THE RELATION BETWEEN VISUAL ACUITY AND ILLUMINATION

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I

INTRODUCTION

The ability of the eye to distinguish detail is dependent, among other things, upon the intensity of the illumination falling upon the object. The measure of this ability is termed visual acuity and is expressed as the reciprocal of the angle (in minutes) subtended by the finest detail distinguishable. Uhthoff (1886, 1890) first investigated the relation of visual acuity to illumination over an extensive range of intensities, and several years later Koenig (1897) reinvestigated it in so thorough a manner that his data have become classic. These data show that the relationship between visual acuity and the logarithm of the illumination is sigmoid.

Since then numerous studies have demonstrated that at least three experimental conditions not controlled in the earlier work may have a profound effect upon the results. The first of these concerns pupil size; the second, the distance of the test object from the observer; and third, the brightness and extent of the field surrounding the test object.

The physiological properties of the retina are concerned with apparent brightness rather than with the external brightness. Since the relation of the two is influenced by the pupil, Troland (1916) proposed the photon as a unit of retinal brightness, and expressed it as external brightness in millilamberts times $10/\pi$ times pupil area in square millimeters. The adequacy of this unit to describe apparent brightness has been questioned by Stiles and Crawford (1933) who showed that the effectiveness of the light in producing brightness sensation falls off markedly when it passes through the more peripheral areas of the lens. This has recently been confirmed by Wright and Nelson (1936). In addition, the size of the pupil affects the image-forming properties of the lens and thus the visual acuity of the eye (Cobb, 1914–15). All previous extensive data suffer on this count since the natural pupil was used. Even the most recent contribution in this field (Lythgoe, 1932) is not entirely free from this error in intensity scale. In his attempt to evaluate the apparent brightness, Lythgoe measured the pupil area of each observer at each intensity and computed the values in photons. As pointed out above, such procedure cannot be considered valid any longer in the light of the data of Stiles and Crawford. Lythgoe's data, moreover, lack completeness of range. Due to his method of measurement in which the test object is exposed 1.6 sec. out of every 9.6 sec., it was impossible to obtain readings at low intensities. The rod portion is entirely missing. Moreover, he was unable to reach the highest intensities on his surround with the result that the upper portions of his curves are doubtful. His experiments with an artificial pupil are also open to criticism in that the condition of a uniform and continuous surround did not obtain in them.

Another uncontrolled variable is the distance of the test object. Aubert and Förster (Aubert, 1865) have shown that in a series of constellations of different sizes, so arranged that they subtend equal geometric angles at the eye, the smaller constellations are resolvable further out in the periphery than the larger ones. Recently Freeman (1932), using a simple visual acuity test, found that larger constellations are more efficient than smaller ones. These two apparently contradictory results may be reconciled as one phenomenon on the assumption that the focal length of the refractive apparatus of the eye changes with fixation distance. Thus, if the nodal point of the lens moves toward the retina with nearer accommodation, the small constellation would give a smaller image on the retina than would the larger. The image of Aubert's smaller constellations would fall nearer to the center of the retina than would be accounted for on external geometrics. The data of Roelofs and Zeeman (1919) also show an anomalous effect of stimulus distance, the smaller constellation being more efficient for the greater range of their measurements. The data on this phenomenon are quite insufficient for a complete understanding. They are enough, however, to show its existence as a source of error.

The effect of the surrounding illumination has been recently demonstrated by Lythgoe and Tansley (1929) and Hecht and Smith (1936) on flicker; by Steinhardt (1936) on intensity discrimination; and by Lythgoe (1932) on visual acuity. Evidently an extensive surround equal in brightness to that of the test field is necessary in all measurements in which the eye is in a stationary state of adaptation. As a corollary, it is equally necessary that the eye be completely adapted to the intensity at which an observation is to be made.

To avoid these various uncontrolled variables, an apparatus was designed which eliminates them. This apparatus presents a test object that may be varied continuously in size over a range of about 1:100 at a fixed distance of 1 meter from the eye. This test object lies in the center of a field that is 30° in extent, and is observed through an artificial pupil of 2 mm. diameter. The illumination is varied discontinuously by means of filters in steps of approximately 0.3 log unit.

II

Apparatus

Fig. 1 shows the optical system of the apparatus. *S*, the source, is an incandescent ball of a tungsten arc. An image of the source is focussed on the projection lens system, *P.L.*, by the condenser *C*. The projection system consists of a Zeiss "Telenegative" of 6 cm. focal length rigidly mounted, and a Zeiss "Tessar" of 15 cm. focal length mounted so that it may be moved along its optic axis for a short distance. This constitutes a highly corrected projection system of variable focal length. Between the condenser and the projection system there is a test object carriage, *T.O.*, which is movable along the optic axis. In addition the carriage can be rotated about its optic axis so that the test object may be presented in a number of different meridians. An image of this test object is projected on the field lens, *F.L.*, after reflection from a front surface plane mirror not shown in the diagram. The test object carriage engages a cam and lever which controls the position of the positive member of the projection system. This is so arranged that the image of the test object is always in the same plane. Thus, an image of variable size of the test object is formed in the plane of the field lens and serves as the test object when viewed through the pupil *P*.

The field lens focusses an image of the projection system, and therefore of the source, at the artificial pupil *P*, which is a circular aperture 2 mm. in diameter. The field thus far presented to the eye at the pupil is only about 4° in extent.

A surround of 30° is furnished by the spherical front surface mirror *M*, having a 30 cm. radius of curvature and a 15 cm. diameter, with a 21 mm. circular hole in the center. Another image of the source is focussed at *S′* by the system of lenses, *C′C′*. The light is then reflected by a right angle prism and diverges to fill the mirror *M*. *M* in turn focusses an image of *S′* at the pupil.

