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Color-Discrimination Perimetry*

Color-discrimination perimetry was performed using Munsell color chips to determine how far from the fovea specific color differences would be just-noticeably different. The results show that color-discrimination limits were larger in the red-to-purple and the blue-to-green regions of the color circle than in the purple-to-blue, the green-to-yellow, and the yellow-to-red regions. Achromatic color-discrimination limits went further into the periphery than did chromatic limits. We also performed color-naming experiments at the fovea and in the periphery (30° nasal). Our results are reasonably well accounted for by the deuteranopic tendencies in the periphery of the retina.

Introduction

A number of investigations have shown that color vision is gradually degraded in the periphery as stimuli are moved from the fovea, and the degree of deterioration in color perception depends on the colors used as stimuli. Perimetric studies have shown that the perception of green drops out in the peripheral retina before that of red, yellow, and blue.[1-5] These color-sensation limits in the peripheral retina are known as "color zones." Ferree and Rand[2] found color zones to extend 25° in the upper, lower, and nasal directions; 60° in the temporal direction for a green stimulus, but 40° in the upper, lower, and nasal directions; and 80° in the temporal direction for red and blue stimuli. Those stimuli were of 2° visual angle in diameter and about 2–14 cd/m^2 presented in a gray surrounding adaptation field. Although the sizes of color zones vary with observing conditions (e.g., field size, luminance level, and adaptation condition) the color zones tend to be larger in the temporal retina than in other directions.

Color-appearance investigations in the periphery with both color-naming[6-8] and color-matching[9] techniques have also revealed peripheral color vision. Boynton et al.[6] and Moreland and Cruz[9] showed that red and especially green sensations deteriorated more rapidly up to about 40° from the fovea than did yellow and blue sensations as eccentricity increased. This deterioration of color vision in the periphery resembles that of deuteranomalous observers. However, Gordon and Abramov[7] pointed out that the color deficiency in the periphery was tritanomalous rather than deuteranomalous. Moreover, deterioration in color perception in the periphery is dependent on stimulus size.[7,8] If a large stimulus is used in the periphery, observers perceive with less degradation in color. Wavelength-discrimination experiments in the periphery also indicate deficiency in peripheral color vision.[10,11] Weale[10] showed that discrimination thresholds of the green, yellow, and red parts of the spectrum are higher than those of blue and violet when stimuli were presented between 25° and 70° from the fovea, indicating a deuteranopic tendency in the periphery.

In everyday life, color discrimination is a more common task than mere detection. Even so, there have been only a few studies[12,13] on color discrimination in the periphery using nonspectral colored lights. In this article we report on a color-discrimination perimetric experiment. Two colors which are easily discriminable at the fovea may not be discriminated in the periphery, and there must be a limit where a given color difference is just noticeably different. The aim of our research was to study, for one field-size condition, color discrimination in the peripheral retina by determining color-discrimination limits.

Method

Stimulus

In Experiment I, Munsell color chips of value 6.0 and chroma 8.0 were used as stimuli. We employed five hues as the test stimuli: 5R, 5Y, 5G, 5B, and 5P. For each test stimulus eight comparison hues were chosen so that four of eight comparison hues were placed in one of two directions from the test hues along the color circle (Fig. 1). In Experiment II, a Munsell neutral chip of N6.0 was used as the test stimulus and eight neutral chips were chosen in 0.5 V steps for comparisons. Four comparison chips were lighter and four chips darker than the test stimulus.

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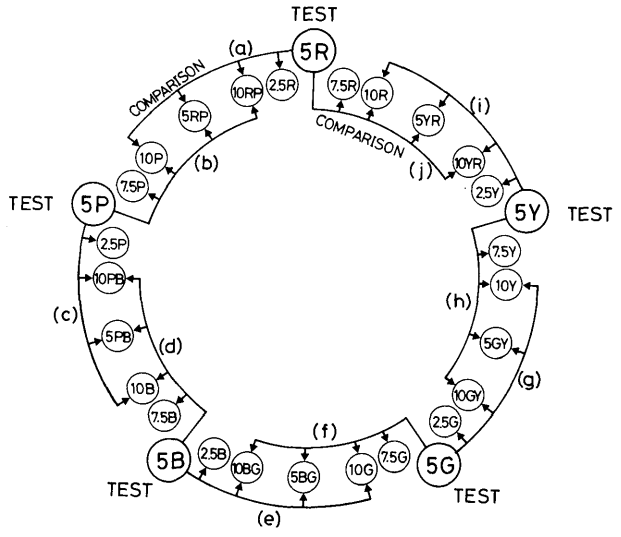


FIG. 1. Test- and comparison-stimulus hue combinations used in the Experiment I. Value and chroma of these stimuli: V/C = 6/8.

