COLOR AND FORM DISCRIMINATION IN THE PERIPHERY OF THE RETINA

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Purkinje was first to call attention to the fact that sensitivity to light has a wider retinal extension than sensitivity to color and that the various colors have retinal zones of different extension. Since his time a great deal of work has been done on this subject. A good historical sketch of the work on peripheral color vision may be found in Baird's monograph on *The Color Sensitivity of the Peripheral Retina* (1905). Practically all the workers in this branch of optics considered the field of vision for white light as coinciding with that of general visual sensibility, and they therefore limited their investigations to such colors as blue, yellow, red and green. Yet insofar as ability to discriminate colors is concerned white is as much an individual color as any of the above, and it appeared to us as interesting to find how far out from the fovea we would still be able to discriminate between white and the other colors. We were led to this work partly because of the results obtained by Piéron and one of us in a study on the speed of establishment of the luminous sensation in the fovea by the action of white light as well as by color excitations (Kleitman and Piéron, 1924, 1925).

It is now universally accepted that the cones are the retinal elements responsible for color vision, whether the colors are perceived in the central or the outlying regions of the retina. Since the cones become less and less dense as we go from the center to the periphery, it occurred to us that by investigating the ability of the peripheral regions of the retina to distinguish the various colors *and white* we might detect any differences, should such exist, much easier than by studying the extremely dense cone region in the center of the retina. When we examined the literature for data on the extent of the visual fields for various colors as obtained by one or another form of perimeter, we found a lack of agreement among the various investigators who studied this subject. Aubert (1865) made a very thorough study of the visual fields for colors, using a black background in one case and a white one in the other. He employed colored paper squares whose sides varied from 1 to 16 mm., and found that the larger the square the farther out it could be seen, but not to the same extent in all directions.

The squares could be seen farther out in the temporal half of the visual field than in the nasal half.

The average (for eight meridians) distance from the fovea for the 4 mm. squares on a black background was as follows: blue, 54°; red, 42°; yellow, 40° and green, 35°. Landolt (Snellen and Landolt, 1874) describes experiments Donders and he performed using direct sunlight, which was entering into a dark room through a narrow slit and was made to fall on pieces of colored paper 1 cm square. In the outer meridian of the visual field they could see all colors at 90° from the fovea. However, using ordinary illumination Landolt (quoted from Baird, 1905) found that the fields for different colors are not the same. Charpentier (1883), studying the outer meridian of the visual field, confirmed the findings of Landolt by a slightly different method.

Baird (1905) reinvestigated this subject very thoroughly, and came to the conclusion that "the position and extent of the color zones are not fixed but variable," and that "their area in any given case depends upon the momentary condition of retinal adaptation, and upon the brightness and saturation of the stimuli employed." Using a Hellpach perimeter where the stimulus is a light coming from a lantern after passing through colored gelatine, he found in five subjects with dark adapted eyes that the fields for blue and yellow are coextensive and larger than the fields for red and green, also coextensive.

Ferree and Rand (1920) found that the far periphery of the retina is deficient but not blind to blue, red and yellow, and that with stimuli of sufficient intensity the limits of these colors coincide with the limits of light vision. The peripheral blindness for green, however, was absolute.

Engelking (1921), employing spots of four different sizes, and investigating four meridians, concludes, like Baird, that the fields for blue and yellow, and for red and green are coextensive, and that the former are larger than the latter.

Finally, Peter (1926) gives, as the average for four meridians, for 5 mm. spots, for blue, 48° from fovea, red, 33°, green, 24°, and quotes de Schweinitz, for the same colors, but 10 mm. spots, as giving blue, 56°, red, 45°, and green 33°. There is then an agreement between Peter and de Schweinitz that the fields for red and green are not coextensive and that the field for red is larger than that for green.

The above mentioned papers represent but a few of the contributions to the subject of peripheral color vision, but they are representative. It will be noted that there is a complete agreement between the results of Landolt and Charpentier, Baird and Engelking, Peter and de Schweinitz.

