CHROMATIC THRESHOLDS OF SENSATION FROM CENTER TO PERIPHERY OF THE RETINA AND THEIR BEARING ON COLOR THEORY

PART I.

BY C. E. FERREE AND GERTRUDE RAND

Bryn Mawr College

INTRODUCTION

In the work reported in this paper a determination of the chromatic thresholds of red, green, blue and yellow in energy terms has been made at near-lying points from the center to the periphery of the retina. The incentive for making this study has been twofold: (1) We have wanted to make an investigation of the chromatic sensitivities of the central and peripheral retina that would be more nearly quantitative than those that have previously been attempted. (2) A detailed investigation of the sensitivity gradient for the four colors red, green, blue, and yellow from center to periphery of the retina has an important bearing on certain points of color theory. Two of these points will be considered in the second part of this paper.

As a part of a general investigation of retinal sensitivities, we had planned several years ago (1) to make determinations both of the achromatic and chromatic sensitivities to wave-length that would be quantitative up to the standard accepted for the physical recording instruments. One of the requirements for such a determination is, as was pointed out at that time, that the stimuli shall be rated in units that can be compared. This requirement could not be met until measuring instruments were obtained which were sufficiently sensitive for work in the visible spectrum and which were non-selective in their response to wave-length. It was further stated that if a rating is to be made which may fairly be considered as quantitative, it must also be possible from the

data at hand to compare numerically the amounts of response as well as the amounts of stimuli used to arouse the response. That is, while a radiometric rating of the stimuli is necessary for this purpose, an equally important point to be considered is what amounts of response can be employed with sureness of principle in meeting the quantitative requirement. In this regard it was pointed out that of the amounts of response that have at different times been used or suggested for the determination of sensitivity—namely, equal amounts, equal sense differences, the liminal threshold, the just noticeable difference, and the average error—perhaps only the first two can by common agreement be regarded as numerically comparable; and that the validity of the use of the others for the more strictly quantitative work should be tested by checking the results against those obtained when the rating is based, for example, on equal amounts taken as standard. This interchecking of results for achromatic sensitivity is now in progress in our laboratory, in which case all of the determinations mentioned above may be made. It can not be done, however, in case of chromatic sensitivity until it is first determined whether the judgment of equal saturations can be made with an acceptable degree of precision. Furthermore, a determination of comparative sensitivities in the peripheral retina, based on equal amounts of response, while not impossible, is neither very convenient nor very feasible. For the purpose of the present paper, therefore, we have been content to deal with the determination of the chromatic threshold for the wave-lengths in question and of their variation from the center to the periphery of the retina, which work has an interest of its own independent of its bearing on a determination of comparative sensitivities, and to reserve a report on the more strictly quantitative features of the general problem for a later paper. In making these determinations it was our intention to work at near-lying points from the center to the periphery of the retina in several meridians. The work was interrupted, however, by the pressure of other investigations when the determinations had been made in only two meridians, the temporal and the

nasal. Results can be given at this time, therefore, for only these two meridians.

CONDITIONS UNDER WHICH THE WORK WAS DONE

The determinations were made under the following conditions. (1) The colored lights used were taken from the spectrum. There are two reasons for this in an investigation of the kind here undertaken. (a) The stimuli should be as homogeneous with regard to the visible wave-lengths as possible,¹ and (b) they should be free from the infra-red and ultra-violet radiations which would affect the thermopile used to measure the intensity of light, but not the eye. The stimuli employed were a narrow band of red in the region of $670\ \mu\mu$; of yellow in the region of $581\ \mu\mu$; of green in the region of $522\ \mu\mu$; and of blue in the region of $468\ \mu\mu$. The breadth of analyzing slit used in isolating these bands was maintained constant at 0.5 mm. The range of wave-lengths obtained was approximately $660\text{--}680\ \mu\mu$; $575\text{--}587\ \mu\mu$; $518\text{--}526\ \mu\mu$; and $468\text{--}474\ \mu\mu$. The spectrum was gotten and the different wave-lengths were presented to the eye by means of the apparatus described in the *Journal of Experimental Psychology*, 1916, 1, pp. 247-284: 'A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral.' In every case the light was examined for impurities at the analyzing slit by means of a small Hilger direct vision spectroscope provided with an illuminated scale. When found, impurities were absorbed out by thin gelatines selected so as to cut out as little of the useful light as pos-

¹ The presence of the alien visible wave-lengths affects the results of a determination of chromatic sensitivity in two ways: (a) through physiological inhibitions and interactions it decreases the amount of the color response, and (b) it increases the energy measurement. In their work on the determination of the visibility of radiation in the red end of the visible spectrum, Hyde and Forsythe (*Astrophysical Journal*, 1915, 44, p. 289) found impurities in the prismatic spectrum to the value of about 20 per cent., at $0.76\ \mu$. In our own work both on achromatic and chromatic sensitivity determinations made with and without provisions for absorbing the scattered light, show differences in result which are great enough to be considered of significance. This is true in particular for determinations of chromatic sensitivity, in which case the chromatic response may be reduced quite appreciably as a result of the physiological interactions produced by the alien wave-lengths. In some cases, for example, even the complementary wave-lengths may be present.

sible. These gelatines were placed over the analyzing slit and were held in position by short clips fastened to the front surface of the jaws the edges of which formed the slit.

