# THE FOUR VARIABLES OF THE VISUAL THRESHOLD.

BY

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In the investigation of questions relating to lighting, it becomes of importance to measure the capacity of the eye to see; and in performing this measurement, we are confronted with the fact that there are almost as many different ways of evaluating visibility as there are different things to look at. It becomes necessary then, as the first step toward the perhaps impossible task of exhausting this subject, to select a limited series of visual objects for study.

In the present work the selection of this series has been guided by two considerations. The major one of these has been the necessity, in scientific work, of dealing with things which are susceptible of exact description and reproduction. The second consideration has been the technical problem of constructing such visual objects which shall also extend over the widest possible ranges of the variables involved.

The eye is capable, under otherwise favorable conditions, of resolving very small objects. The familiar test-card of the ophthalmologist is an illustration of this. In practice, it is found that two objects may be distinguished when they are separated by as little as one minute of visual angle. In this case, however, as with the letters on the test-card, the objects must be marked off from their background by a high factor in brightness. The white surface of the card reflects perhaps 80 per cent. of the light falling upon it; the ink with which the letters are printed, perhaps 5. The difference, 75, is then about 94 per cent. of the brightness of the card, which, in this case, we may look upon as the general level of brightness to which the eye is exposed.

While these conditions may be held to apply, without great modification, to most of the reading and clerical work which the eyes are called upon to perform, it is otherwise in many cases where vision is of the highest importance.

The best illustration of these conditions is perhaps the appearance of a large object, such as a building, when it is no more than just visible through a fog. As we approach such an object, when it first becomes visible it is seen only in its outlines, within which is included an area of the visual field which is extremely large as compared with the critical letter on the test-card. But on the other hand, the brightness-difference between this area and its background, which makes it visible at all, is slight. The area, in silhouette, appears of a very pale gray, which may be, say, one or two per cent. darker than the surrounding background. As we approach the object, the visual angle increases and at the same time the depth of the layer of intervening fog is reduced with corresponding increases in the contrasts. In consequence, the details of the building come to be visible upon the silhouette, first, the larger ones as the doors and windows, later the shingles, clapboards or bricks as the case may be.

These two extreme conditions for vision, as well as all intermediate stages, may be produced in the laboratory by comparatively simple means,[1] as was the case in the experimental work here to be described. Test-objects (Fig. 1)

FIG. 1.

THE FORM OF THE TEST-OBJECT.

The interval between the dark rectangles is equal to their width and is one-third of their length. When this interval is 1.745 mm., it subtends 1 minute visual angle at the eye, 6 meters distant. The "size" in visual angle is computed upon this basis.

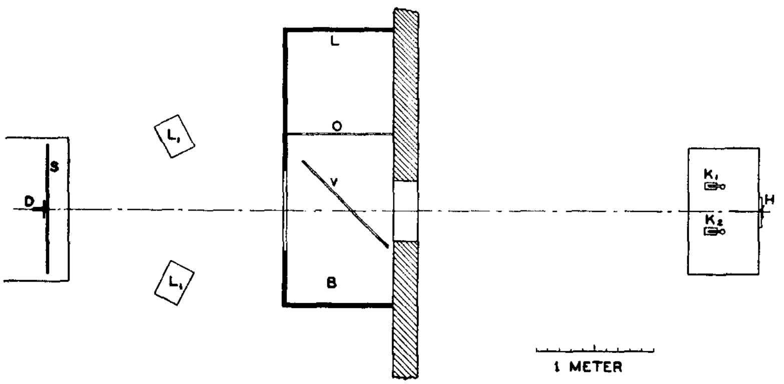
of various sizes were made of the deepest black on white. One of these was placed at the center of a large, white screen *S* (Fig. 2) at six meters distance from the eyes of the subject at *H*. About half way between, a sheet of plate glass *V* is interposed in the line of vision, making an angle of about 45° therewith, in such a way that the subject sees, reflected in

[1] A more detailed description of the technique used is to be found in an earlier communication on this subject in the *Journal of Experimental Psychology*, August, 1927, Vol. X, pp. 350 to 364.

the plate glass and superimposed upon the screen, the image of a large sheet of opal-flashed glass $O$, illuminated uniformly from behind. Under such conditions, with separate control of the illuminations upon the test-object by means of lamps $L_1$, $L_1$, and upon the large diffusing surface o, whose image (the "veil") is seen in the oblique reflector, by lamps at $L$, it is possible to construct visual objects of various sizes and of all grades of brightness-difference, from the deepest black, through the palest gray to the point of complete extinction.