We performed two series of experiments: first, on color discrimination, and second, on form discrimination.

First series. Aware of the discrepancies in the results obtained by others, we decided to rule out the question of luminosity by adding a neutral grey and white to the four fundamental colors we started out to investigate. It may be argued that grey as well as white are not colors. But looking at a grey or a white spot with the foveal retina we can recognize them as such and distinguish them easily from blue, red, etc. The question we wanted answered was how far outward from the fovea will we still be able to distinguish between green and grey, or between white and yellow as well as we can by making them fall on the fovea.

Method. For mapping out the visual fields we used a McHardy recording perimeter. The tests were performed in a white walled room illuminated by sunlight. The walls dispersed the sunlight and no shadows fell on the perimeter. The stimuli consisted of colored paper sectors in a disc 5 cm. in diameter which could be made to move in and out along the curved band of the perimeter, 5 cm. wide, by means of a thumb screw placed behind a central shield that held a small ivory colored button on which the eye was fixed. The radius of curvature of this band was 35 cm., and that was the distance of the colored paper from the eye at all times. The disc with the colored sectors was covered by a black disc which had a variable circular opening, and which could be rotated so as to expose one or another of the colored sectors. We tried several apertures, and finally adopted two, one of 5 mm. and another of 10 mm. Thus our stimuli consisted of white, grey, blue, green, yellow and red discs of the above mentioned diameters, and they were moved in from the periphery on a black background and without being touched. The subject was to name one of the six colors as it was moved from the periphery to the center as soon as he was sure that he recognized it. The aperture was shifted and the color-stimulus changed at the very periphery, and while the subject looked away. The visual field was mapped out in the same test for all six colors, which were presented without definite order. In a certain definite meridian (or half-meridian, as some prefer to designate it) one or more, but never all six colors were tested, so that generally it was necessary to go around the circle several times before all the limiting points were charted. A record was kept of all colors named wrong. At first we studied 24 meridians, or every 15 degrees, but in our later experiments we found that by testing only 12 meridians we obtained very smooth perimeters. The smoothness of the line that connected the various points was, for us, an indication of lack of fatigue at the end of the experiment as well as of the value of the results. In our early experiments the perimeters obtained were irregular, having a star-shaped or zigzag outline, and when superimposed the perimeters for various colors crossed and recrossed each other. After a period of training, which consisted in learning to keep the eye on the point of fixation while viewing the colored disc in the periphery of the field of vision, we began to obtain smoother and smoother outlines for the fields for the different colors. It is for this reason that we did not extend our observations to many subjects, even though it would be desirable to confirm the results we obtained on other individuals. We ourselves acted alternately as observer and subject, and only a few tests were made on a third subject, who was a careful and trained observer. Only one eye, right or left, was used for all tests. On some occasions we used only three or four colors, telling the subject about it. The subject was thus aware at all times of the various possibilities in colors that he was called upon to distinguish.

Results. We found, as did Aubert and others, that the limit of the visual field for different colors is different in one meridian from what it is in another.

TABLE 1

The average extension of the visual fields for colors, in degrees from the fovea, based on figures for extension along twelve meridians, obtained with one six-color and two three-color discrimination tests

COLOR	10 MM. DISCS			5 MM. DISCS	
	Subject K	Subject L	Subject B	Subject K	Subject B
Blue	47	46	42	37	32
White	30	31	27	24	22
Red	33	32	34	23	22
Yellow	29	25	21	18	18
Green	25	23	20	18	15
Grey	23	22	25	21	18
Blue	55		44	41	38
White	56		36	42	35
Red	46		39	36	29
Blue	57		42		
Yellow	56		34		
Red	45		35		