(2) The determinations of the threshold were made in energy terms. Measurements were made at two places: at the analyzing slit and at the eye. In making the threshold determinations of the stimulus light it was found to be convenient first to make the colors all equal in energy value. The reductions needed for the equalization were made by appropriate adjustments of the collimator slit. Since the blue represents the smallest amount of energy of any of the colors employed, they were all made equal in energy to the blue of the spectrum used, namely, the prismatic spectrum of a Nernst filament operated by 0.6 ampere of current. From this intensity they were reduced to the threshold by means of the especially constructed sectored discs described in an earlier paper,¹ and the energy values computed from the simple law of the disc. These discs, it will be remembered, were cut from hard sheet aluminum, No. 20 B. and S. gauge, 0.9 mm. thick, and of two sizes for just noticeable difference determinations, 19.5 and 17 cm. in radius. The total variation of range of open aperture is from 0° to 348.75° . A strong objection to the use of sectored discs when fine changes are needed such as are required, for example, in threshold and just noticeable difference work, is the difficulty of obtaining and measuring accurately sufficiently small amounts of change. Such discs are ordinarily constructed with two or more open sectors and a change in one is multiplied as many times as there are open sectors. Moreover, an error made in the measurement of one sector is multiplied by the number of open sectors. This latter difficulty becomes especially significant in working with intensities at or near the threshold, where a small error may represent a high percentage of the total open sector. We have sought to overcome these difficulties in three ways. (1) Our discs for a low total aperture are so constructed that one sector may be varied at a time. (2) The sector is moved by

¹ *Journal of Experimental Psychology*, 1916, 1, pp. 271-274.

means of a micrometer screw. This device for minute changes in the value of the open sector is so constructed as to be readily attached and removed from the disc. And (3) a special protractor has been designed fitted with a movable arm carrying a knife edge and Vernier scale graduated to read to minutes. Obviously some such precise means of making and measuring small changes in the disc are of prime importance in the work of determining the threshold and just noticeable difference. If such means are not at hand the average error of setting and measurement is apt to exceed that of the sense judgment.

The method of making the energy measurements by means of a thermopile has already been described in a previous paper. However, because the procedure is as yet somewhat unfamiliar it may not be out of place to give again brief description of how the measurements are made. A description at one of the places at which they were made, namely the analyzing slit, will be sufficient to show in a general way the method we have employed. The thermopile to be used was placed in position immediately behind the slit and a blackened aluminum shutter was interposed in the path of the beam of light between the slit and the end of the objective tube of the spectroscope. Preliminary to the exposure of the thermopile to the light to be measured, the current sensitivity of the galvanometer was tested by means of a special device¹ provided for this purpose in the construction of the galvanometer. With regard to this procedure it may be pointed out that the current sensitivity of the galvanometer varies with the period or time of the single swing of its needle system. Since it is not possible to control the field so as to get this period always the same, it is necessary, if results are to be compared, to take some sensitivity as standard and to convert all readings into deflections for the standard sensitivity by means of a correction factor determined at each sitting. For a detailed description of the method of de-

¹ This device consists of a special galvanometer coil, dry battery circuit, and switch board with finely graduated resistance. For a description of this device, see 'Radiometric Apparatus for Use in Psychological and Physiological Optics,' *PSYCHOL. REV. MONOG.*, 1917, 24, No. 2, pp. 63-65.

termining this factor, see PSYCHOL. REV. MONOG., 1917, 24, No. 2, pp. 60-65.

The thermopile was next connected with the galvanometer and the light allowed to fall on its receiving surface until a temperature equilibrium was reached (ca. 3 sec. for our thermopile). The deflections were read by means of the telescope and scale and the readings are corrected to standard sensitivity by means of the factor previously determined. The final step in the process of measuring was the calibration of the apparatus, *i. e.*, the value of 1 mm. of deflection in radiometric units was determined for the area of thermopile exposed. To do this a radiation standard, the value of the radiations from which is already known, had to be employed. The standard used by us was a carbon lamp specially seasoned and prepared for the purpose by W. W. Coblentz (4) of the radiometric division of the Bureau of Standards. This lamp was placed on a photometer bar 2 meters from the thermopile and operated at one of the intensities for which the calibration was made, in our case 0.40 ampere. The thermopile was exposed to its radiations with the same area of receiving surface as was used in case of the lights measured, and the galvanometer deflection was recorded. From the deflections obtained the value of 1 mm. of deflection, or the radiation sensitivity of the apparatus under the conditions given, was computed from the known amount falling on the surface of the thermopile. Having the factor expressing the radiation sensitivity of the apparatus, the deflections produced by the wave-lengths of light measured were readily converted into energy units. The radiation sensitivity of the linear thermopile used by us was computed in a given case, for example, from the following data. The energy value of the radiations per sq. mm. at a distance of 2 m. from the standard lamp operated by 0.40 ampere was 90.70×10^{-8} watt. The deflections of the galvanometer produced by this intensity of radiation falling on the same area of receiving surface as was used in measuring the lights employed as stimuli, when corrected (*a*) to a sensitivity of $i = 1 \times 10^{-10}$ ampere, and (*b*) for the absorption of the glass cover of the thermo-

pile, was 346.870 mm. The area of the surface exposed was 4.400 sq. mm., and the time of exposure was 3 sec. The sensitivity of the instrument per sq. mm. of receiving surface was, therefore, 115×10^{-10} watt. By means of this factor the galvanometer readings produced by the different wavelengths of light may readily be converted into the energy value of light falling on the receiving surface of the thermopile.