Designating the brightness of the background of the test-

FIG. 2.




GENERAL ARRANGEMENT OF APPARATUS.

The test object was placed at the center of the screen $S$, lit by the lamps $L_1L_1$. The subject's head was steadied by a head-rest at $H$. A sheet of plate-glass $V$ reflected the image of the opal glass $O$, lit by a bank of lamps at $L$. The illumination on $S$ and the brightness of the image of $O$ were independently controllable.

object as $s$ (screen), and that of its black elements as $s_0$, when the veil is superimposed, these are each seen with an equal brightness, $v$ (veil), added to them. The brightness of the background then becomes $s + v$, that of the figure of the test-object, $s_0 + v$, and the percentage contrast, as expressed here:

$$100 \frac{(s + v) - (s_0 + v)}{(s + v)} = 100 \frac{s - s_0}{s + v}.$$

With a series of test-objects ranging in size from 0.80 to 16.0 minutes visual angle, the percentage contrast was determined at which each test-object was just at the border of visibility, the brightness of the background $(s + v)$, being maintained at 20 ml. This procedure was repeated at 100 ml. brightness of background, and again at 1 ml. For these three sets of data the time of exposure of the test-object was uniform at 170 $\sigma$ (thousandths of a second). The test-object (Fig. 1) was mounted centrally on a disc seen at the center of the screen $S$ (Fig. 2). This disc rotated at the rate of 120 revolutions per minute and could be almost instantaneously stopped and started by a magnetic clutch, which in turn was controlled by a switch in the arc of a pendulum. This arrangement made it possible to stop and start the disc with a very short and measurable interval; and the duration of this stoppage is the time of exposure just stated.

It was also of interest to determine the effect of changing the time of exposure of the test-object. Accordingly, at 1 ml., and at 100 ml. brightness of ground, and with test-objects of three selected and representative sizes, three parallel series of measurements were made in which the three times of exposure were 75 $\sigma$, 170 $\sigma$ and 300 $\sigma$.

TABLE I.

*Mean Percentage Contrast for the Threshold, for Various Sizes of Test-objects (First Column) and for Nine Different Subjects.*

The last column gives the geometric mean for the nine individuals. Exposure-time 0.170 second.

| Minutes Visual Angle. | Brightness, 100 ml. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C. | M. | T. | Cm. | P. | Cl. | K. | W. | B. | Mean. |
| 0.65 | 70.4 | 71.7 | | | | | 59.0 | | 67.8 | |
| 0.80 | 24.6 | 32.7 | 45.5 | 56.5 | 47.6 | 92.8 | 26.9 | 84.0 | 35.2 | 44.8 |
| 1.17 | 11.6 | 9.65 | 14.8 | 16.5 | 13.4 | 29.8 | 10.3 | 28.0 | 13.7 | 15.2 |
| 1.63 | 6.50 | 4.96 | 9.09 | 7.68 | 8.42 | 13.7 | 5.91 | 15.5 | 6.51 | 8.13 |
| 2.41 | 3.73 | 3.20 | 5.43 | 4.28 | 5.21 | 7.65 | 3.22 | 7.95 | 3.73 | 4.67 |
| 3.95 | 1.91 | 1.73 | 3.51 | 1.48 | 1.96 | 4.86 | 2.12 | 3.57 | 2.39 | 2.43 |
| 7.98 | 1.33 | 1.00 | 1.95 | 1.41 | 1.70 | 2.21 | 1.15 | 1.76 | 1.35 | 1.50 |
| 16.02 | 1.05 | 0.87 | 1.40 | 1.19 | 1.16 | 1.29 | 0.93 | 1.36 | 1.09 | 1.14 |