We prefer to speak of meridians of the visual field instead of retina, the temporal meridian of the field corresponding to the nasal meridian of the retina, and so on along the circle. The visual field even if it is small extends more in the temporal direction than in the nasal one, and about the same distance up and down. It is thus roughly egg-shaped and resembles greatly the outline of the general field of vision, which some erroneously call the field of vision for white. To compare the extent of the visual field for one color with that for another, we thought it best to determine the average extent in all directions by adding the values obtained for each of the 24 or 12 meridians, and dividing by the number of meridians. The figures for such average meridians are given in table 1. For two subjects, K and L, using 10 mm. discs, the order of extension of the visual fields is exactly the same and the figures for the individual colors are very close to each other. Blue shows the largest field, and red, white, yellow, green, grey follow in the order named. For the third subject, B, the order for blue, red, white is the same as in the other two, but the field for grey is larger than the fields for yellow and green. With the 5 mm. discs all the fields are smaller. Blue again leads, red and white are smaller and about the same, and grey, green and yellow are smallest, the order being grey, yellow, green. There is then an outer zone where only blue can be made out distinctly, a middle zone where white and red can also be distinguished from the others, and a much smaller region where grey, green and yellow can be individually identified. Each color had to be identified hundreds of times, but although the colored discs were exposed to the eye about the same number of times, there was quite a variation in the mistakes made in naming the different colors.

It is of interest to note the relation between the size of the visual field of a certain color and the ease with which it can be distinguished from the other colors. From tabulation of the mistakes made during the individual experiments, we found that subject K did not once mistake blue for another color; B did that twice. The number of mistakes for blue, which has the largest visual field, was the smallest obtained. Grey follows with no mistake by B and three by K, a total of three. Red comes next with a total of six mistakes, and white follows with a total of twenty. Yellow and green were mistaken the greatest number of times, namely, twenty-three and thirty-seven respectively. With the exception of grey, then, there is a definite correlation between the size of the field and the ease with which the particular color could be correctly identified. For yellow and green, which were mistaken for other colors the greatest number of times, the nature of the mistakes was as follows. Yellow was mistaken for green 11 times and for white 7 times; green was mistaken for yellow 18 times and for white 10 times. White, which was mistaken 20 times, was called grey 17 times. It is evident that the inability to distinguish white from grey was responsible for the tardiness which characterized the naming of this color as it came in from the periphery. Green and yellow were also troublesome, each of them having been mistaken for white a number of times.

It was to be expected that the removal of these confusing colors would give us larger visual fields for white. We performed a group of tests eliminating grey, green and yellow, thus using only blue, red and white. The values obtained are given in table 1, and it will be noted that each of the three visual fields both for 5 and 10 mm. discs were larger than the fields for the same colors when a six color determination was required (fig. 1). The increase in the average meridian for the field of blue was smallest, as would be expected, and it amounted to about 5°. The increase for red was next in value, equalling 10°; that for white was largest, amounting to approximately 17°. Whereas in practically all cases, with two sizes of discs studied, K's fields of vision were larger than the corresponding fields for B, this difference is accentuated when the number of colors is diminished, and the size of the fields increases. Thus the average meridian for blue, white and red with a 10 mm. disc was 37° for K and 34° for B, when a six color discrimination was required; the same averages, when only the three colors were used, were 52° for K and 40° for B, an increase, on the average, of 15° for K and 6° for B. When the corresponding averages for 5 mm. discs were obtained, it was found that the increase in the case of K was from 28° to 40°, and in the case of B, from 25° to 35°. The ability to extend the visual field by the diminution in the number of colors to be discriminated is greater in K than in B, but much more so in the case of the larger fields than in the smaller ones.

