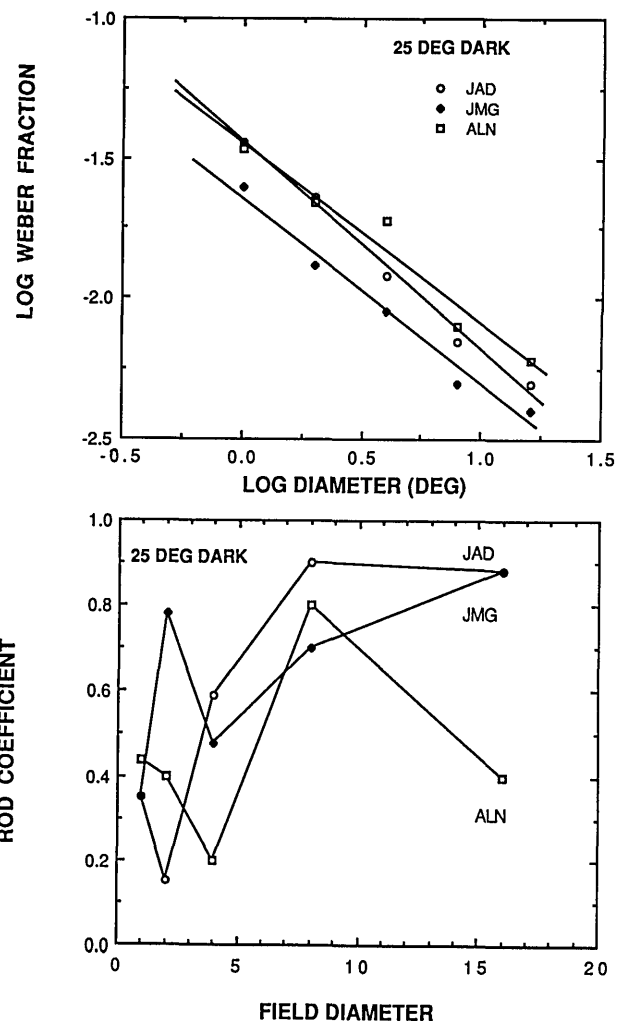


Fig. 10. Weber fractions and rod coefficients required for fitting the dark-adapted data for different field sizes.

The Boynton-Kambe equation does a good job of characterizing variations in red-green thresholds with eccentricity and field size during the cone plateau. The error in predicting mean thresholds for individual observers is generally less than 10% or within one standard error of the mean measured threshold.

It would be a simple matter for us to evaluate the coefficients at a few retinal locations with a few field sizes in order to develop a predictive system that would be useful for predicting discrimination thresholds for any stimulus at any retinal location. The plots of the coefficients as a function of field size (see Figs. 5 and 6) suggest that $\log k$ decreases linearly with \log field diameter, while c increases linearly with field diameter at both eccentricities tested. Also, note that we had to vary the value of the coefficient a in order to achieve good fits, particularly for observers ALN and JAD. However, it is not clear whether the value of a varies in a regular way with eccentricity or field size. The design of our experiments does not permit a particularly good estimate of a , particularly for the shallower U-shaped functions. A larger number of points on each threshold function would permit a better estimate of the value of a . The variations in a might be attributable to experimental error, to individual differences, or perhaps to systematic variations with eccentricity and field size. Our data are not particularly suited for a decision among these alternatives, and this point should probably be examined further. The usefulness of such a predictive system under varying adaptation conditions and luminance levels requires further evaluation. Since rod signals affect the thresholds, it is also necessary to add a rod term to the equation for accurate prediction under many peripheral viewing conditions.

B. Rods and Red-Green Discrimination

Rod signals appear to elevate thresholds for all four test wavelengths used in this study. We were able to find only one other study in which the effects of rod signals on red-green discriminations were studied. Stabell and Stabell¹⁸ used a bleach-and-recovery procedure to study effects of rod signals on wavelength discrimination at an eccentricity of 7.5 deg. They found little or no effect of rods at stimulus luminance levels of 100 Td or more. Below this level, recovery of the rods increased thresholds for wavelengths shorter than 600 nm but reduced thresholds for wavelengths longer than ~600 nm.

All stimuli in our study were presented at a luminance level of 17.0 cd/m² or a retinal illuminance of ~214 Td [estimated from Fig. 2 (2.4.5) on page 106 of Ref. 19]. Thresholds were elevated by rod signals for all four test wavelengths, including the stimulus with a dominant wavelength of 608 nm. Thus our results are not in complete agreement with those of Stabell and Stabell.¹⁸ The differences may be due to methodological and procedural differences as well as to the difference in eccentricities. In any case, the results suggest that rod signals may affect red-green discriminations at higher luminance levels than those suggested by Stabell and Stabell. The magnitude of the rod influence is dependent on field size at least for fields smaller than 8 deg in diameter. For fields larger than this, the increase in threshold that is due to rods may be similar for different field sizes.

The modified form of the red-green equation predicts

thresholds in the dark-adapted state quite well. The form of the equation suggests that the effect of the rod signal is similar to desaturating the stimulus. With this form of the equation it may be possible to describe thresholds for any stimulus field size, at any retinal location, at any luminance level, with appropriate values for the coefficients. However, further research is probably needed to establish whether this model is sufficient and to extend it to the tritan chromatic dimension. Our experiments were conducted at only one luminance level, which is at the high end of the functional range for rods. At lower luminance levels the rod signals may be able to contribute to discrimination and to reduce thresholds.

CONCLUSIONS

Overall, the results of this study support the view that peripheral red-green color-discrimination mechanisms are similar to foveal mechanisms. When peripherally viewed stimulus fields are large, discrimination thresholds are quite similar to those measured with smaller fields in the fovea. Changes in thresholds with decreases in the size of peripherally viewed fields can be well described by changes in the coefficients of the Boynton-Kambe⁹ equation. Two factors appear to affect the change in threshold with field size. As expected, one of these factors is summation. The other factor appears to be the degree of opponent-level adaptation. Together these two factors appear to account for variations in threshold with field size and eccentricity during the cone plateau. Rod signals also affect peripheral thresholds when the observer is dark adapted. Dark-adapted thresholds are well described by a modified version of the equation that includes a rod term.

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