(3) The field surrounding the stimulus, and the preëxposure were always maintained as nearly as possible at the same brightness as the stimulus at the threshold value of sensation. For want of better pigment materials these surfaces were made from the Hering standard gray papers. It was found to be necessary to change the brightness of the surrounding field and preëxposure frequently for each stimulus because the brightness value of the color at the chromatic threshold changed quite rapidly from the center to the periphery of the retina. There were two causes for this change. (a) The intensity of the light had to be increased quite a great deal from center to periphery to give the chromatic threshold from point to point; and (b) the achromatic value of the colors does not remain the same from the center to the periphery of the retina. The gray that matched the stimulus in achromatic value at each point was determined by the equality of brightness method.¹ With reference to these determinations, it may be said that with the stimulus reduced to the chromatic threshold the color difference between the stimulus and the gray was so small that the equality of brightness judgment was not difficult to make. The match was made in every case for the part of the retina under investigation. It had to be attained by a series of approximations. That is, the threshold was first obtained at the given point with no especial control of brightness of preëxposure and surrounding

¹ The Hering papers did not present a sufficiently wide range of reflection coefficients to match the brightness range of the threshold value of the stimulus light from the center to the periphery of the retina. For example, at the threshold of sensation at the center of the retina, the darkest of the Hering papers illuminated by the rather strong light of the room was brighter than the stimulus light; and in the far periphery of the retina through a zone varying in breadth from 2 to 13 degrees for the different colors, the lightest of this series of papers was darker than the stimulus color.

field. The brightness of preëxposure and surrounding field was then made to match this value of the stimulus and the threshold was redetermined. This procedure was repeated until a threshold was obtained that required no further change in these surfaces to match it in brightness. In order to make the specification of the brightness of the preëxposure and the surrounding field independent of the illumination of the room and of the variability of the reflection coefficients of different issues of the Hering papers, the brightness was in each case determined in candlepower per sq. in. This determination was made by means of a Sharp-Millar portable photometer with the test plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal. By this method the reflecting surfaces were used as detached test plates. The readings were converted into candlepower per sq. in. by the following formula: $\text{Brightness} = \frac{\text{foot candles}}{\pi \times 144} .^1$

For the sake of reproducibility of conditions from time to time in a given laboratory or in different laboratories, it is obvious that a photometric specification should be given in all cases not only of the general illumination of the room but of the brightness of all surfaces for which precision of control is of importance to the results of the work.

(4) The illumination of the room was kept at a constant value. Two features are necessary for this control. (a) A means must be had of detecting small changes of illumination. This may be accomplished by a portable photometer of the Sharp-Millar or Macbeth type, for example, furnished with a daylight screen, or of the simpler type described by the writers in a previous article (5). And (b) a means must be had also of producing small variations in the illumination of the room, else the changes due to fluctuations in the external light can not be compensated for with the precision and minuteness of control that is needed. This is accomplished in our optics room by two systems of thin white curtains running

¹ By multiplying these values in turn by 486.8 they may be converted into millilamberts, a term frequently used by engineers to specify small brightness quantities.

on spring rollers beneath the skylight. One of the systems of white curtains and the light-proof curtain run lengthwise of the room; the other system of white curtains runs across the room. By means of the white curtains either small local or small general changes can be produced in the illumination of the room; and by means of the light-proof curtain larger changes may be produced ranging from full illumination to the darkness of a moderately good dark room. The light-proof curtain is of a breadth equal to that of the room and runs in a deep light-tight boxing. The white curtains are narrower and are made to overlap at the edges. These curtains run on wire guides so distributed as to prevent any sagging or wrinkling. Above these curtains are pivoted two large diffusion sashes of glass ground on one side completely filling the skylight opening. These sashes diffuse the light in the room giving an even distribution of illumination and rendering, because of that fact, an even and precise control easier to accomplish. In a careful specification of the conditions under which the work is done a very important item is to give a photometric specification of the illumination of the room. This may be done in foot or meter-candles as desired. If the illumination is uneven it should be done systematically throughout the room. If, on the other hand, it is pretty uniform, it is usually sufficient to give its value in three or more directions at the point of work. In case of the present work, for example, the value of the horizontal component was 30.49 foot candles; the vertical component, 121.95 foot candles; and the 45 degree component, 82.97 foot candles.

(5) The amount of light entering the eye was made independent of variations in the size of the pupil. Independence of change in size of pupil was especially needed in this work because of the large variations in the intensity of light used. Such control is very easy to accomplish with the means of presenting the light to the eye that is used in our apparatus. All that is needed is to keep the image that falls on the pupil of a constant size and smaller than the pupil throughout its entire range of variations in the given series of experiments. Not only can this variation be determined in preliminary

experiments as a guide to the size of the image that is needed, but the image itself can be compared with the pupil at each observation. For details of the method of exercising this control see 'A Substitute for an Artificial Pupil,' *PSYCHOL. REV.*, 1916, 23, 380-383.¹

RESULTS

A statement of the results of the investigation is given in Tables I.-VIII. The nearness of the points investigated to each other was determined by the rapidity with which the sensitivity decreased in the meridian in question. In those regions in which the decrease was gradual the determinations were made at points separated by as much as 5 degrees. In regions, however, where the rate of decrease was rapid or unusual features were present, the determinations were made at points separated only by 1 degree. A graphic representation of the results of these tables is given in Charts I.-IV. In these charts degree of eccentricity is plotted along the abscissa and the value of the threshold in watts (10^7 ergs per sec.) is plotted along the ordinate. In Charts I. and II. the values of the threshold from the center of the retina to the limits of sensitivity are plotted. In case of the red, yellow and blue, it will be remembered from statements made in former papers that the limits of sensitivity for lights of high intensity coincide with the limits of the field of white light vision. This, however, was not the case for the green stimulus. By no increase of intensity were we able to make the limits of green sensitivity coincide with the limits of white light vision. In Charts III. and IV. the above values from the center of the retina through the region of gradual decrease of sensitivity are plotted on a larger scale. This is done because when plotted on the scale used in Charts I. and

¹ Since the article referred to above was published we have devised and constructed a very convenient attachment for our analyzing slit by means of which the length of aperture of the slit may be varied by half millimeter steps. Space will not be taken here for a detailed description of this device. In brief, it consists of two knife edged jaws moving in the vertical, operated by means of a ratchet and spring. Still finer control could be secured, of course, by means of a micrometer screw. Constructed in this latter form the device would be very serviceable as a means of producing finely graded changes of intensity.