Just within the artificial pupil are the filters, *F*, that control the intensity. The first one is a circular glass with 3 sectors of Wratten neutral filters of densities 0.0, 0.3, and 0.6; the second with 5 sectors of densities 0, 1, 2, 3, and 4; the third with 2 sectors of densities 0 and 4. With these it is possible to achieve an intensity range of 8.6 logarithmic units in steps of 0.3 of a unit. In addition, space is available for one of a series of Wratten monochromat filters for work with isolated spectral regions. In most of the measurements to be reported here, this space was occupied by a neutral filter of density 2. All the filters were calibrated for white light by means of a Martens polarization photometer. The maximum intensity obtainable in this apparatus is over 800,000 millilamberts which are equivalent here to over 8,000,000 photons.

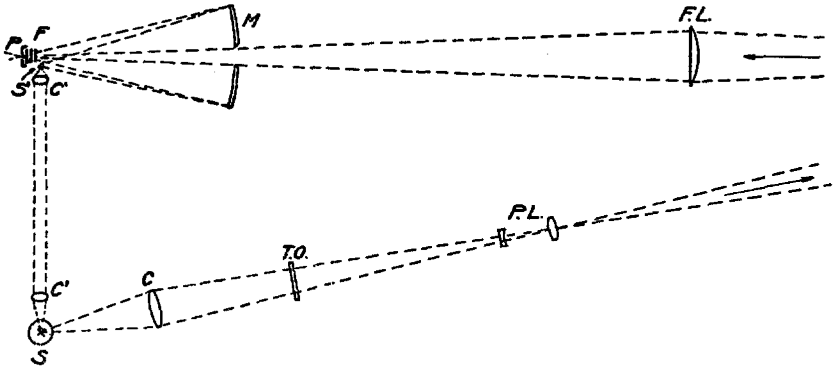

FIG. 1. The diagram of the optical arrangement of the apparatus.

All the parts shown in Fig. 1 are mounted on two optical bench bars each 1 meter long. These in turn are bolted to two structural steel bars at the ends, forming a rigid unit. The plane mirror not shown is supported from the narrow end of the main unit by means of a light aluminum and duraluminum frame work. A sheet metal hood to shield the observer from stray light is mounted from the other end. The whole rests on a table top with a three point contact.

The test object carriage is movable on its optical bench bar by means of a coarse screw mounted beneath it. This screw is driven by the observer from a conveniently located knob through a light chain drive. A pawl and ratchet wheel limits this motion to one direction only, namely towards an increase in the test object size. The recorder can easily disengage the test object carriage from its screw drive by releasing a pin to reset the test object. A millimeter scale, engraved on the optical bench, serves to locate the position of the test object. The total motion of the carriage is 38 cm. This produces a 3 to 1 change in the size of the image at the field lens. A series of 7 test objects, no one larger than twice the previous one, enables us to cover the complete range with adequate overlapping.

The image of a large test object was measured at a series of scale positions. The data were plotted as log visual acuity against the scale readings. A table was then constructed from the smooth curve through these data, giving the log visual acuity for every millimeter of the scale. A logarithm factor for each test object is then added to the table reading to give the exact log visual acuity for each plate at its position on the scale.

Two different types of test objects are available. One of them is a grating of alternate opaque and transparent bars of equal width. This series was engraved on glass disks for us by Max Levy and Company of Philadelphia, Pa. The other is the Landolt's broken circle or C in which the width of the line and the gap is one-fifth the total outside diameter of the letter. This series was prepared photographically by a special high resolution method, because the smallest C had to be 0.25 mm. in diameter. A negative C of 20 mm. diameter was accurately formed of sheet brass. Optical flats were thinly coated with a hot 15 per cent gelatin solution and dried. The gelatin was then sensitized with potassium dichromate and the plate exposed in a camera through the glass so that the insoluble portion would be adjacent to the plate. After washing the unexposed gelatin off with hot water, the remaining gelatin was stained with Heidenhain's iron hematoxylin. This stain, perhaps the most commonly used one in cytology and histology, is not a dye but a solid blue black precipitate. These test objects show a perfectly sharp edge at a magnification of 100 diameters. The graininess becomes just visible at 500 times magnification. They were sealed under cover glasses with Canada balsam and measured under a microscope with a filar micrometer. Chromated gelatin is an extremely insensitive photographic material; by using a condensing lens behind the negative C to focus the image of the source on a fully opened f:3.5 photographic objective, the exposures were cut down to reasonable values.

The constancy of the brightness of the test field was experimentally verified. The illumination of the surround was intercepted by means of an opaque shield placed over C', and the light from the test field only was permitted to fall on a Weston photronic cell connected to a sensitive galvanometer. The test object carriage with the smallest C plate was then moved over its entire range. No change in the galvanometer deflection was observable even though a change of 1/4 of 1 per cent could be easily detected with this set-up.

With the grating test object, an extreme intensity difference of about 20 per cent was observed in different combinations of distance and grating size. This is caused by the fact that the diffraction pattern of the source image falling on the projection lens system is varied in extent by the size and distance of the grating. By inserting two ground glasses between the source and the condensers and using these as secondary sources of greater area, most of the variation in intensity was eliminated; the residual change being less than 2 per cent. As a result the maximum intensity obtainable was somewhat lower. In addition, the intensity was cut in half by the use of the grating, since a field covered by an unresolvable grating appears uniformly illuminated with half the intensity. This necessitated the removal of the neutral filter of density 2 described above when measurements with the grating were made.

III

Procedure

Measurements were begun at the lowest intensities after the observer was dark adapted for about 20 minutes. The observer kept his right eye as near to the artificial pupil as possible and steadied his head by means of a chin rest. After complete adaptation to the intensity of the field, he brought the test object carriage nearer until resolution of the letter was possible. The test object was then reset by the recorder, and the determination repeated. In most of the measurements with the C, two determinations agreed sufficiently to be considered adequate. For reasons to be presented later, four determinations were made at each intensity with the grating. The intensity was then increased by suitably altering the filters and the process repeated. By this means a complete run was obtained at one sitting of less than 3 hours duration.

The data to be reported here were obtained with two experienced observers, both emmetropes. With the C as test object, A. M. C. was able to cover the entire range well within 3 hours and without undue fatigue. E. L. S. was not so adept, and his measurements begin at that illumination at which the cones first control visual acuity.