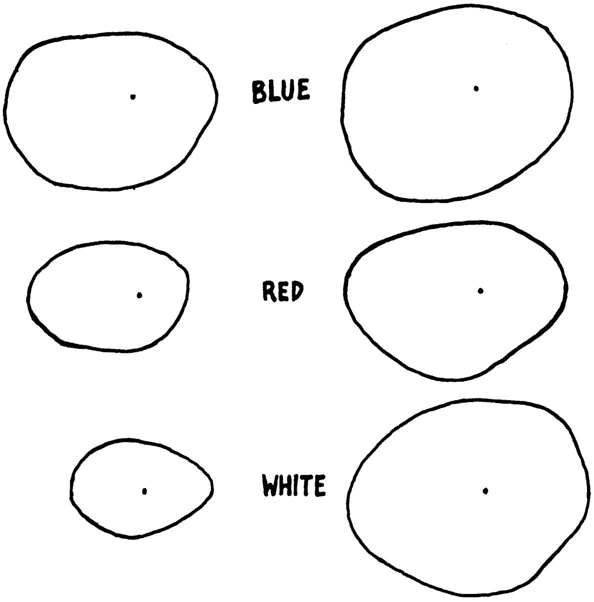

Fig. 1. K, left eye, 10 mm. discs. On the left are the perimeters for blue, red and white, when a six color discrimination test was made. On the right are the perimeters for the corresponding colors, when only blue, red and white were to be discriminated from each other.

In another group of tests we again used three colors, blue, yellow and red. As was to be expected the field for yellow was much larger than the one obtained in the first group of tests. Thus, with a 10 mm. disc, and the

the six color discrimination, the average meridian for yellow was 29° for K and 21° for B, with the blue, yellow, red discrimination, the averages were respectively 56° and 34°. We shall discuss the significance of this later.

Before proceeding any further, we decided to find out if there was any difference in the ability of K and B to distinguish colors by means of the fovea, and also whether there was any difference in the size of the fields of general visibility, called by some authors the field for white or grey. For the relative sensitivity of the fovea to color discrimination, we employed 3 and 5 mm. color discs on a black background. The subject approached the colored disc from a great distance looking directly at it all the time. The greatest distance at which he could name the particular color correctly was noted, and duplicate figures were obtained for each of the six colors.

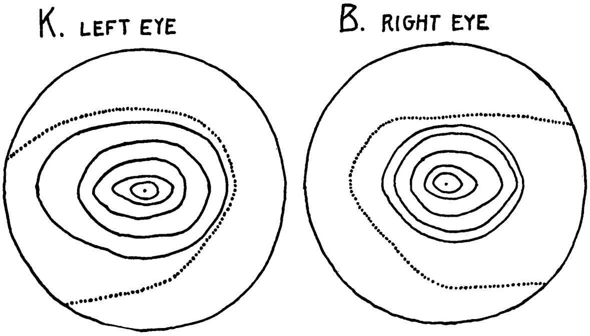

Fig. 2. The visual fields, from inside out, are for figures of 3, 5, 10, 15, 20 mm. having angular sizes of 0.50°, 0.86°, 1.72°, 2.58°, 3.44° respectively. Left eye of K and right eye of B. These perimeters are based on the average values obtained with four geometrical figures: circle, square, triangle, and five-pointed star. Dotted lines indicate general fields of vision of the two eyes.

These figures were about the same for K and B, the distances for some colors being slightly larger in one subject that in the other, and vice versa. Red and white were the most easily seen colors in both subjects, green and yellow follow, and blue and grey were the ones that had to be approached most closely before they could be correctly identified. A few mistakes were made in identification, and consisted in the main of calling yellow white in four cases, grey in two cases, and green in one case.

The general visual fields were determined by moving the black disc from the periphery to the center and asking the subject to report when he first saw "something" in his field of vision. The fields mapped out were normal in both cases, practically following the ones printed on perimeter charts. The average meridian was 58.5° for K and 57° for B, which makes them practically the same (fig. 2).

SECOND SERIES. It having been found that the general fields of vision as well as the color sense of the fovea were identical for both subjects, the differences between the sizes of the visual fields for color could be ascribed only to an unequal number of retinal receptors (cones) in the peripheries of the respective retinas. To test that possibility physiologically we decided to investigate the ability of the peripheral portions of the retina to distinguish geometrical figures, such as a circle, square, triangle and five-pointed star. These figures could be made in a number of different sets, each of uniform dimensions, and the visual fields for each set mapped out.