The results of the three size-contrast sets are given in detail, for each of the nine subjects used, in Tables I, II, and III for 100, 20, and 1 ml. respectively. In Tables IV and V are given the results of the time-sets at 100 and at 1 ml. respectively. In these two tables the figures in parentheses are extrapolated or interpolated, as the case may be, using

Lagrange's formula applied to the logarithm of the visual angle and the logarithm of the percentage contrast. This particular procedure was justified by its application to corresponding data in the size-contrast sets, within which the extrapolated data could be checked directly against the empirical.

TABLE II.

*Mean Percentage Contrast for the Threshold, for Various Sizes of Test-objects (First Column) and for Nine Different Subjects.*

The last column gives the geometric mean for the nine individuals. Exposure-time 0.170 second.

| Minutes Visual Angle. | Brightness, 20 ml. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C. | M. | T. | L. | P. | H. | K. | W. | B. | Mean. |
| 0.80 | | 89.1 | 89.0 | 78.2 | | | 62.2 | | 82.8 | |
| 0.99 | 47.0 | 39.1 | 50.2 | 43.8 | 56.0 | 57.0 | 35.3 | 74.0 | 44.3 | 48.5 |
| 1.17 | 26.6 | 21.1 | 34.0 | 27.7 | 33.2 | 38.7 | 22.1 | 51.4 | 26.2 | 30.1 |
| 1.35 | 17.7 | 15.2 | 23.9 | 19.8 | 23.3 | 30.5 | 15.1 | 32.7 | 17.3 | 20.9 |
| 1.63 | 12.6 | 9.62 | 16.0 | 12.4 | 14.0 | 23.6 | 10.7 | 22.9 | 11.6 | 14.1 |
| 1.93 | 9.25 | 7.13 | 11.6 | 8.75 | 10.4 | 17.4 | 7.76 | 13.4 | 7.66 | 9.96 |
| 2.41 | 6.42 | 4.62 | 8.37 | 6.46 | 7.86 | 12.3 | 5.12 | 9.02 | 4.76 | 6.87 |
| 3.20 | 3.93 | 3.29 | 6.85 | 4.02 | 6.10 | 9.26 | 3.96 | 6.19 | 3.44 | 4.92 |
| 3.95 | 3.29 | 2.54 | 4.97 | 3.23 | 4.33 | 6.46 | 3.20 | 3.92 | 2.81 | 3.71 |
| 5.67 | 2.55 | 1.95 | 3.50 | 2.35 | 3.17 | 4.20 | 2.34 | 2.94 | 2.13 | 2.71 |
| 7.98 | 2.07 | 1.60 | 2.91 | 1.90 | 2.71 | 2.98 | 1.81 | 2.23 | 1.75 | 2.16 |
| 11.31 | 1.72 | 1.38 | 2.22 | 1.58 | 2.30 | 2.24 | 1.54 | 1.84 | 1.65 | 1.80 |
| 16.02 | 1.50 | 1.27 | 1.85 | 1.42 | 1.79 | 1.96 | 1.34 | 1.61 | 1.51 | 1.57 |

TABLE III.

*Mean Percentage Contrast for the Threshold, for Various Sizes of Test-objects (First Column) and for Nine Different Subjects.*

The last column gives the geometric mean for the nine individuals. Exposure-time 0.170 second.