Measurements with the grating as test object are much more difficult and take more time to make. The unresolved grating presents a uniformly illuminated field offering no point of fixation, with the result that the stripes appear rather suddenly and without warning. An attempt to supply a fixation point by pasting a small circular black paper dot on the field lens was only partially successful in overcoming this difficulty, since the resolution does not take place at the fixation point. This is unlike the C which can be fixated and resolved at the point of fixation.

Another difficulty is the pronounced retinal astigmatism found in every eye thus far examined. It is possible to rotate a just resolved test field so slowly that the observer can follow the direction of rotation, and yet have the field become unresolvable at certain angles. This is probably caused by the necessity of having a fairly large number of retinal elements functioning to resolve a grating as compared with the number required to resolve the opening in the C. On the basis of a distribution of threshold for the various retinal elements as suggested by Hecht (1928), it is probable that the functional elements might be more numerous or denser along one axis than along another. This explanation is borne out by two observations. One is that this astigmatism is more pronounced at the lower intensities where the curve of log visual acuity *versus* log I is steep, and practically disappears at the higher values where the curve levels off. The other one is the fact that the more easily resolved angle is not constant throughout the range at one sitting nor is it the same at each point at different sittings. Thus, for example, in one run for E. L. S. on June 10, 1936, at a log I value of -1.057 photons, the values for the log visual acuity were -0.529 for the angle 45° to the right, and -0.725 for 45° to the left, a difference of about 0.2 logarithmic unit. At about 0.7 logarithmic unit higher in intensity the values were -0.173 for 45° to the right and -0.058 for 45° to the left, a difference about half as large and in the opposite direction. Finally at a log I value of 0.118, no astigmatism could be detected.

For these reasons it was found necessary to take a reading at each of the four positions of the grating at each intensity. Each value was usually taken only once. This is equivalent to taking only one reading at each intensity with the C. Hence, these data are not so smooth as those taken with the C. Eight readings at each intensity were of course indicated, but the desire to cover a large range at one sitting precluded that. Even so the range that could be covered comfortably was greatly shortened. The measurements, however, were so arranged that one observer, A. M. C., began his measurements at the lowest intensities and continued as far as possible, while the other, E. L. S., started at the beginning of the cone range and carried the curve to completion.

IV

Results with C as Test Object

The data are given in Table I. Each datum of log visual acuity is the average of the determinations made in three different complete runs. They are given in the form of log *I* and log visual acuity; the same form in which they are recorded from the readings of the apparatus.

TABLE I

Visual Acuity and Illumination

C test object				Grating test object		
Log I in photons	Log visual acuity			Log I in photons	Log visual acuity	
	No special fixation	Central fixation at all intensities above 0.1 photon				
	A.M.C.	A.M.C.	E.L.S.		A.M.C.	E.L.S.
I	II	III	IV	V	VI	VII
−2.433	−1.358	−1.468		−2.804	−1.157	
−2.146	−1.230	−1.283		−2.363	−0.961	
−1.862	−1.121	−1.157		−2.076	−0.899	
−1.413	−1.021	−0.981		−1.792	−0.835	
−1.127	−0.932	−0.896		−1.343	−0.691	−0.698
−0.843	−0.836	−1.004	−1.007	−1.057	−0.531	−0.561
−0.441	−0.651	−0.725	−0.724	−0.773	−0.438	−0.338
−0.154	−0.450	−0.515	−0.518	−0.371	−0.206	−0.174
0.130	−0.260	−0.332	−0.335	−0.084	−0.099	−0.087
0.525	−0.141	−0.132	−0.149	0.200	0.015	−0.032
0.812	−0.054	−0.039	−0.055	0.595	0.096	0.030
1.096	0.042	0.059	0.031	0.882	0.099	0.074
1.488	0.162	0.151	0.125	1.166	0.142	0.124
1.775	0.214	0.212	0.186	1.558	0.158	0.144
2.059	0.271	0.249	0.234	1.845	0.179	0.157
2.507	0.300	0.292	0.270	2.129	0.195	0.192
2.794	0.327	0.315	0.268	2.577		0.208
3.078	0.347	0.343	0.294	2.864		0.207
3.480	0.363	0.367	0.313	3.148		0.231
3.767	0.384	0.371	0.324	3.550		0.238
4.051	0.396	0.390	0.345			
4.446	0.385	0.397	0.340			
4.733	0.382	0.399	0.326			
5.017	0.389	0.415	0.345			

The data of column II were obtained in the usual way without special fixation, so that the most sensitive portion of the eye at each intensity was used. The subjective observations are that the first five values are mediated by the periphery of the eye and represent the function of the rods. Each succeeding value is determined by a region of the retinal periphery nearer the center of the eye than the preceding one. The next four values are determined by cones that are not centrally located. As with the rods, each succeeding one of these is determined by a region nearer to the fovea than the preceding one. All the other values are mediated by the fovea of the eye.

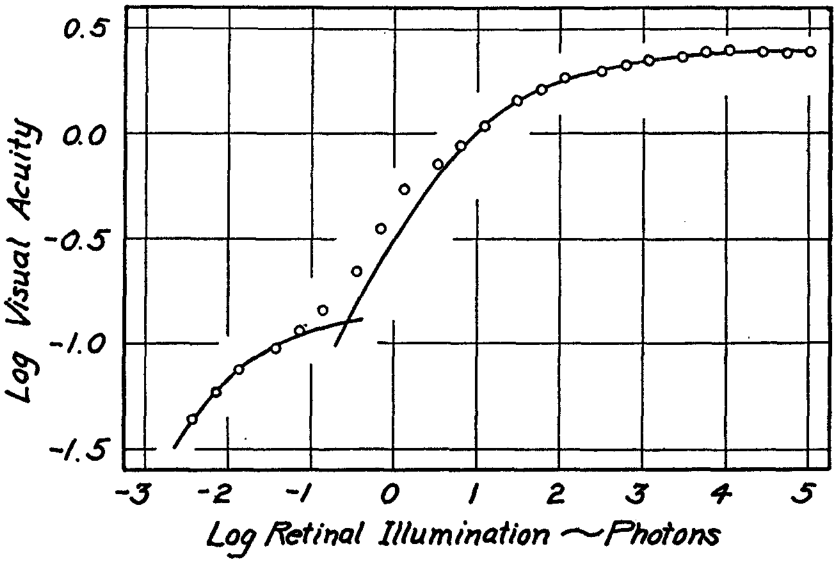

FIG. 2. The data of A. M. C., Table I, column II, showing the relation between log visual acuity with the C and log I when the most sensitive portion of the retina is used. The first five points represent the function of the rods, the next four that of the para-foveal cones, and the remainder that of the central cones. The curve for the rods is of the equation (3) and that for the central cones, equation (2).