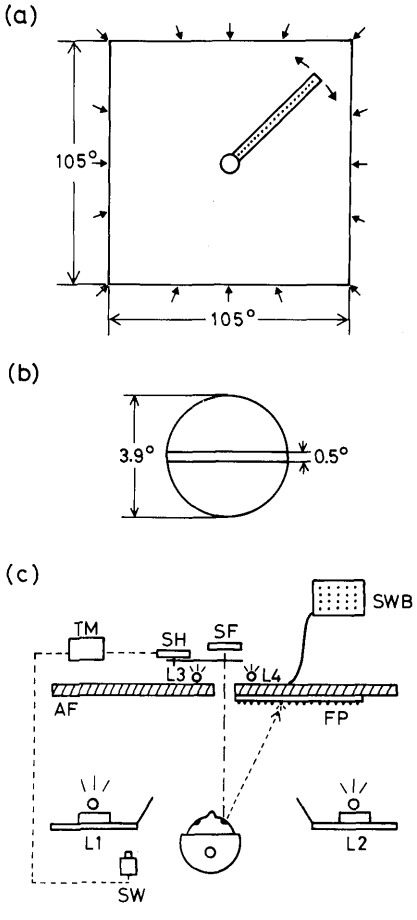


FIG. 2. (a) The gray surrounding adaptation field. The bar with 21 fixation points is rotated and fixed at one of 16 radial directions. (b) The stimulus field. Test stimuli are presented in the top half, and comparison stimuli in the bottom half. The gap in the middle of the field is formed with a Munsell N6 chip. (c) A schematic view of the whole apparatus. See text for details.

The CIE 1931 (x, y) chromaticity coordinates and luminous reflectances Y of all stimuli are shown in Tables I and II. The (x, y) values were measured with an EG&G spectroradiometer, and luminances of all stimuli were measured with a Prichard photometer relative to that of magnesium carbonate ($MgCO_3$), the reflectance of which is known,[14] in order to determine the Y values. We also express chromaticity coordinates of the stimuli in the CIE 1976 L^* a^* b^* terms[15] as shown in eq. (1). Equation (2) shows the formula used to calculate color difference ΔE^*_{ab} between stimuli.*

$$L^* = 116(Y/Y_0)^{1/3} - 16,$$
$$a^* = 500[(X/X_0)^{1/3} - (Y/Y_0)^{1/3}], \quad (1)$$
$$b^* = 200[(Y/Y_0)^{1/3} - (Z/Z_0)^{1/3}],$$
$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}. \quad (2)$$

Values of L^*, a^*, and b^* for all stimuli are also shown in Tables I and II.

Apparatus

The apparatus for this experiment is shown in Fig. 2. Figure 2(a) shows a gray surrounding adaptation field of 105° × 105° visual angle. A bar with 21 fixation points could be rotated on the adaptation field and fixed at one of 16 equally spaced directions. These fixation points were placed every 2.5° from the center. The fixation point closest to the stimulus field was a black cross mark drawn on the bar, but others were red LEDs. At the center of the adaptation field there was a hole through which the stimulus field was observed. The distance between the hole and the observer's eye was 50 cm.

Test stimuli were presented in the top half of a 3.9° horizontally divided bipartite field, and the comparison stimuli were in the bottom half as shown in Fig. 2(b). A gap of 0.5°, formed with a Munsell N6 chip, separated test and comparison fields. This gap was removed in Experiment II, where test and comparison gray chips were juxtaposed in the stimulus field.

Figure 2(c) illustrates the whole apparatus. The adaptation field, AF, was illuminated by two fluorescent lamps (GE, daylight, F20·T12·D), L_1 and L_2. The (x, y) chromaticity coordinates of the adaptation field were 0.315, 0.333, and its luminance was 51 ± 9 cd/m^2 when measured at the place of the observer's eye. Two small fluorescent lamps (Westinghouse, daylight, F6·T5·D), L_3 and L_4, were

* The reasons we used the CIE 1976 L^* a^* b^* formula to calculate color differences between stimuli are as follows. The L^* a^* b^* formula represents Munsell chips in a fairly uniform color space when Munsell chips are illuminated by CIE Illuminant C. We used fluorescent lamps which are slightly different from CIE Illuminant C to illuminate Munsell chips. Nominal Munsell steps in different color regions may not be equal under this illumination. Therefore, it was necessary to employ some formula to describe color differences between test and comparison colors.

TABLE I. CIE 1931 (x, y, Y) and CIE 1976 (a^*, b^*, L^*) values of the test (*) and comparison stimuli used in Experiment I.[a]

Hue	x	y	Y	a^*	b^*	L^*
2.5R	0.3954	0.3331	26.92	27.33	7.03	58.90
*5R	0.4193	0.3497	29.05	29.24	15.69	60.83
7.5R	0.4313	0.3650	29.88	27.75	22.28	61.55
10R	0.4481	0.3801	30.71	27.61	30.11	62.26
5YR	0.4493	0.4126	28.70	17.78	39.20	60.51
10YR	0.4507	0.4475	30.83	9.06	51.62	62.36
2.5Y	0.4491	0.4620	29.41	4.91	55.27	61.14
*5Y	0.4308	0.4794	30.59	−3.86	56.71	62.16
7.5Y	0.4211	0.4851	30.00	−7.63	55.52	61.66
10Y	0.4184	0.4960	31.54	−10.92	59.42	62.96
5GY	0.3882	0.5044	31.42	−20.81	53.78	62.86
10GY	0.3405	0.4816	29.65	−29.14	36.50	61.35
2.5G	0.3114	0.4540	28.58	−31.81	24.73	60.41
*5G	0.2935	0.4343	28.46	−33.23	17.59	60.30
7.5G	0.2821	0.4133	28.46	−32.25	11.27	60.30
10G	0.2701	0.4031	27.63	−33.74	7.31	59.55
5BG	0.2538	0.3741	28.22	−32.76	−1.37	60.09
10BG	0.2341	0.3229	27.04	−25.78	−16.14	59.01
2.5B	0.2301	0.3159	26.21	−25.05	−18.22	58.23
*5B	0.2305	0.2968	26.44	−18.74	−23.38	58.46
7.5B	0.2287	0.2802	25.97	−13.61	−28.13	58.01
10B	0.2328	0.2661	26.09	−6.47	−31.95	58.12
5PB	0.2486	0.2602	27.16	2.89	−32.51	59.12
10PB	0.2748	0.2638	27.63	12.52	−28.61	59.55
2.5P	0.2850	0.2636	27.51	16.71	−27.45	59.44
*5P	0.2905	0.2642	26.44	18.39	−26.27	58.46
7.5P	0.3066	0.2685	27.27	22.93	−23.30	59.23
10P	0.3244	0.2777	27.51	25.65	−18.37	59.44
5RP	0.3591	0.3032	26.21	26.82	−6.31	58.23
10RP	0.3873	0.3278	26.68	26.70	4.38	58.68