II. the curves fall so closely together that the relative sensitivities to the four colors are not clearly represented. That is, the range of the values for the threshold from the center to the extreme periphery of the retina is so great that in Charts I. and II., in which the entire range is represented, a scale value had to be chosen which is so large as almost to obscure the smaller differences in relative sensitivity to the different colors in the region of gradual decrease in sensitivity.

TABLE I

CHROMATIC THRESHOLDS FOR RED, NASAL MERIDIAN

In this table are given the values of the threshold for red ($670\text{ }\mu\mu$) at 22 points in the nasal meridian. The intensity of light at the analyzing slit was 94.27×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye ($\text{Watt} \times 10^{-11}$)	Density of Light at Campimeter Opening ($\text{Watt} \times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye ($\text{Watt} \times 10^{-12}$ per Sq. Mm.)
0	0.000764	0.375	30.80	0.174	9.34
5	0.000764	0.375	30.80	0.174	9.34
10	0.000764	0.438	36.00	0.203	10.90
14-17		Blind Spot			
20	0.000764	0.75	61.70	0.349	18.68
25	0.002125	1.00	82.20	0.465	24.90
30	0.003744	2.50	205.50	1.163	62.25
35	0.005088	3.75	308.30	1.744	93.38
40	0.005088	4.00	328.80	1.860	99.60
45	0.005210	4.50	369.90	2.093	112.05
50	0.005210	5.00	411.00	2.325	124.50
55	0.005902	6.00	493.20	2.790	149.40
60	0.006268	8.00	657.60	3.720	199.20
65	0.006838	12.25	1007.00	5.696	305.00
70	0.007408	20.00	1644.00	9.300	498.00
75	0.01140	23.00	1890.60	10.695	572.70
80	0.01262	26.00	2137.20	12.090	647.40
82	0.01587	34.00	2794.80	15.810	846.60
85	0.02116	50.00	4110.00	23.250	1245.00
87	0.02686	114.00	9370.80	53.010	2838.60
88	0.03093	180.00	14796.00	83.700	4482.00
90	0.05088	270.00	22194.00	125.550	6723.00
92	0.05088	338.00	27783.60	157.170	8416.20

In this and the following tables the light was taken from the spectrum of a Nernst filament operated by 0.6 ampere of current. In all cases the pre-exposure and surrounding field were made as nearly as possible the same brightness as the stimulus.

With reference to the results given in Tables I.-VIII., the following points may be noted. (I) The characteristics of response of the eyes for which results are given have been

very widely investigated for both central and peripheral vision. They have been chosen for this and other work especially because of their normality and practised precision of behavior. Their spectrum luminosity curve, for example, agrees (6) very closely with the average curve obtained by

TABLE II

CHROMATIC THRESHOLDS FOR RED, TEMPORAL MERIDIAN

In this table are given the values of the threshold for red ($670\text{ m}\mu$) at 25 points in the temporal meridian. The intensity of light at the analyzing slit was 94.27×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye ($\text{Watt} \times 10^{-12}$)	Density of Light at Campimeter Opening ($\text{Watt} \times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye ($\text{Watt} \times 10^{-12}$ per Sq. Mm.)
0	0.000764	0.375	30.80	0.174	9.34
5	0.000764	0.375	30.80	0.174	9.34
10	0.000764	0.438	36.00	0.203	10.90
15	0.000764	0.75	61.70	0.349	18.68
20	0.002125	1.00	82.20	0.465	24.90
25	0.003867	2.75	226.10	1.279	68.48
30	0.005902	8.00	657.60	3.720	199.20
33	0.006431	14.00	1150.80	6.510	348.60
35	0.007408	17.00	1397.40	7.905	423.30
40	0.01404	29.00	2383.80	13.485	722.10
44	0.01791	38.00	3123.60	17.670	946.20
45	0.02686	104.00	8548.80	48.360	2589.60
46	0.03093	160.00	13152.00	74.400	3984.00
47	0.03663	216.00	17755.20	100.440	5378.40
48	0.03663	216.00	17755.20	100.440	5378.40
49	0.03663	216.00	17755.20	100.440	5378.40
50	0.03663	216.00	17755.20	100.440	5378.40
51	0.03663	216.00	17755.20	100.440	5378.40
52	0.03663	216.00	17755.20	100.440	5378.40
53	0.03663	216.00	17755.20	100.440	5378.40
54	0.03663	216.00	17755.20	100.440	5378.40
55	0.03663	245.00	20139.00	113.925	6100.50
58	0.05088	270.00	22194.00	125.550	6723.00
60	0.05088	300.00	24660.00	139.500	7470.00
61	0.05088	315.00	25893.00	146.475	7843.50

Nutting (7) for 18 observers. Also their normality of chromatic response has, at various times, been checked up by a number of observers. Data on this point may be found in nearly all of the work that has been published from this laboratory. In case of the present work the systematic point by point determination has been made only upon the one

CHART I. Chromatic Thresholds for the Four Colors, Nasal Meridian. In this chart and Chart II., degree of excentricity in the field of vision is plotted along the abscissa and the value of the threshold along the ordinate. Of the three values of the threshold given in the tables, the total amount of light at the campimeter opening and at the eye is represented.

CHART II. Chromatic Thresholds for the Four Colors, Temporal Meridian.