| Minutes Visual Angle. | Brightness, 1 ml. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C. | M. | T. | Cm. | P. | H. | K. | W. | B. | Mean. |
| 1.17 | 78.5 | 68.8 | | | 85.8 | | 70.0 | | 77.0 | |
| 1.35 | 46.3 | 45.7 | 68.1 | 88.2 | 58.8 | 75.8 | 43.5 | 92.8 | 46.0 | 60.3 |
| 1.63 | 33.8 | 31.4 | 47.7 | 56.7 | 39.7 | 52.1 | 27.7 | 56.9 | 31.1 | 40.5 |
| 1.93 | 24.5 | 19.2 | 37.4 | 39.4 | 26.6 | 34.0 | 18.1 | 42.9 | 20.9 | 27.9 |
| 2.41 | 14.7 | 11.2 | 23.8 | 23.9 | 16.9 | 23.8 | 12.8 | 23.3 | 11.8 | 17.2 |
| 3.20 | 9.34 | 7.27 | 15.5 | 13.4 | 11.3 | 17.9 | 7.46 | 14.7 | 7.12 | 10.9 |
| 3.95 | 6.79 | 4.97 | 10.6 | 9.02 | 7.0 | 13.0 | 5.36 | 8.67 | 4.89 | 7.39 |
| 5.67 | 4.05 | 3.16 | 6.70 | 4.85 | 3.90 | 6.41 | 3.42 | 5.98 | 3.15 | 4.43 |
| 7.98 | 2.91 | 2.38 | 4.74 | 3.32 | 2.92 | 4.07 | 2.54 | 4.19 | 2.56 | 3.20 |
| 11.31 | 2.46 | 1.75 | 3.46 | 2.53 | 2.24 | 2.95 | 1.86 | 3.05 | 2.04 | 2.42 |
| 16.02 | 1.89 | 1.58 | 2.62 | 1.98 | 1.83 | 2.41 | 1.60 | 2.35 | 1.62 | 1.95 |

The relative probable errors [2] of the results stated in Tables I, II, and III are given in Tables I*A*, II*A*, and III*A* respectively, and in an exactly corresponding way. The

TABLE I*A*.

*Relative Probable Errors of the Threshold Values Given in Tables I, II, and III.*

These are derived in each case from the five separate serial values. The probable error of the mean $E_m$, last column, is derived from the nine corresponding individual values $E$, by formula $E_m = 1/N\sqrt{\Sigma E^2}$, in which $N = 9$. The variations due to the systematic differences between the individuals are therefore not included in $E_m$.

| Minutes Visual Angle. | Brightness, 100 ml. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C. | M. | T. | Cm. | P. | Cl. | K. | W. | B. | Mean. |
| 0.65 | .047 | .036 | | | | | .039 | | .016 | |
| 0.80 | .054 | .048 | .066 | .034 | .040 | .040 | .036 | .027 | .016 | .014 |
| 1.17 | .051 | .060 | .023 | .030 | .055 | .056 | .036 | .085 | .016 | .017 |
| 1.63 | .034 | .026 | .060 | .031 | .046 | .056 | .026 | .043 | .019 | .013 |
| 2.41 | .007 | .068 | .034 | .013 | .081 | .105 | .017 | .038 | .017 | .018 |
| 3.95 | .020 | .049 | .038 | .033 | .078 | .025 | .030 | .042 | .044 | .014 |
| 7.98 | .017 | .021 | .018 | .021 | .032 | .058 | .026 | .027 | .023 | .010 |
| 16.02 | .023 | .014 | .013 | .037 | .028 | .028 | .015 | .021 | .019 | .008 |

TABLE II*A*.

*Relative Probable Errors of the Threshold Values Given in Tables I, II, and III.*

These are derived in each case from the five separate serial values. The probable error of the mean $E_m$, last column, is derived from the nine corresponding individual values $E$, by formula $E_m = 1/N\sqrt{\Sigma E^2}$, in which $N = 9$. The variations due to the systematic differences between the individuals are therefore not included in $E_m$.