The literature on peripheral discrimination of form is much smaller than that on color. We could find only two researches that dealt with what is often called visual acuity. One of these represented a study of visual acuity only in horizontal meridians, the temporal and nasal, and was limited to only one subject (Fick, 1898). He found that visual acuity falls off very rapidly at first, slowly afterwards, from the fovea outward in both directions. Discrimination in the periphery is better in the temporal meridian of the visual field than in the nasal one. The other work by Wertheim (1894), done earlier and not so well known, was much more extensive in that four meridians instead of two were explored.

Method. For the mapping out of the visual fields for figures we employed the same perimeter that we used previously for colors. The four figures to be distinguished from each other were white on a black background, and were moved in slowly from the periphery until named by the subject. Five sets of figures of different sizes were investigated separately. The circles were 3, 5, 10, 15, 20 mm. in diameter, and the other three figures were inscribed in circles whose diameters were 1 mm. larger, i.e., 4, 6, 11, 16, 21 mm. In this way the differences between the areas of the circles and the other three figures of the particular set were minimized. The angular sizes of the figures of the five sets were 0.50°, 0.86°, 1.72°, 2.58° and 3.44°. Twenty-four meridians were explored with each figure of each set.

Results. Twenty separate visual fields were mapped out for each eye studied (left eye of K and right eye of B). The perimeters for the four figures of a given set when superimposed upon each other were found to be practically identical. They crossed and recrossed many times, visibility for one figure along a certain meridian being extended a little farther out than that for another, whereas along the next meridian the situation might be reversed. The average extension for all meridians was obtained in the same way as for color vision, and this average extension was about the same for all figures of a given size. The differences were too small to warrant a separate treatment for the individual figures, and so we determined the average extension of visibility for all figures of each set, for each of the meridians explored. This gave us one perimeter for all the figures of a given size, and the perimeters for the five different sizes are given in figure 2. It will be noticed at once that the perimeters for the smaller figures, 3, 5 and 10 mm., are identical in both subjects; the perimeter for 15 mm. figures is slightly larger, and for 20 mm. figures much larger in K than in B. The average extension of the visual fields for all meridians studied, for the five sets of figures, were, respectively, 7°, 13°, 24°, 37° and 51° for K, and 7°, 13°, 25°, 35° and 40° for B.

To determine any differences in the ability to recognize the four figures when their images fell on the fovea we employed the same method that we used for colors. Both subjects could distinguish the triangle at the greatest distance while approaching the figures from afar; the circle and the square next; the star had to be looked at closest to be correctly named. In angular sizes these figures had to subtend angles of about 0.075° (4.5′) to be recognized by the foveal retina. This compares very favorably with the 5′ letters of Snellen's test type.

If we consider the visual acuity for any point on the retina to be smaller the greater the angular size of the just distinguishable figure as compared to the size of the figure just seen by the fovea, we can determine the acuity along the lines represented by the perimeters for the figures of various dimensions by dividing the angular size of the particular set of figures by 0.075. If we do this we find that the perimeter for the 3 mm. figure (0.50°) represents a line on the retina where the visual acuity is seven times less than on the fovea (fig. 2). By the same token the other perimeters for 5, 10, 15 and 20 mm. figures pass through zones of the retina where the visual acuity is respectively 15, 23, 34 and 46 times less than that at the fovea.

It is evident that the visual acuity falls off from the fovea outward in both subjects, more rapidly in certain meridians than in others, and in a general way more rapidly in B than in K. We next decided to find out whether this falling off occurred in a definite manner throughout the retina. For this purpose we plotted the extension of visibility along each of the twelve meridians as abscissae with the angular size of the five sets of figures as ordinates (fig. 3). When the abscissa is zero, i.e., when one observes the figure with the fovea, the ordinate is 0.075. It is seen from the figure that the curves obtained for all meridians are straight lines in the case of K, and curved lines, concave upward, in the case of B.