CHART III. Chromatic Thresholds for the Four Colors, Nasal Meridian. In this chart and Chart IV., the values represented in Charts I. and II. respectively, from the center of the retina through the region of gradual decrease of sensitivity are plotted on a larger scale. This is done because when plotted on the scale used in Charts I. and II., the curves fall so closely together that the relative sensitivities are not clearly represented.

CHART IV. Chromatic Thresholds (enlarged scale) for the Four Colors, Temporal Meridian.

observer. However, one or more check observers have been used on points of the work of especial importance to theory, such as the irregular distribution of sensitivity to the pairs of colors, the criss-crossing or interlacing of limits, the areas analogous in type to the Schumann case of color-blindness, the deficiency of sensitivity of the far periphery of the retina to green, and the inability to get a red or green that is stable in color tone for all parts of the retina.

TABLE III

CHROMATIC THRESHOLD FOR YELLOW, NASAL MERIDIAN

In this table are given the values of the threshold for yellow ($581 \mu\mu$) at 23 points in the nasal meridian. The intensity of light at the analyzing slit was 93.10×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$)	Density of Light at Campimeter Opening (Watts $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.002125	0.20	16.30	0.092	4.94
5	0.002125	0.25	20.40	0.115	6.175
10	0.002125	0.375	30.56	0.172	9.263
14-17		Blind Spot			
20	0.003378	0.75	61.13	0.346	18.525
25	0.003867	1.25	101.88	0.576	30.875
30	0.006431	2.375	193.56	1.094	58.663
35	0.006919	2.875	234.31	1.325	71.013
40	0.006956	3.50	285.25	1.614	86.450
45	0.007326	4.50	366.75	2.074	111.150
50	0.007408	4.875	397.31	2.247	120.413
55	0.007408	4.875	397.31	2.247	120.413
60	0.007977	5.00	407.50	2.305	123.500
65	0.008547	5.125	417.69	2.363	126.588
70	0.009768	5.75	468.63	2.651	142.025
75	0.01140	6.75	550.13	3.112	166.725
80	0.01384	8.00	652.00	3.688	197.600
85	0.01404	10.75	876.13	4.956	265.525
87	0.01587	22.00	1793.00	10.142	543.400
88	0.02523	38.00	3097.00	17.518	938.600
89	0.03093	144.00	11736.00	66.384	3556.800
90	0.05088	216.00	17604.00	99.576	5335.200
91	0.05088	270.00	22005.00	124.47	6669.000
92	0.05088	330.00	26895.00	152.130	8151.000

(2) Up to 15-20 degrees the accuracy of the threshold values is doubtless lessened by the difficulty of making and reading the adjustments for such small open sectors, even with our micrometer device for making the adjustment and the

Vernier scale for reading it. On this account it may well be that the threshold at the center is somewhat high for all of the colors, inasmuch as open sectors of less than one-tenth of a degree are rather infeasible to use. For the exact deter-

TABLE IV

CHROMATIC THRESHOLDS FOR YELLOW, TEMPORAL MERIDIAN

In this table are given the values of the threshold for yellow ($581 \mu\mu$) at 29 points in the temporal meridian. The intensity of light at the analyzing slit was 93.10×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$)	Density of Light at Campimeter Opening (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.002125	0.20	16.30	0.092	4.94
5	0.002125	0.25	20.38	0.115	6.175
10	0.003175	0.50	40.75	0.231	12.350
15	0.003378	0.625	50.94	0.288	15.438
20	0.003456	0.75	61.13	0.346	18.525
25	0.003867	0.875	71.31	0.403	21.613
30	0.005210	1.125	91.69	0.519	27.788
33	0.005779	1.50	122.25	0.692	37.050
34	0.007326	2.75	224.13	1.268	67.925
35	0.009768	4.50	366.75	2.075	111.150
36	0.01140	7.00	570.50	3.227	172.900
37	0.01262	9.00	733.50	4.149	222.300
38	0.01262	11.25	916.88	5.186	277.875
39	0.01262	12.50	1018.75	5.763	308.750
40	0.01262	11.00	896.50	5.071	271.700
41	0.01262	10.00	815.00	4.610	247.000
42	0.01262	9.50	774.25	4.380	234.650
43	0.01262	9.00	733.50	4.149	222.300
44	0.01262	11.50	937.25	5.302	284.050
45	0.01404	26.00	2119.00	11.986	642.200
46	0.01791	42.00	3423.00	19.362	1037.400
47	0.02686	106.00	8639.00	48.866	2618.200
48	0.05088	180.00	14670.00	82.980	4446.000
50	0.05088	240.00	19560.00	110.640	5928.000
52	0.05088	270.00	22005.00	124.470	6669.000
55	0.05088	304.00	24776.00	140.144	7508.800
58	0.05088	330.00	26895.00	152.130	8151.000
60	0.05088	340.00	27710.00	156.740	8398.000
61	0.05088	350.00	28525.00	161.350	8645.000

mination of the absolute values of the threshold in this part of the retina, the discs can be used with more accuracy when a substantial reduction is first made by means of some other device. In considering the absolute values given above, the state of general adaptation of the eye must also be kept in

mind. The horizontal component of illumination at the point of work was, it will be remembered, 30.49 foot-candles; the vertical component, 121.95 foot-candles; and the 45 degree component, 82.97 foot-candles.

TABLE V

CHROMATIC THRESHOLDS FOR GREEN, NASAL MERIDIAN

In this table are given the values of the threshold for green ($522 \mu\mu$) at 23 points in the nasal meridian. The intensity of light at the analyzing slit was 91.50×10^{-12} watt.