[a] Value and chroma of these stimuli: V/C = 6/8.

used to illuminate the stimulus field, SF, uniformly. The (x, y) chromaticity coordinates of these lamps were 0.322, 0.338, which is close to the chromaticity of CIE Illuminant C. The luminance of the stimulus field was 226 cd/m^2 measured with the Munsell N6 chip in place.

A solenoid-activated shutter, SH, was placed between the stimulus field and the hole in the adaptation field. When the shutter was closed fluorescent lamps L_3 and L_4 illuminated the shutter blade, which was covered with a Munsell N6 chip, so that a gray color with the same reflectance as the test and comparison colors appeared in the visual field. The shutter was controlled by the observer using a timer, TM, and switch, SW. The stimulus duration was 500 ms throughout all experiments. Twenty switches on the switch box, SWB, permitted the experimenter to light one of the LED fixation points located on the bar. The observer's head was held fast by a helmet and only the right eye was used. All experiments were performed in an otherwise dark room.

Observers

Two observers, a male (KU) and a female (HU) 29 and 28 years of age, respectively, participated in all experiments. They had normal color vision as tested by the Farnsworth–Munsell 100 Hue Test and normal or corrected visual acuity.

Procedure

A modified method of limits was used in both Experiments I and II to determine how far from the fovea a certain color difference would be just-noticeably different. In a trial, a pair of test and comparison stimuli were first presented in the far periphery where the observer could not detect the color difference between the test and the comparison. The observer fixated the fixation point and, when ready, pushed switch SW to present stimuli. Then the experimenter moved the fixation point by one step toward the center. The observer was required to identify the difference

TABLE II. CIE 1931 Y and CIE 1976 L^* values of the test (*) and comparison stimuli used in Experiment II.[a]

Value	Y	L^*
N4.0	10.67	39.02
N4.5	14.23	44.56
N5.0	18.38	49.95
N5.5	22.77	54.83
*N6.0	26.86	58.79
N6.5	33.80	64.80
N7.0	40.08	69.53
N7.5	47.31	74.39
N8.0	55.50	79.33

[a] CIE 1931 (x, y) and CIE 1976 (a^*, b^*) values of these stimuli: (x, y) = (0.3214, 0.3455), (a^*, b^*) = (0,0).