To avoid the use of different regions of the retina for each succeeding determination, at least for the cones, the next series of measurements, given in columns III and IV, were made with central fixation as soon as the cones took over the function: namely, at a brightness of about 0.1 photon. This was made possible by the fact that the C test object can be fixated centrally long before resolution of the opening is possible. This fixation can be maintained readily until central resolution is achieved in spite of the fact that resolution by adjacent regions of the retina may be possible earlier.

The data of column II are plotted in Fig. 2 and those of columns III and IV in Fig. 3, with those of E. L. S. in column IV displaced 0.5 log unit below those of A. M. C. The logarithm of the visual acuity is plotted against the logarithm of the illumination. Such double log plots are superior to the single log plots on three counts. One, they serve to bring out more strikingly the discontinuity in the function of rods and cones [see Hecht, 1934 (intensity discrimination); Hecht and Shlaer, 1936, and Hecht and Smith, 1936 (flicker)]; and that they do so here may be judged by comparing these double log plots with the single log plots in Fig. 4. Two, this type of plot shows deviations of equal percentage throughout the complete range; and is again illustrated by a comparison with Fig. 4 where the deviations

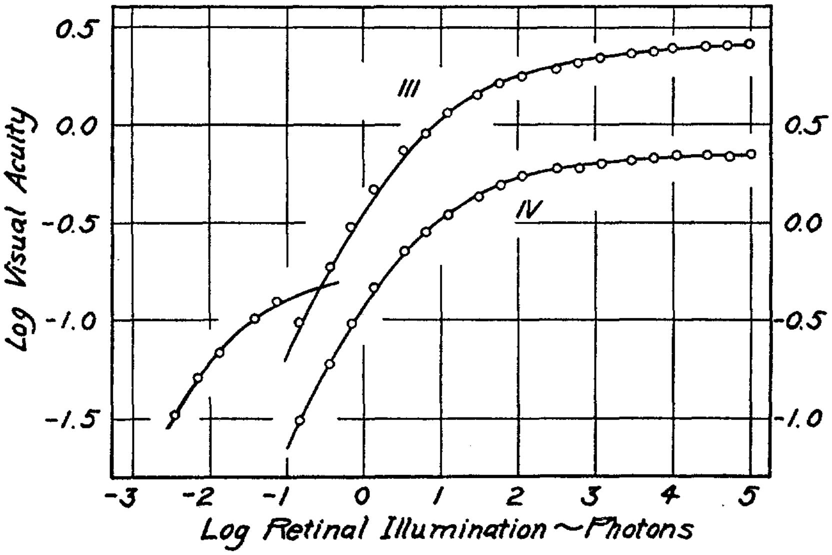

FIG. 3. The data of A. M. C., Table I, column III, and for E. L. S., Table I, column IV, showing the relation between log visual acuity with the C and log I when central fixation is maintained for the entire cone portion of the data. The ordinates for A. M. C. are at the left and those for E. L. S. are at the right. The curve for the rods is of the equation (3), that for the cones, equation (2).

become larger the higher the visual acuity. Three, in such plots the shape of the curve through the data is independent of the particular units involved. This greatly simplifies the selection of a theoretical curve to describe the data.

The same curve is drawn through all the rod data; and a slightly different one through all the cone data in both these figures. These curves are theoretical and will be discussed presently. It may, however, be pointed out here that the subjective observations made during the measurements plotted in Fig. 2 manifest themselves by the fact that the first four cone points, representing the function of a non-homogeneous group of para-foveal cones, do not fall on the theoretical curve but lie above it.

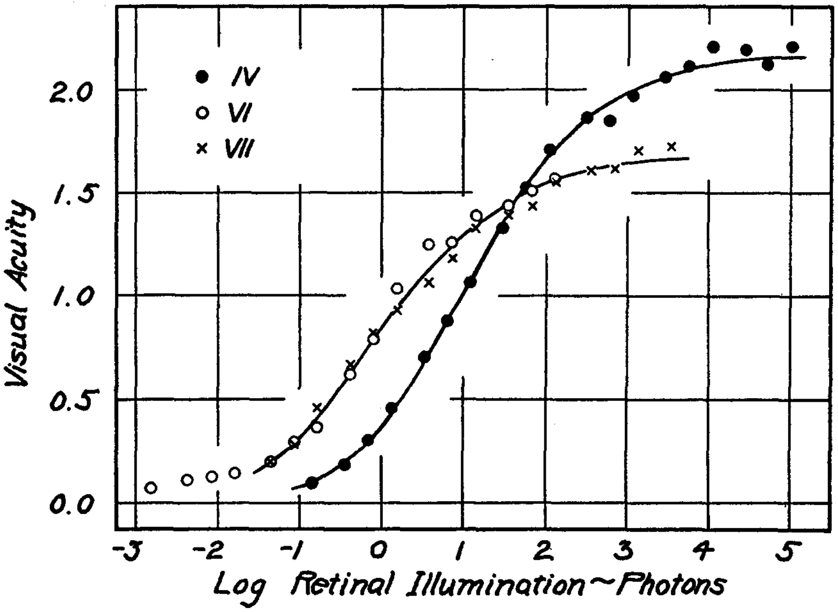

FIG. 4. The single log plot of some of the previously plotted data showing the increased scatter at high visual acuities and the change in slope of the sigmoid curve with change of the maximum visual acuity. The filled circles are the data of E. L. S., Table I, column IV, with the C. The circles are for A. M. C., Table I, column VI, and the crosses are for E. L. S., Table I, column VII, both with the grating. The curves are for the cones only and are of equation (2).