Degree of Excentricity.	Surrounding Field and Pre-exposure (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye ($\text{Watt} \times 10^{-12}$)	Density of Light at Campimeter Opening ($\text{Watt} \times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye ($\text{Watt} \times 10^{-12}$ per Sq. Mm.)
0	0.002125	0.10	8.00	0.045	2.425
5	0.002125	0.10	8.00	0.045	2.425
10	0.002125	0.125	10.00	0.057	3.031
14-17		Blind Spot			
20	0.003175	0.167	13.33	0.076	4.042
25	0.003378	0.375	30.00	0.170	9.094
30	0.003744	0.625	50.00	0.283	15.156
35	0.003867	0.75	60.00	0.340	18.188
40	0.005210	1.00	80.00	0.453	24.250
45	0.005779	1.25	100.00	0.566	30.313
48	0.005983	1.50	120.00	0.680	36.375
50	0.006268	1.875	150.00	0.849	45.468
51	0.006919	6.50	520.00	2.945	157.625
52	0.007408	10.00	800.00	4.530	242.500
55	0.007977	13.50	1080.00	6.116	327.375
57	0.008954	16.00	1280.00	7.248	388.000
59	0.01018	22.50	1770.00	10.193	545.625
61	0.01425	40.00	3200.00	18.120	970.000
63	0.02116	94.00	7520.00	42.582	2279.500
65	0.02686	212.00	16960.00	96.036	5141.000
66	0.03093	238.00	19040.00	107.814	5771.500
67	0.03663	263.00	21040.00	119.139	6377.750
68	0.05088	315.00	25200.00	142.695	7638.750
69	0.05088	338.00	27040.00	153.114	8196.500

(3) The numerical values in Column I of these tables represent, of course, points in the field of vision. What the corresponding points on the retina are, could not be determined without knowing the net displacement, if there be such displacement, of the image towards the principal axis of the refracting system as the beam of light enters the eye more and more obliquely. Just what the factors are that might contribute to this displacement in a refracting system so

complex as that of the eye, is somewhat difficult to determine. The following are perhaps worthy of consideration: the difference in the optical density of the media traversed by the incident and the emergent rays, and the greater combined refracting power of the cornea and the anterior surface of the lens than of the posterior surface of the lens. Another

TABLE VI

CHROMATIC THRESHOLDS FOR GREEN, TEMPORAL MERIDIAN

In this table are given the values of the threshold for green (522μ) at 19 points in the temporal meridian. The intensity of light at the analyzing slit was 91.50×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle Power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$)	Density of Light at Campimeter Opening (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.002125	0.10	8.00	0.045	2.425
5	0.002125	0.125	10.00	0.057	3.031
10	0.002125	0.125	10.00	0.057	3.031
15	0.003175	0.167	13.33	0.076	4.042
20	0.003378	0.25	20.00	0.113	6.063
25	0.003456	0.375	30.00	0.170	9.094
26	0.005779	1.50	120.00	0.680	36.375
28	0.007408	10.00	800.00	4.530	242.500
30	0.01018	32.00	2560.00	14.496	776.000
31	0.01140	36.00	2880.00	16.308	873.000
33	0.01384	65.00	5200.00	29.445	1576.250
34	0.02116	100.00	8000.00	45.300	2425.000
35	0.02523	144.00	11520.00	65.232	3497.000
37	0.02686	180.00	14400.00	81.540	4365.000
40	0.02686	201.50	16120.00	91.280	4886.375
41	0.03093	226.00	18080.00	102.378	5480.500
43	0.03663	270.00	21600.00	122.310	6547.500
44	0.05088	305.00	24400.00	138.165	7396.250
45	0.05088	335.00	26800.00	151.755	8123.750

thing which should be taken into consideration in the use of the campimeter, is the fact that the front of the cornea, and not the optic center of the refracting system of the eye (roughly speaking), is the point from which the graduations on the instrument are laid out. From considerations such as these, it can be understood, perhaps, why an object of an excentricity of 92° as read on the campimeter scale, or approximately 2° back of the plane tangent to the anterior surface of the cornea at or near the point of entrance of the line of

regard, is still visible. In this connection the difference in the curvature of the cornea of different eyes should also be taken into account.

TABLE VII

CHROMATIC THRESHOLDS FOR BLUE, NASAL MERIDIAN

In this table are given the values of the threshold for blue (468μ) at 26 points in the nasal meridian. The intensity of light at the analyzing slit was 91.97×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Campimeter Opening (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.000764	0.10	8.06	0.046	2.440
5	0.000764	0.10	8.06	0.046	2.440
10	0.002125	0.167	13.40	0.076	4.067
14-17		Blind Spot			
20	0.002125	0.25	20.15	0.114	6.100
25	0.002125	0.25	20.15	0.114	6.100
30	0.003175	0.25	20.15	0.114	6.100
35	0.003378	0.375	30.23	0.171	9.150
40	0.003456	0.375	30.23	0.171	9.150
45	0.003744	0.50	40.30	0.228	12.200
50	0.003744	0.625	50.38	0.285	15.250
55	0.003867	1.125	90.68	0.513	27.450
60	0.003867	1.50	120.90	0.684	36.600
65	0.003867	1.50	120.90	0.684	36.600
70	0.003867	1.75	141.05	0.798	42.700
75	0.003867	1.875	151.10	0.855	45.750
76	0.003989	3.00	241.80	1.368	73.200
77	0.005210	12.00	967.20	5.472	292.800
78	0.005779	29.00	2337.40	13.224	707.600
80	0.006956	82.00	6609.20	37.392	2000.800
83	0.01262	116.00	9349.60	52.896	2830.300
85	0.03093	183.00	14749.80	83.448	4465.200
86	0.03093	198.00	15958.80	90.288	4831.200
87	0.03663	234.00	18860.40	106.704	5709.600
88	0.03663	277.00	22326.20	126.312	6758.800
90	0.05088	295.00	23777.00	134.520	7198.000
92	0.05088	328.00	26436.80	149.568	8003.200

That there is this wide extension of the field of vision in the temporal meridian seems to be well established by other investigators. Baas, for example, quoted by de Schweinitz (8), finds the average limit for ten observers to be 99° . Traquair (9) and others also find the limits to extend beyond 90° . In our own work we have found it to be carried out as far as 92° in a number of cases. For the explanation of this

TABLE VIII

CHROMATIC THRESHOLDS FOR BLUE, TEMPORAL MERIDIAN

In this table are given the values of the threshold for blue (468μ) at 26 points in the temporal meridian. The intensity of light at the analyzing slit was 91.97×10^{-8} watt.