Discussion. The larger fields obtained with the 10 mm. discs as compared to the five would seem to indicate a general thinning-out of the "effective" retinal elements, in this case, the cones. It is generally conceded that there are several million cones and many more million rods, whereas there are only about 500,000 fibers in the optic nerve. It is clear enough that it is not the number of rods or cones in a unit area in one or another portion of the retina that will determine acuity of vision, but the number of fibers in the optic nerve that come from a unit of area in that region. In the fovea, each cone neurone probably connects through the intermediate neurone with one ganglionic neurone which gives rise to a fiber of the optic nerve. In the periphery of the retina, even though a cone should connect individually with an intermediate neurone, there must perforce be several intermediate neurones to one fiber of the optic nerve. For this reason the effective elements of one or another portion of the retina are the number of ganglionic neurones that make connections with the cones in a unit of area in that region, and it is upon the denseness of these effective elements that the resolving power of the retina depends.

Our results for the four fundamental colors are not in agreement with those of Baird and Engelking in that the fields for blue and yellow and for red and green are not coextensive. They confirm the data obtained by Aubert and by Peter and others who found that the field for green is always smaller than the field for red. But by introducing grey and white we were able to establish on numerous occasions and in three subjects that the field for white is smaller than that for blue, and that the field for grey, far from being the field for general sensibility for light, is in reality one of the smallest, about the size of the fields for yellow and green. At first our results appeared to us paradoxical. They were clearly against the Hering theory of color vision and in favor of the Young-Helmholtz theory, but this latter assumes that the sensation of white is due to the simultaneous stimulation of the three photosensitive substances, which when individually stimulated give rise to sensations of red, green and blue. However, in

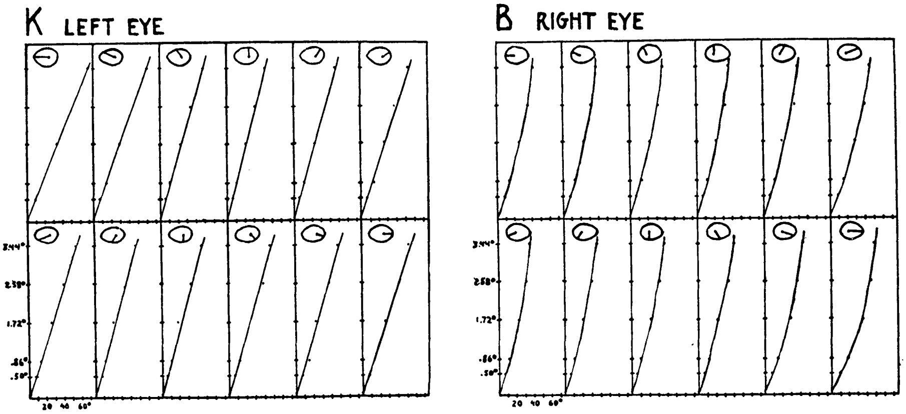

Fig. 3. These curves represent the relationship between the angular size of the figures and the distance from the fovea (in degrees) at which they can just be distinguished from other figures, along each of twelve meridians studied. The particular meridian is indicated in the upper left hand corner of each box. Left eye of K and right eye of B.

perusing our mistakes, we found that both yellow and green were frequently mistaken for white, and it appeared to us that the smaller field for white was the result of the reluctance on the part of the subject to name white until he could be certain that the disc was neither green nor yellow. To test this possibility we determined the perimeters for red, blue and white only. The field for blue was thereby scarcely affected at all, blue being the most easily recognized color in the periphery of the retina. Some increase in the red was apparently due to the absence of the disturbing yellow and green, but the increase in the field for white was very striking indeed. In K the field for blue and white now became coextensive, but in B that was not quite the case (fig. 1). We were then encouraged to investigate the field for yellow with the disturbing white and green absent. In mapping out the fields for blue, yellow and red, we obtained results that resembled very strikingly indeed the figures for the blue, white, red discrimination tests. The average meridian for the field of vision for yellow increased from 29° to 56° in the case of K and from 21° to 34° in the case of B. This partially explains why some investigators who did not use white found blue and yellow to be coextensive.