The maximum visual acuity for E. L. S. is somewhat lower than that for A. M. C. In a single log plot as in Fig. 4 this manifests itself in a lower slope of the sigmoid curve as well as a lower maximum.

The measurements with A. M. C. were on one occasion carried on for about two more logarithmic units in brightness. The values of visual acuity neither rose nor fell throughout this change of 100 times in the intensity. This is taken to indicate both that the maximum intensity here recorded is adequate to achieve the maximum visual acuity of the eye as well as that the surround is adequate in area and in brightness. Measurements on various functions of vision (Lythgoe (1932) on visual acuity; Hecht and Smith (1936) on flicker; Hecht (1935) and Steinhardt (1936) on intensity discrimination) have shown that a surround inadequate in either area or intensity or both is invariably manifest by a decrease in sensitivity at the highest intensities.

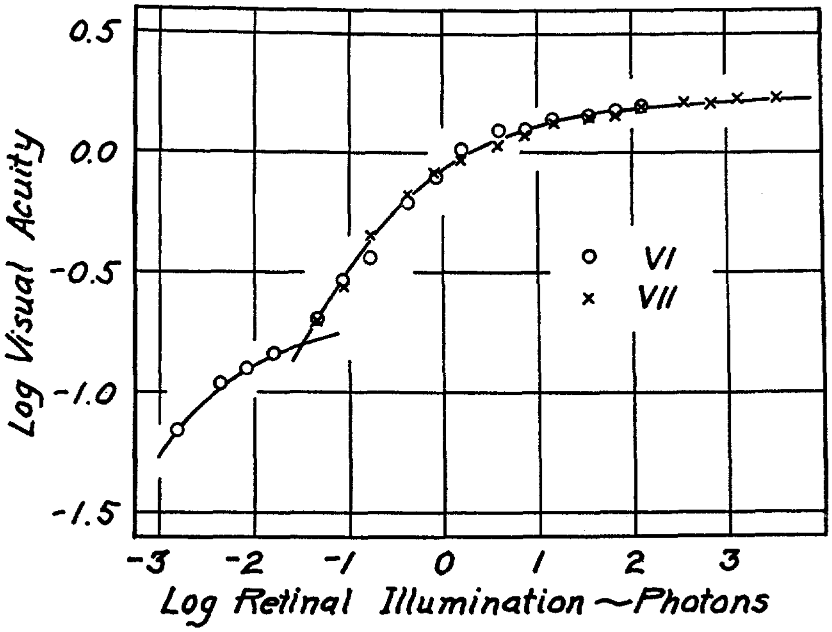

FIG. 5. The data of A. M. C., Table I, column VI, circles, and of E. L. S., Table I, column VII, crosses, showing the relation between log visual acuity with the grating and log I. The curve for the rods is of equation (3) and that for the cones, equation (2).

V

Results with the Grating as Test Object

The visual acuity data with a grating as the test object are presented in the last three columns of Table I and plotted in Fig. 5. The grating was chosen as a second test object primarily to elucidate the problem of area *versus* distance in detail perception. Should this property be measured by a distance, such as visual acuity, or by an area? For a grating, the area involved is directly proportional to the distance between bars because the length remains unchanged, while for the C the area is proportional to the square of the distance. If area is the basis for detail perception, then visual acuity should be squared for the C; and multiplied by a constant, corresponding to the effective length of the bar, for the grating in order that they be comparable. This means that in a double log plot of visual acuity against intensity of illumination the curve for the C should be one-half the slope of that for the grating. The data plotted in Fig. 5 are adequately described by the same two curves that described the data with the C test object, showing that detail discrimination is a function of distance rather than area. This justifies fully the use of visual acuity as here defined, and usually used, as a measure of this property of the eye.

VI

Factors Limiting the Resolving Power of the Eye for a Grating

Another reason for the choice of the grating is that it lends itself to a quantitative evaluation of the limiting factors in the resolving power of the eye. The factors that might be operating here are three in number: (1) the "deterioration" of the retinal image as a result of aberrations of the lens and diffraction at the pupil together with the intensity discrimination of the retina; (2) the diameter of the pupil in its relation to the transmission of the diffraction spectra resulting from the test object; and (3) the resolving power of the retina as a function of the separation between retinal elements.

In the case of the grating it is possible to compute the point by point intensity distribution in the retinal image as a result of chromatic aberration of the dioptric system and diffraction pattern of the pupil. The problem is similar to that of an edge of an extensive dark area adjacent to an extensive light area due to the fact that the bars are very long compared to their width. Such computations with the C test object are very much more difficult and have never been carried out due to the shortness of all dimensions of the opening. Using the curve computed by Hartridge (1922) and reproduced in Fig. 6A that gives the distribution of intensity across the retinal image of an edge when chromatic aberration and diffraction are taken into account, the distribution of intensity in the image of the grating corresponding to a

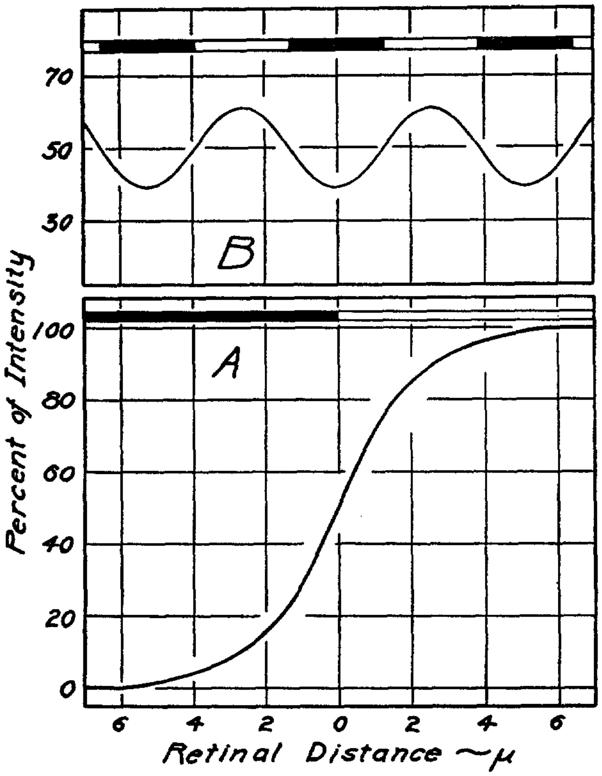

FIG. 6. A. The distribution of the light in an image of an extensive edge on the retina when chromatic aberration and diffraction are taken into account. Values are from Hartridge (1922).