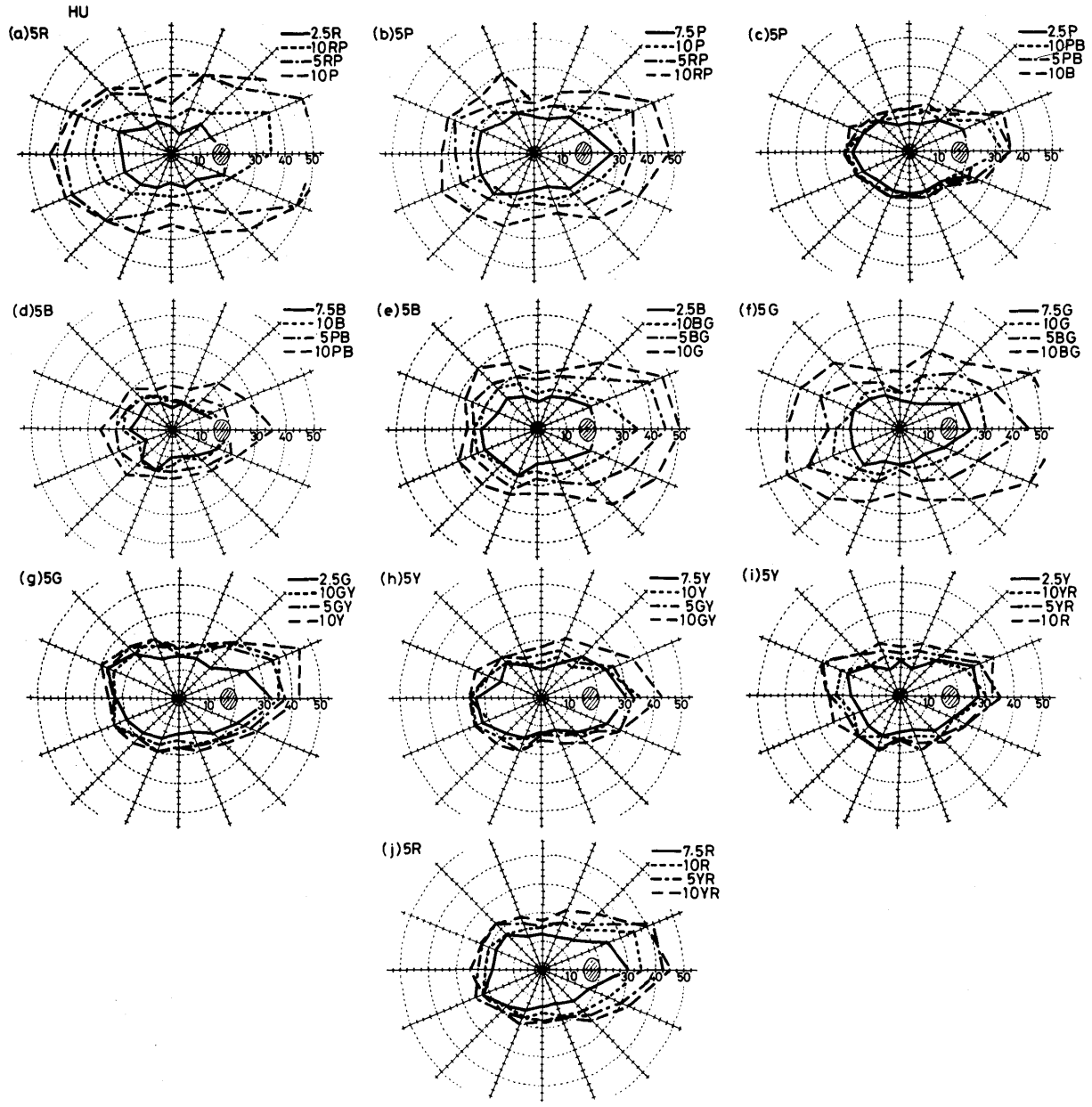


FIG. 3. Color-discrimination limits obtained in Experiment I for the observer HU. Test colors are shown at the upper left, and comparison colors at the upper right in each part.

in the perceived colors between the top half and the bottom half of the field. For example, if the test stimulus was 5R and the comparison 10YR, and the response "reddish in the top half and yellowish in the bottom" was obtained, we assumed that two colors were discriminated correctly.* When the observer could not discriminate two colors, he or she responded "No." The stimulus was presented until two consecutive correct responses were obtained. The color-discrimination limit in a trial was defined as the position of the stimulus with the first response of those two correct responses. The interval between presentations was less than about 3 s, and during this interval the observer looked at the next fixation point. Between trials the observer looked around the center of the adaptation field.

Experiment I consisted of 20 sessions. In one session, only one test stimulus was used, and four of the eight comparison stimuli were chosen for that test stimulus. In the next session, the other four comparison stimuli were used for the same test stimulus. Three trials for each pair of test and comparison stimuli were performed for each direction in a session. A trial determined a discrimination limit for a given condition. A total of 12 trials were conducted in a random order for a fixed direction, and directions were randomly chosen in a session. Four sessions were conducted for each test stimulus, for a total six trials of each pair of

* The discrimination criterion used in this experiment yielded stable responses from the observer. This criterion resembles that used by Boynton and Kambe[16] with which they required observers to indicate in which direction a color change had occurred. They reported that their procedure stabilized the subject's criterion of difference.