Degree of Excentricity	Surrounding Field and Pre-exposure. (Candle-power per Sq. In.)	Value of Threshold			
		Degrees Open Sector	Total Amount of Light at Campimeter Opening and at Eye (Watt $\times 10^{-12}$)	Density of Light at Campimeter Opening (Watt $\times 10^{-12}$ per Sq. Mm.)	Density of Light at Eye (Watt $\times 10^{-12}$ per Sq. Mm.)
0	0.000764	0.10	8.06	0.046	2.440
5	0.000764	0.10	8.06	0.046	2.440
10	0.000764	0.10	8.06	0.046	2.440
15	0.002125	0.167	13.40	0.076	4.067
20	0.002125	0.25	20.15	0.114	6.100
25	0.003175	0.375	30.23	0.171	9.150
30	0.003378	0.625	50.38	0.285	15.250
33	0.003456	0.75	60.45	0.342	18.300
35	0.003456	1.00	80.60	0.456	24.400
40	0.003744	1.25	107.50	0.570	30.500
41	0.003867	2.25	181.35	1.026	54.900
42	0.005088	4.00	322.40	1.824	97.600
43	0.005779	7.00	564.20	3.192	170.800
44	0.01262	80.00	6448.00	36.480	1952.000
45	0.03093	120.00	9672.00	54.720	2928.000
46	0.03093	164.00	13218.40	74.784	4001.600
46.5	0.03663	270.00	21762.00	123.120	6588.000
47-48			Blind to Blue		
49	0.03663	270.00	21762.00	123.120	6588.000
50	0.03663	234.00	18860.40	106.704	5709.600
52	0.03663	180.00	14508.00	82.080	4392.000
55	0.03663	230.00	18538.00	104.880	5612.000
56	0.03663	250.00	20150.00	114.000	6100.000
57	0.05088	270.00	21762.00	123.120	6588.000
58	0.05088	290.00	23374.00	132.240	7076.000
59	0.05088	306.00	24663.60	139.536	7466.400
61	0.05088	338.00	27242.80	154.128	8247.200

fact there is of course the alternative possibility of a loss of exact fixation, which possibility we have not ignored in our own thinking. However, if there is a loss of fixation, we have not been able to detect it by any means we have as yet been able to devise.

DISCUSSION OF RESULTS

From data such as are presented in these tables and charts the following comparisons may be made in so far as the threshold may be regarded as a measure of sensitivity: (a) the sensitivity to a given range of wave-lengths from point to point

in the same meridian; (b) the sensitivity at corresponding points in different meridians; and (c) the sensitivity to the different wave-lengths in any given meridian. From the latter comparison, if properly made, an estimate of the selectiveness of the chromatic response at the threshold of sensation may be had. In making these comparisons several points of interest may be noted.

(1) *The Irregularities in the Curve of Sensitivity for the Different Colors in a Given Meridian.*—The rate of decrease in sensitivity after a certain degree of excentricity has been reached shows a great irregularity for the individual colors. This irregularity is greater in the temporal than in the nasal meridian. The following are some of the more notable examples. (a) The plateau in the curve for red in the temporal meridian. That is, the curve representing the amounts of energy required to arouse the just noticeable red sensation in this meridian rises almost imperceptibly from the center of the retina to about 20 degrees. From there it rises sharply to about 44 degrees. From 44 to 47 degrees the curve is almost vertical. Between these two points the energy required to arouse just noticeable sensation changes from 31.236×10^{-10} – 177.552×10^{-10} watt. From 47 to 54 degrees occurs the plateau referred to. Between these two points there is practically no change in sensitivity. (b) The hump in the curve for yellow in the temporal meridian occurring between 33 and 43 degrees. From 36 to 39 degrees there is a sharp drop in sensitivity and from there to 43 degrees almost as sharp a rise. Between 36 and 39 degrees the energy required to arouse just noticeable sensation changed from 5.705×10^{-10} to 10.188×10^{-10} watt. This is an area of deficiency or partial blindness to yellow. There is in this area no corresponding loss in sensitivity to the blue stimulus nor to the other colors. Moreover, there is no detectable change in the cancelling or after-image reactions to yellow. That is, this area shows the characteristics of the Schumann case of color blindness. (c) The quick rise in the curve for all of the colors near the limits of sensitivity. This feature is very marked both in the nasal and temporal meridians, but more marked in the nasal than

in the temporal meridian. In the temporal meridian the rise begins around 45 degrees for red, yellow and blue and at 26 degrees for green. In the nasal meridian it begins around 75 to 85 degrees for red, yellow and blue; and at 51 degrees for green. In this region were found the limits of sensitivity in our previous work with the Hering pigment papers with the degree of illumination, etc., employed. And (d) the area of total blindness to blue from 47 to 49 degrees in the temporal meridian. On all sides of this area is a border of lowered sensitivity, the sensitivity falling off quite sharply as the area is approached. This area also shows the characteristics of the Schumann case of color blindness. That is, there is no corresponding decrease in sensitivity to yellow, red or green and no corresponding change in the cancelling or after-image reactions.