B. The distribution of light in an image of a grating corresponding to a visual acuity of 1.7 on the retina when chromatic aberration and diffraction are taken into account.

visual acuity of 1.7 was computed. The intensity goes through a sinusoidal distribution around 50 per cent as shown in Fig. 6B. The maxima reach only to 61 per cent, and the minima go down to only 39 per cent. Assuming for the moment that the spacing in the image corresponds to the spacing of adjacent rows of cones in the retina, the average intensities on them is 57 per cent and 43 per cent. Calling the intensity on the brighter row 100 per cent, that of the dimmer one is about 75 per cent, a difference of about 25 per cent. Calculations made by Hartridge (1922) show that in the image of a just resolvable single line the maximum intensity difference on two adjacent rows of cones is only about 10 per cent. The difference for the grating comes out to be over twice that value, indicating that perhaps the intensity difference in the image is not the limiting factor.

It is possible to test this by means of visual acuity measurements with three special gratings. One grating is similar to those used in that the opaque bars are equal in width to the spaces between them, and may be designated as 1/2. The second grating has the same number of lines per centimeter as the first, but the width of the lines is only half and may be designated as 1/4. The third grating has lines only half as wide again as those in the second grating and may be designated as 1/8. The distribution of intensity in the retinal image of the first grating is as described in the preceding paragraph and drawn in Fig. 6B. The second grating at the same magnification gives an intensity distribution of the same periodicity as the first, but somewhat shallower, and symmetrical about the 75 per cent value instead of the 50 per cent value. The maximum intensity difference on two adjacent rows of cones is then only about 12 per cent. The third grating behaves similarly and gives only about a 6 per cent maximum difference in intensity for two adjacent rows. The expectation is then that the same maximum visual acuity should be achieved with the 1/4 as with the 1/2 grating, while the 1/8 grating should give a considerably reduced value. The average values for the maximum visual acuity for both observers with these three different gratings are: with the 1/2, 1.86; with the 1/4, 1.84; and with the 1/8, 1.75. It is therefore definitely established that the intensity discrimination of the retina in the "deteriorated" image is far from being a limiting factor in the resolving power of the eye for a grating.

The small, almost insignificant, lowering of the maximum visual acuity by means of the 1/8 grating led me to investigate further the basis of Hartridge's minimum value of a 10 per cent intensity difference in the image of a just resolvable single line. It was found that a 5 μ wire placed in front of the field lens could be seen quite readily, while a 4 μ wire could not. By means of a 2.2 μ wire[1] mounted in the test object carriage the limiting values were found to be between 4.2 μ and 4.6 μ. These correspond to a visual angle of about 1 second of arc. The computation of the intensity distribution in the retinal image is quite inaccurate for such small separations, and the values of intensity difference on two adjacent rows of cones cannot be relied on to better than perhaps a factor of 2, but the value thus arrived at is between 1.5 and 2.0 per cent.

The second possible limiting factor concerns the pupil size, not as it affects the retinal image as a result of diffraction at the pupil and the aberrations of the dioptric mechanism of the eye, but in its relation to the amount of the diffraction spectra formed by the grating test object that it can transmit. Abbe (1873), in his work on the theory of microscope optics, demonstrated that in order for an image of a grating to be formed, the aperture of the objective must transmit the zero and at least one first order spectrum of the source. That this conclusion is not unique to microscope optics but applies to macroscopic optics as well is readily demonstrated by an experiment devised by A. B. Porter (1906) and described by Wood (1934).

Calculation showed that with a grating corresponding to a visual acuity of 1.8, a pupil 2 mm. in diameter transmits the zero order spectrum and one entire first order spectrum up to about a wave length of 630 mμ. A pupil of 3 mm. diameter was therefore put into the apparatus, and the maximum visual acuity was determined as before. It increased about 15 per cent to a value of 2.12. In order to transmit up to λ630 mμ of the first order spectrum of a grating corresponding to a visual acuity of 2.1, the pupil need be only 2.3 mm. diameter. Such a pupil, actually measuring 2.35 mm., when put into

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[1] The 4 and 5μ test wires were gilded quartz strings obtained from the Cambridge Instrument Co., Inc., of New York City and mounted between optical flats in air. The 2.2μ wire was a platinum Wollaston wire obtained from Baker and Co., Inc., of Newark, N. J., and mounted between a thin coverslip and an optical flat with Canada balsam.

the apparatus, yielded the same maximum visual acuity as did the 3 mm. one, namely a value of 2.12. It is therefore clear that pupil size when it is less than 2.3 mm. in diameter is the limiting factor in the resolving power of the eye for a grating.