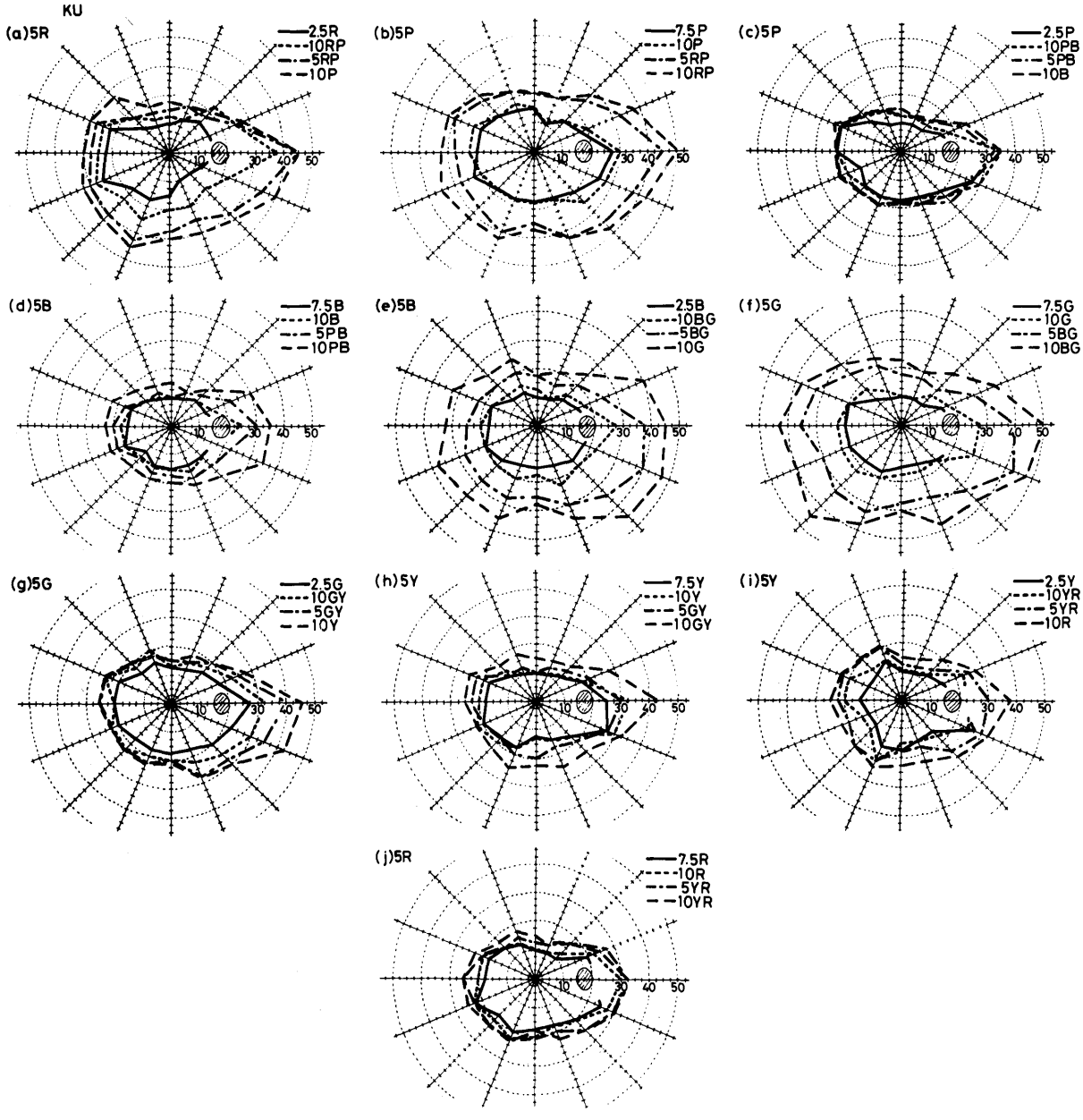


FIG. 4. Same as Fig. 3, but for the observer KU.

stimuli in one of 16 directions. Dummy comparison stimuli, having the same colors as test stimuli, were presented two or three times in a session in order to improve the reliability of the observer's responses.

In Experiment II, using achromatic stimuli, the procedure was the same except that all eight comparison stimuli were used in one session. Two consecutive sessions were run for a total of six trials for each pair of test and comparison stimuli in one of 16 directions.

We also performed a color-naming experiment, presenting stimuli to the fovea and 30° nasal using the Munsell color chips, to obtain a better understanding of our results in Experiment I. The procedure of these experiments will be described later.

Results and Discussion

Color-Discrimination Limits

Figure 3 shows the results of Experiment I for the observer HU, and Fig. 4 for KU. In each part of Figs. 3 and 4 color-discrimination limits are shown for four different comparison colors, each compared with the same test color. Test colors used in each part are shown at the upper left, and comparison colors at the upper right. Each point in one radial direction is an average of six trials. Comparison colors in each part (a)–(j) in Figs. 3 and 4 come from the corresponding region (a)–(j) of the color circle of Fig. 1. For example, the comparison colors in Fig. 3(a), 2.5R, 10RP,

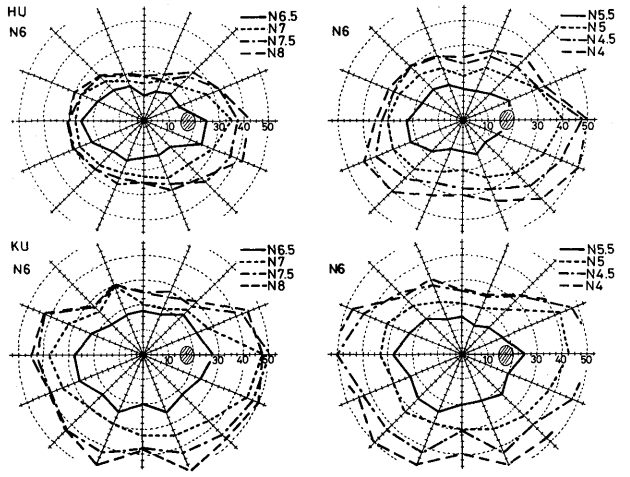


FIG. 5. Color-discrimination limits obtained in Experiment II. The upper parts are for observer HU, and the lower parts for KU. Test colors are shown at the upper left and comparison colors at the upper right in each part.

5RP, and 10P, come from the red–purple region (a) of Fig. 1. Two adjacent parts shown in Figs. 3 and 4 are the results obtained with comparison colors in the same color region but with two different test colors. It was not possible to determine color-discrimination limits in the blind spot (hatched area) or when these limits exceeded the available size of the apparatus.*

As can be seen in both Figs. 3 and 4, color-discrimination limits turned out to be greater in the horizontal directions, especially the temporal direction, and almost symmetrical along the vertical direction for HU, but a little bigger in the lower direction for KU. The shape of the color-discrimination limit closely resembles that of the color zone obtained in previous perimetric studies.[2] The average standard deviation obtained for each point on the color-discrimination limits was 2.06° for HU and 2.15° for KU. These values tend to be bigger on the temporal side.

Color-discrimination limits shown by the solid, dotted, dot-and-dashed, and dashed lines in all parts of Figs. 3 and 4 were obtained with Munsell hue-step differences 2.5, 5, 10, and 15, respectively, between the comparison and test colors. It is clearly seen in these figures that the color-discrimination limits increase as the Munsell step difference between comparison and test colors increases. Furthermore, the size of the color-discrimination limit depends on the combination of test and comparison colors. Especially for the color combinations in Figs. 3(a), (b), (e), and (f) and Fig. 4(a), (b), (e), and (f), color-discrimination limits tend to increase further in the periphery compared with those for other color combinations.

The results of Experiment II are shown in Fig. 5. The values of test and comparison Munsell neutral chips are indicated at the upper left and upper right of each part, respectively. Color-discrimination limits for neutral chips also increase in all directions as reflectance differences between test and comparison stimuli increase. The shape of these discrimination limits resembles those of colored chips in Figs. 3 and 4 in general, but appears more symmetrical along the horizontal directions.