(2) *The Great Difference in Sensitivity at Corresponding Points in the Temporal and Nasal Meridians, more Especially in the more Remote Portions of the Retina.*—This difference is already so well known in a general way as to need no especial discussion here. Our data, however, may be considered as contributive in two regards: (a) the large number of points investigated and (b) the rating of the stimuli in units that can be compared numerically. In comparing the distribution of sensitivity at corresponding points in the two meridians it may be of interest among other things to note the difference in the order in which the sensitivity to the different colors falls off in case of red, yellow and blue as the limits of sensitivity are approached. So far as the relative sensitivity to red and green is concerned, this point bears upon the changes in the color tone of red in the two meridians in passing from the center to the periphery of the retina. As will be noted later in a more detailed statement of color tone changes, the red stimulus employed in the investigation was sensed as red in the nasal meridian from the center to 60 degrees, from 60 to 86 degrees as yellowish red or orange, and 86 to 92 degrees as red. In the temporal meridian it was sensed as red from the center to 30 degrees, from 30 to 47 degrees as yellowish red or orange and from 47 to 61 degrees as red. That

is, the zone in the far periphery of the retina in which the weakly aroused yellow component of the excitation is below the threshold in red, is relatively broader in the temporal than in the nasal meridian, as the relation of the curves of sensitivity to red and yellow would indicate should be the case.

(3) *The Striking Absence of Uniformity of Ratio of Sensitivity to the Pairs of Colors, Red and Green, and Blue and Yellow, from Center to Periphery of the Retina.*—From the center to about 27 degrees in the temporal meridian and about 51 degrees in the nasal meridian, the sensitivity to green is greater than to red. At these points a radical reversal of sensitivity takes place and the sensitivity to red is much greater than to green. A reversal of sensitivity occurs also for blue and yellow; but at a point farther removed from the center of the retina, namely, at about 44 degrees in the temporal meridian and at about 77 degrees in the nasal meridian. Even up to the points of reversal with their radical deviations in relative sensitivity, an inspection of the charts, especially III. and IV., will show how very little ground there is for any claim that constancy of ratio exists between the colors red and green, and blue and yellow from center to periphery of the retina. (A further discussion of this point will be given in the second part of this paper: 'Bearing of Results on Color Theory.')

And (4) *the Correspondence of the Distribution of Sensitivity to Red, Green and Yellow with what might be expected from the Changes in the Color Tone of Red and Green in Passing from the center to the periphery of the retina.*—For example, in passing from the center to the periphery of the retina the red stimulus used in making the threshold determinations given in the foregoing curves was sensed as red from the center to about 60 degrees; from 60 degrees to about 86 degrees it was sensed as a yellowish red or orange; and from 86 degrees to the limits of sensitivity it was sensed again as red. Corresponding to this, it will be noted that there is in this meridian a fairly close agreement in sensitivity to red and yellow from the center to about 60 degrees, at which point there is a rela-

tively sharp decrease in sensitivity to red. That is, from about 60 to 86 degrees there is much less sensitivity to red than to yellow. At about 86 degrees there is a sharp decrease in sensitivity to yellow, and from this point on to the limits of sensitivity a fairly close agreement again in sensitivity to the two colors. In the temporal meridian the red stimulus was sensed as red from the center of the retina to about 30 degrees; from there to about 47 degrees as yellowish red or orange; and from 47 degrees to the limits of sensitivity as red. Similarly in this meridian there is a fairly close agreement in sensitivity to red and yellow from the center to about 30 degrees; from 30 degrees to about 47 degrees there is considerably greater sensitivity to yellow than to red; and from this point on to the limits greater sensitivity to red than to yellow. In case of green, in the nasal meridian the greater loss in sensitivity to green as compared with yellow begins at about 51 degrees; and in the temporal meridian at about 26 degrees. Correspondingly at these points the green stimulus began to be sensed as yellowish green and continued to be sensed in this tone until the limits of sensitivity to green were reached, from which point on for a short distance it was sensed as yellow.

BIBLIOGRAPHY

1. FERREE, C. E., AND RAND, G. A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units. *Amer. Jour. of Psychol.*, 1912, 23, pp. 328-332.
2. FERREE, C. E., AND RAND, G. A Spectroscopic Apparatus for the Investigation of the Color Sensitivity of the Retina, Central and Peripheral. *Jour. of Exper. Psychol.*, 1916, 1, pp. 271-274.
3. FERREE, C. E., AND RAND, G. The Selectiveness of the Achromatic Response of the Eye to Wave-length and its Change with Change of Intensity of Light. *Studies in Psychology. Titchener Commemorative Volume*, 1917, Worcester, Mass., pp. 285-287.
4. COBLENTZ, W. W. Measurements on Standards of Radiation in Absolute Value. *Bulletin Bureau of Standards*, 1914, 11, pp. 87-100.
5. FERREE, C. E., AND RAND, G. A Simple Daylight Photometer. *Amer. Jour. of Psychol.*, 1916, 27, pp. 335-340.
6. FERREE, C. E., AND RAND, G. *Op. cit.* *Titchener Commemorative Volume*, pp. 304-306.
7. NUTTING, P. G. The Visibility of Radiation. *Philos. Mag.*, 1915, 29 (6), pp. 301-309.
8. DE SCHWEINITZ, G. E. *Diseases of the Eye*. 8th ed., W. B. Saunders Co., 1916, p. 81.
9. TRAQUAIR, H. M. *British Journal of Ophthalmology*, 1917, 1, p. 216.