The maximum visual acuity when the pupil size is not the limiting factor is 2.1. Since the grating is a repeated pattern, the smallest resolvable one must represent a spacing exactly equivalent to that of the elements in the retina. A smaller pattern would result in each cone being covered by a fraction of the light and dark stripes. A different situation obtains with a single object. There the maximum visual acuity may be much higher as it actually is here with the C, being 2.2 for E. L. S. and over 2.5 for A. M. C. and may even reach 30 times the grating value with a single stripe or line. This is analogous to the situation in the eye of the bee where the smallest grating resolvable is one that corresponds to the smallest ommatidial angle (Hecht and Wolf, 1929), while a single bar need be only about a quarter as wide to be seen (Buddenbrock, 1935) because a single row of ommatidia can detect an intensity change of about 25 per cent (Wolf, 1933*a*, *b*). Assuming the finest resolvable grating to correspond to the spacing of the retinal elements and taking the focal length of the eye to be 15.5 mm., the computed distance between adjacent rows of foveal cones comes out to be about 2.1 μ. Østerberg (1935), counting the number of cones in an area of 0.031 mm. radius around the fovea, found the density of cones to be about 147,000 cones per sq. mm. Assuming the space occupied by a cone to be hexagonal, the distance between centers of adjacent cones comes out to be 2.8 μ and that between adjacent parallel rows of cones 2.4 μ. This value is an average over a relatively large area and is probably too large for the most central region as evidenced by the fact that Rochon-Duvigneaud (1906) found the cones in the central bundle of the retina to be from 2.0 to 2.5 μ in diameter.

The fact that the final value of the width of a row of cones is smaller than had been previously assumed in the calculation of the intensity difference on two adjacent rows of cones does not appreciably change the conclusions drawn. The previously assumed value was 2.6 μ. When a width of 2.1 μ is substituted, the percentage difference in the intensity rises from 25 per cent to 27 per cent.

It is of interest to note here that although the average diameter of the pupil under high illumination is about 2.5 mm. yet the smallest pupil diameter in the literature, that of P. R. in Reeves' (1918) paper, is only 1.9 mm. Thus the eye is built so that the two limiting factors, the pupil diameter and the cone separation, operate at nearly the same value.[2]

There are two other interesting points about the grating data. One is that the function of the para-foveal cones is not manifest in the measurements. Since the eye is presented by an extensive test field of 4°, one would expect the most sensitive elements to control the resolution at all times, resulting in a curve similar to that of Fig. 2. That such is not the case may be explained on the notion that a considerable homogeneous population of functional retinal elements is necessary for grating resolution. No such large homogeneous population of cones exists outside the fovea proper except perhaps in the periphery where the rods are more numerous and control the function of that area.

The other point has to do with the relative visual acuities for the two test objects at a given intensity. In Fig. 7 the curve for A. M. C. of Fig. 3 and the curve of Fig. 5 are drawn correctly spaced on their respective axes. It will be seen that below about 30 photons the grating gives superior visual acuity values, while at higher intensities the C is superior. Comparison of the rod curves and the first portion

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[2] A question might arise in the experiments on the relation of pupil diameter to maximum visual acuity as to whether the observers' pupils were 2.35 mm. in diameter and that the further increase in the artificial pupil produced no effect. That this is not so may be gathered from the following. When the apparatus is arranged for work with the grating, there are two overlapping images of the ground glass sources in the plane of the pupil. Because the grating decreases the intensity of the test field, that of the surround has to be decreased also. This is accomplished by means of a diaphragm on the ground glass source that supplied the surround illumination. The result is that whereas the image of the source from the test field always fills the pupil, that from the surround is always smaller. In order to facilitate work with the 1/2, 1/4, and 1/8 gratings, this diaphragm is an iris that can be readily adjusted to give a brightness match for the two parts of the field under different circumstances. When the 3 mm. pupil is substituted for the 2.35 mm., the test field becomes brighter than the surround for both observers, necessitating the opening of the iris controlling the surround brightness. This definitely shows that the natural pupils of both observers are wider than 2.35 mm.

of the cone curves for the two test objects shows that in order to achieve equal visual acuities about 10 times more light is necessary for the C than for the grating. This is not surprising when one considers that long before the opening in the C can be resolved the letter looks like an O; and that therefore the resolution of the O is more nearly comparable to the resolution of the lines in the grating. That the cone curves cross is the result of the fact that a higher maximum visual acuity is attainable with the C. Thus the maximum visual acuity with the grating is reached at about 1 logarithmic unit lower in intensity.

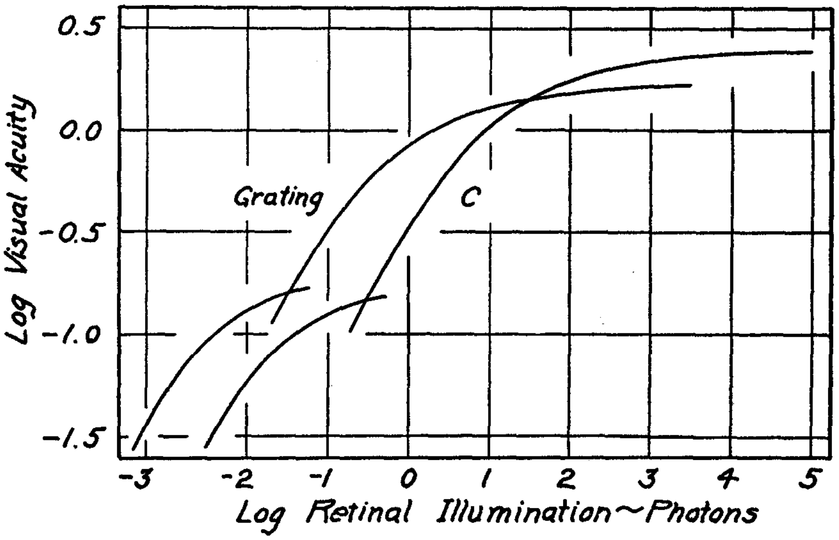

FIG. 7. The curve for A. M. C. of Fig. 3 and the curve of Fig. 4 showing the relative position on the axes of the two functions for the two different test objects.

VII

Comparison with Previous Data

For comparison with previous data, I corrected Koenig's (1897) measurements with white light, to give relative retinal brightnesses. His intensity values were first converted into millilamberts. They were then multiplied by the photon factor (Troland, 1916), the pupil diameters being derived from the average found by Reeves (1918).

These values were then multiplied by a pupil efficiency factor derived from the data of Stiles and Crawford (1933). The data were then averaged in groups of five consecutive values, and plotted as log visual acuity against the logarithm of the retinal brightness in Fig. 8. The curves drawn in this figure are the same ones drawn through our own data.