Just-Noticeable Color Difference as a Function of Retinal Position

As mentioned before, we employed the CIE 1976 L^* a^* b^* formula to calculate color difference ΔE^*_{ab} between test and comparison colors [cf. eqs. (1) and (2)]. Figure 6 shows four examples from Experiment I, which were derived from Figs. 3 and 4. The ΔE^*_{ab} values for all test–comparison color combinations are plotted at the positions of their discrimination limits in a given direction. (See insert for the direction used in each section of the figure.) Therefore, each curve indicates the just-noticeable color difference (in terms of ΔE^*_{ab}) as a function of distance from the fovea. The solid and dotted curves correspond to test–comparison color combinations indicated by solid and dotted arrows shown in the bottom of Fig. 6. Figure 6(A) shows HU's results in the lower-right direction and Fig. 6(B) those of KU in the lower-left direction. The just-noticeable color differences represented by solid lines in Figs. 6(A) and (B) increase with much steeper slopes than the dotted lines, indicating different characteristics for the detection of color differences in the periphery for test–comparison color combinations (c), (d), (g), (h), (i), and (j) from those of (a), (b), (e), and (f).

Figures 6(C) and (D) show the results in the upper-left direction for HU and the upper-right direction for KU, respectively. Although the tendency observed in Figs. 6(A) and (B) is not clearly seen in these directions, the color combinations represented by solid lines also increase with steeper slopes in both Figs. 6(C) and (D). Thus, Fig. 6 clearly indicates that the just-noticeable differences increase more slowly for combinations of test and comparison colors in the regions between 5R and 5P [(a) and (b)] and between 5B and 5G [(e) and (f)] than for other combinations. This tendency holds for all other directions and for both observers.

Color-Naming Experiments

We performed color-naming experiments for all Munsell chips of value 6.0 and chroma 8.0 at intervals of 2.5 hue steps, including the test and comparison hues used in Experiment I. Two retinal locations, 0° and 30° in the nasal direction, were tested for observers HU and KU. The color-naming procedure was the same as that described by Boynton et al.[6] except that we did not estimate the whiteness of the stimuli. The observers gave one or two (dominant and nondominant) color names. Although it rarely happened, the observer could respond "neutral" when no hue was seen. The point values assigned to the color-name responses were

* At the far periphery the stimulus appeared distorted, which is probably due to poor spatial resolution in the periphery. However, it was not difficult to discriminate two colors with a stimulus size of 3.9° diameter.

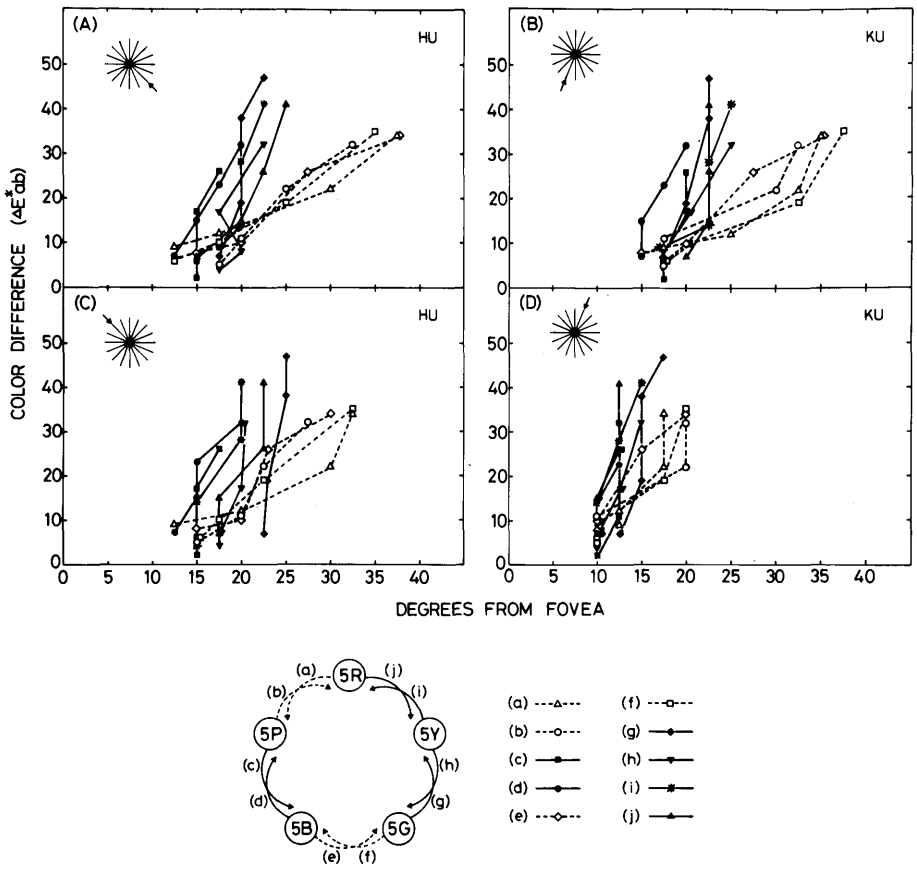


FIG. 6. Just-noticeable color differences as a function of distance from the fovea. (A, C): HU; (B, D): KU. The directions are shown in inserts of each section. Each symbol corresponds to the test–comparison color combination shown at the bottom of the figure.