It seems then that not only are the retinal fields for the various colors different, but their size depends upon the number and kind of colors that the subject is required to distinguish from one another. Since one cannot suppose that the effect made upon the retinal elements by a red, blue or yellow disc of a certain size is dependent upon the number of colors the subject is called upon to discriminate, we must conclude that there is a central (cerebral) factor which plays an important part in determining the size of the visual fields. The fewer the number of colors (especially confusing colors) the surer the subject feels of his recognition of a particular color.

Our results also point to the erroneousness of designating the field of general sensibility to light as the field for either white or grey. Looked upon as a color, grey has a very small visual field, and for the following reasons. Most colored discs on a black background appear as bright spots when they fall on the periphery of the retina, as was already pointed out by Aubert. As the grey spot moves in, the subject reserves his judgment until he is sure that the bright spot is not going to appear blue, red, or any other color, and only then is he prepared to call it grey on the basis of its luminosity.

Insofar as the thinning out of the effective retinal elements is concerned this does not take place in all meridians at the same rate, but proceeds more rapidly on the temporal half of the retina (nasal half of visual field) than on the nasal one. Moreover, there is an individual variation in the rate at which the thinning proceeds along any given meridian. Thus, when one compares the visual fields for the different colors using the 10 mm.

discs one can see that the thinning took place at about the same rate in the eyes of K and L, at a greater rate in B (table 1). This came especially in evidence when only three colors were used and large visual fields were obtained. The visual field for the blue in K extended on an average to 56° from the fovea, but only to 43° in B. With the 5 mm. discs, the differences in the sizes of the visual fields for colors were practically negligible.

It is evident that in the various meridians from the fovea outward, the thinning of the effective retinal elements goes on at about the same rate in both K and B for about 20° on the average, but farther out the decrease in B becomes more marked as compared to K so that the density of the retinal elements in the forties of B is about the same as that in the fifties of K. It is to test the correctness of this supposition that we undertook the mapping out of the visual fields of geometrical figures of five different sizes. As was seen from figure 2, the results fully confirmed our expectations. Furthermore, in figure 3 we demonstrated that the thinning occurs in the same manner in all meridians of the retina of a given eye, the curve being a straight line for every meridian of K's eye and a curve concave upward in every meridian of B's eye. Two cases are insufficient for generalizations, but the constancy of the nature of the curve for all the meridians of each of the two eyes studied would seem to point to the manner of thinning out of the retinal elements as characteristic of a given retina throughout its extent.

We quite agree with Wertheim that the maximum extent of the visual field can be obtained only after a long practice. But not only the extent of the visual field but also the smoothness of its outline shows a great improvement with exercise. It is doubtful if any information can be obtained by examining the periphery of a patient's retina *once* for the discrimination of either color or form.

We thank Dr. A. B. Luckhardt, who served as a subject in some tests and who gave us some valuable suggestions in the course of this work.

SUMMARY

1. The visual fields as determined simultaneously for six colors in three subjects can be arranged as follows in decreasing order in extension: blue, red, white, yellow-green-grey.

2. A central or cerebral element affecting the extent of the visual field was demonstrated. The fields for blue, red, white and yellow will be larger, when the number of colors to be discriminated is smaller. That applies especially to yellow and white.

3. There is an individual variation in the extension of the fields of vision for different colors.

4. The fields of vision for form as determined by discrimination of geometrical figures are practically identical for figures of the same size, and are larger the greater the size of the figure.

5. Visual acuity, both for color and form, falls off from the fovea outward, but at an unequal rate in different directions.

6. The manner in which the visual acuity decreases is the same along all meridians explored and would seem to be a personal characteristc (based on two subjects).

7. The ability to distinguish color and form in the periphery of the retina improves with practice.

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