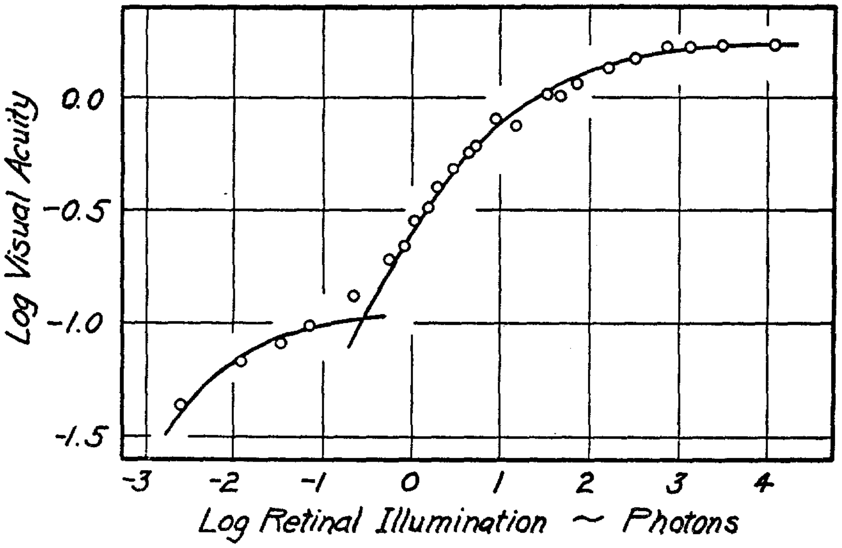

FIG. 8. The data of Koenig for white light with his intensity scale converted into retinal brightnesses by means of the data of Reeves on pupil area and the data of Stiles and Crawford on pupil efficiency and plotted as log visual acuity against log I. The curve for the rods is of equation (3) and that for the cones of equation (2).

VIII

Theory

The curves drawn through all the data represent two varieties of the stationary state equation developed by Hecht (1934) upon the most general considerations of the requirements of a photoreceptor process. Assuming a photosensitive material S which is changed by light to photoproducts P, A, B, . . . and which is reformed again by a thermal reaction of some of these products, he derives the equation for the stationary state as

$$KI = x^n/(a - x)^m \qquad (1)$$

where I is the light intensity, $(a\text{-}x)$ and x are the concentrations of sensitive material and photoproducts respectively, m and n are constants giving the orders of the photochemical and thermal reactions, and K is a constant.

Setting the initial concentration $a = 1$, the values for KI for a series of values of x may be computed for the four cases where $m = 1$, $n = 1$; $m = 2$, $n = 1$; $m = 1$, $n = 2$; and $m = 2$, $n = 2$. By putting these values in the form of their logarithms, the nature of their dependence becomes independent of the values of the constants K and a, and may be plotted as log KI *versus* log x or log x^n for each of the four cases. In this form the curves may be used to test any set of data that are plotted in the form of log visual function against log I by simple superposition. They then indicate the values of m and n. Such treatment has yielded gratifying results with the data of intensity discrimination (Hecht, 1935), flicker (Hecht and Shlaer, 1936; and Hecht and Smith, 1936), photosynthesis (Smith, 1937), instantaneous threshold (Hecht, 1937), and here, visual acuity.

The curve drawn through the cone data in this communication is that of equation (1) when $m = 2$, $n = 2$; and where visual acuity is proportional to x^n. Equation (1) may then be written

$$KI = \frac{V.A.}{(V.A._{\max}^{\frac{1}{2}} - V.A.^{\frac{1}{2}})^2} \tag{2}$$

This is identical with the form found to fit the data of intensity discrimination (Hecht, 1935) for the cones and differs from that found to fit the data of flicker only by the fact that flicker is proportional to x (Hecht and Smith, 1936).

Keeping visual acuity proportional to x^n, the data for the rods may be fitted about equally well either when $m = 1$, $n = 2$, or when $m = 2$, $n = 1$. The latter was chosen here to complete the similarity with the data of intensity discrimination, and may be written as

$$KI = \frac{V.A.}{(V.A._{\max} - V.A.)^2} \tag{3}$$

IX

SUMMARY

1. An apparatus for measuring the visual acuity of the eye at different illuminations is described. The test object is continuously vari-

able in size and is presented at a fixed distance from the eye in the center of a 30° field. Observation of the field is through an artificial pupil. The maximum intensity obtainable is more than enough to cover the complete physiological range for the eye with white light though only 110 watts are consumed by the source. Means for varying the intensity over a range of $1:10^{10}$ in small steps are provided.

2. The relation of visual acuity and illumination for two trained observers was measured, using two different types of test object, a broken circle and a grating. The measurements with both test objects show a break at a visual acuity of 0.16, all values below that being mediated by the rods and those above by the cones. The grating gives higher visual acuities at intensities less than about 30 photons and lower visual acuities above that. The maximum visual acuity attainable with the grating under the same conditions is about 30 per cent lower than that with the C. It is shown that the limiting factor in the resolution of the eye for the grating is the diameter of the pupil when it is less than 2.3 mm. and the size of the central cones when the pupil is larger than that. The value of the diameter of the cone derived on that basis from the visual acuity data agrees with that derived from direct cone count in a unit of area.

3. The data for the cones made with both test objects are adequately described by one and the same form of the stationary state equation derived by Hecht for the photoreceptor system. This fact, together with certain considerations about the difference in the nature of the two test objects with regard to the resolvable area, leads to the conclusion that detail perception is a function of a distance rather than an area. All the data for the rods can likewise be described by another variety of the same equation, although the data are too fragmentary to make the choice of the form as certain as might be desired.

It is a pleasure to acknowledge the author's indebtedness to his professor and colleague, Dr. Selig Hecht, to whose friendly guidance throughout their many years of association the author owes much; and to his colleagues, Dr. Aurin M. Chase and Dr. Emil L. Smith who gave amply of their time and patience to make all the measurements here recorded, measurements which are perhaps the most arduous in the entire field of vision to make.

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