3 points for a color described with a single name, 2 points for the dominant color of a color described with two names, 1 point for the nondominant color of a color described with two names, and 0 point for no observable hue. Each stimulus was presented 10 times for 500 ms.

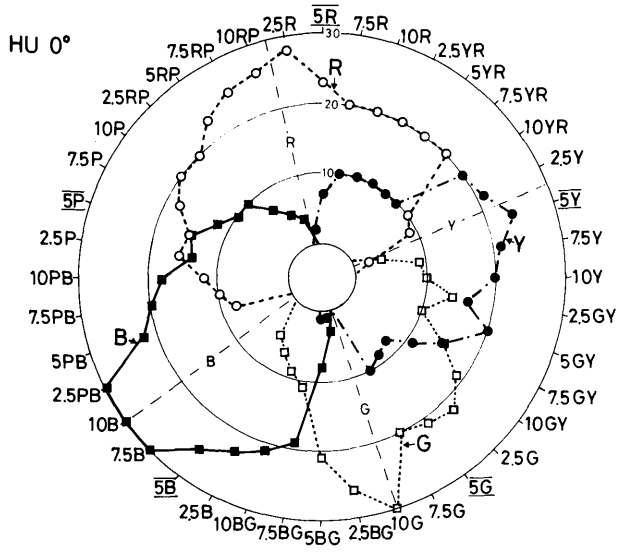
Figures 7 and 8 show color-naming results for both observers at 0° and 30° in nasal, respectively. The stimulus hues tested are shown along the circumference and the distance from the center circle represents the color-naming point value for each hue. The loci of unique hues are also indicated by dotted lines in the figures. It is readily seen that red and especially green responses are smaller in the periphery than in the fovea, and blue and yellow responses dominate in the periphery.

Comparing Fig. 7 with Fig. 8 indicates that in the periphery stimulus color appearance changes markedly in the regions between 5R and 5P and between 5B and 5G, whereas in the region between 5P and 5B the color appearance of the stimuli does not change as much. It was shown in Experiment I that color-discrimination limits expanded further into the periphery with test and comparison stimuli in the regions between 5R and 5P and between 5B and 5G. These regions exactly correspond to those where rapid color-appearance changes occur along the color circle in the periphery. Furthermore, when test and comparison stimuli were in the region between 5P and 5B, color-discrimination limits did not increase as shown in Figs. 3 and 4. This region, again, exactly corresponds to that where small color-appearance changes take place in the periphery. The unique red was placed between 7.5RP and 10RP, and the unique green between 2.5BG and 5BG in the 30° periphery for both observers (Fig. 8). Thus it it seen that color discrimination in the periphery is better in the color regions of unique red and green—that is, where transitions from yellow to blue and blue to yellow sensations occur—than in other color regions.

It should be noticed in Fig. 8 that 5RP and 5BG were seen almost as white in the periphery for both observers. The chromaticity coordinates of these stimuli, and those of the N6 stimulus (see Tables I and II), plot very closely along one of the deuteranopic confusion loci[17] (dominant wavelength of about 500 nm). Therefore, the results from the color-naming experiments under the present experimental conditions indicate the deuteranopic tendency in the peripheral color vision.

Three Types of Just-Noticeable Color-Difference Functions

We plotted four examples of the just-noticeable color



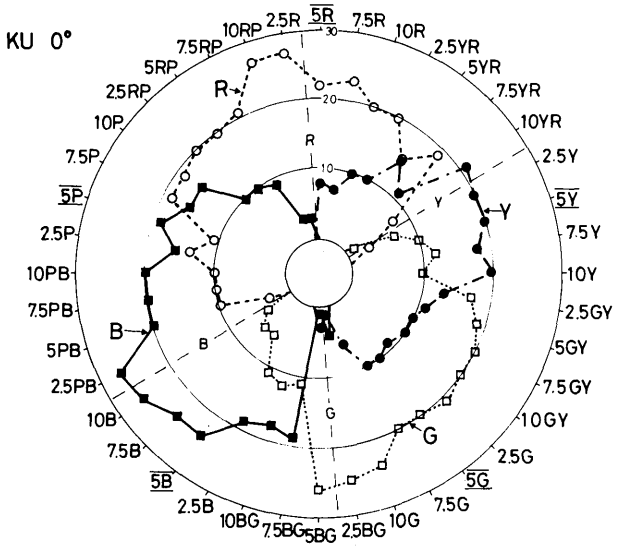
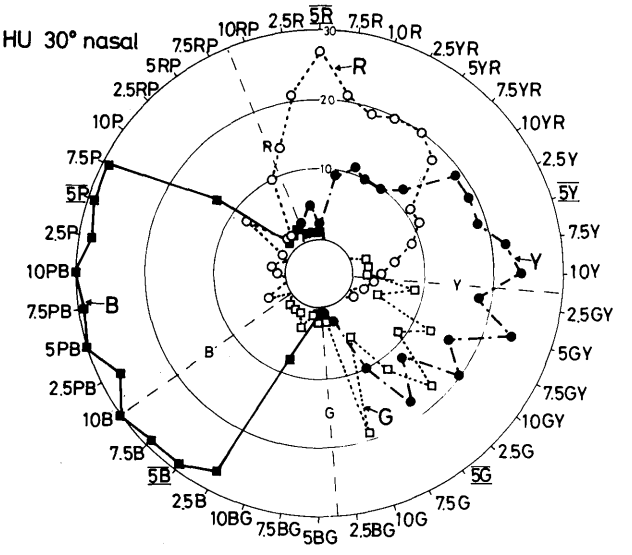


FIG. 7. Color-naming point values, represented by the distance from the center circle, obtained at the fovea. The stimulus hues are shown along the circumference. Top: HU, bottom: KU.



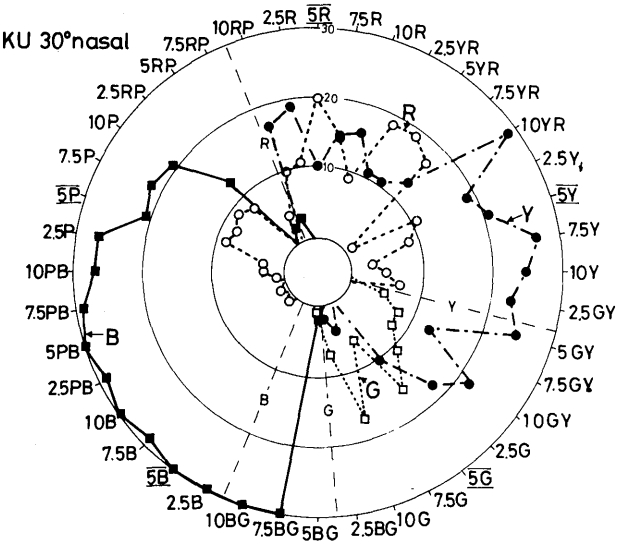


FIG. 8. Same as Fig. 7, but obtained at 30° in nasal.

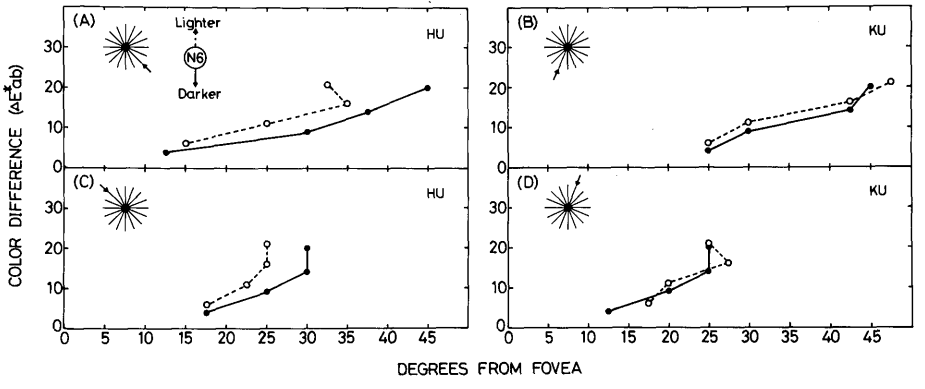


FIG. 9. Just-noticeable color difference as a function of distance from the fovea with neutral Munsell chips. (A, C): HU; (B, D): KU. The directions are shown in inserts of each section.

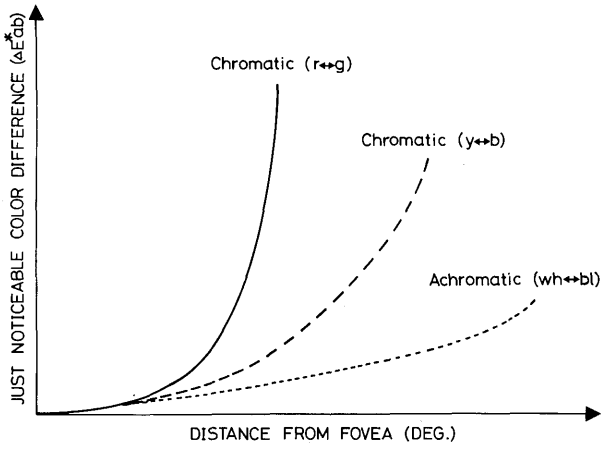


FIG. 10. The relationship between two chromatic and achromatic just-noticeable color-difference functions shown schematically.

differences obtained from Experiment II in Fig. 9. The radial directions shown in each graph of Fig. 9 are the same as those in Fig. 6 for each observer. Provided that the CIE 1976 L^* a^* b^* space is uniform in the achromatic domain as well as in the chromatic domain, and that color differences in each of those domains can be compared by the color difference formula ΔE^*_{ab}, the just-noticeable color differences increase more slowly in the periphery for achromatic stimuli than for chromatic stimuli (cf. Fig. 6). Moreover, as shown in Fig. 9, the just-noticeable color differences tend to be slightly greater with lighter comparison stimuli than with darker ones.

It has been shown in the present investigation that the just-noticeable color differences in the periphery obtained in Experiments I and II may divided into three different types. Figure 10 illustrates these types. The solid line represents just-noticeable color differences between chromatic stimuli which are primarily discriminated by their red and green components, the dashed line those discriminated by their yellow and blue components. The dotted line comes from achromatic stimulus discrimination. The absolute values of slopes of the curves vary with directions in the visual field, but the relationships between the three curves hold for all directions. These relationships can be accounted for by the deuteranopic tendency in the periphery which was partly shown in the present color-naming experiment.

The research by Gordon and Abramov[7] showed the relative maintenance of color-vision properties if the size of the stimulus increases as it moves from the fovea to the periphery. It must be remembered that our initial venture into this research area uses a field of fixed size. Therefore our data are comparable only with those studies which also maintained this constancy.

Acknowledgments

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