| Minutes Visual Angle. | Brightness, 20 ml. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C. | M. | T. | L. | P. | H. | K. | W. | B. | Mean. |
| 0.80 | | .030 | .042 | .047 | | | .016 | | .031 | |
| 0.99 | .041 | .092 | .076 | .047 | .087 | .044 | .056 | .036 | .060 | .021 |
| 1.17 | .053 | .048 | .064 | .016 | .060 | .022 | .087 | .032 | .028 | .017 |
| 1.35 | .056 | .051 | .036 | .050 | .083 | .047 | .064 | .025 | .020 | .017 |
| 1.63 | .055 | .030 | .039 | .053 | .044 | .049 | .044 | .032 | .044 | .015 |
| 1.93 | .038 | .047 | .028 | .047 | .063 | .043 | .045 | .015 | .055 | .015 |
| 2.41 | .035 | .061 | .026 | .072 | .057 | .055 | .034 | .038 | .040 | .016 |
| 3.20 | .020 | .044 | .044 | .038 | .031 | .036 | .038 | .035 | .050 | .013 |
| 3.95 | .024 | .063 | .039 | .035 | .040 | .034 | .034 | .018 | .033 | .012 |
| 5.67 | .048 | .056 | .022 | .042 | .048 | .043 | .051 | .011 | .023 | .014 |
| 7.98 | .049 | .055 | .038 | .026 | .048 | .016 | .020 | .028 | .023 | .012 |
| 11.31 | .034 | .052 | .021 | .038 | .066 | .036 | .030 | .013 | .023 | .013 |
| 16.02 | .054 | .056 | .034 | .032 | .042 | .030 | .050 | .031 | .027 | .014 |

[2] By "relative probable error" is meant the probable error of the mean, divided by the mean. It is therefore the probable error in terms of the mean as unity.

TABLE III*A*.

*Relative Probable Errors of the Threshold Values Given in Tables I, II, and III.*

These are derived in each case from the five separate serial values. The probable error of the mean $E_m$, last column, is derived from the nine corresponding individual values $E$, by formula $E_m = 1/N\sqrt{\Sigma E^2}$, in which $N = 9$. The variations due to the systematic differences between the individuals are therefore not included in $E_m$.

| Minutes Visual Angle. | Brightness, 1 ml. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | C. | M. | T. | Cm. | P. | H. | K. | W. | B. | Mean. |
| 1.17 | .068 | .067 | | | .040 | | .045 | | .029 | |
| 1.35 | .047 | .096 | .041 | .031 | .035 | .039 | .050 | .020 | .037 | .016 |
| 1.63 | .047 | .063 | .014 | .030 | .054 | .043 | .042 | .016 | .038 | .014 |
| 1.93 | .061 | .097 | .015 | .032 | .040 | .073 | .030 | .044 | .038 | .018 |
| 2.41 | .040 | .097 | .045 | .057 | .035 | .099 | .059 | .054 | .037 | .021 |
| 3.20 | .019 | .072 | .037 | .071 | .038 | .071 | .019 | .036 | .027 | .016 |
| 3.95 | .037 | .076 | .035 | .061 | .069 | .072 | .013 | .038 | .021 | .017 |
| 5.67 | .034 | .061 | .041 | .048 | .044 | .044 | .034 | .046 | .008 | .014 |
| 7.98 | .038 | .042 | .006 | .038 | .068 | .060 | .007 | .056 | .026 | .014 |
| 11.31 | .023 | .040 | .020 | .016 | .062 | .050 | .020 | .049 | .035 | .013 |
| 16.02 | .017 | .032 | .017 | .028 | .038 | .006 | .020 | .046 | .021 | .009 |

relative probable errors of the means, last column, are each derived from those in the corresponding line of the table in such a way as not to be augmented by the differences between the individual subjects, since the latter are regarded as systematic and as not affecting the trend of the final result. An idea of the extent of the individual differences may be gained by intercomparison of the results within Tables I, II, III, IV, and V. The random selection of a totally different group of subjects might yield results different from those given, in excess of the uncertainty indicated by the probable errors stated.

The method of serial groups was used in each measurement. Each individual tabulated result represents the average from five series. Thus 2185 series are represented in the tables. Although the series are of variable length, the number of observations in each series averages not far from 50. Thus the results given represent something like 100,000 observations.

### TABLE IV.

*Mean Percentage Contrast for Three Exposure-times.*

Values which have been interpolated or extrapolated are given in parentheses.

| Minutes Visual Angle. | Exposure-Time, Seconds. | Brightness, 100 ml. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C. | M. | T. | Cm. | P. | Cl. | K. | W. | B. | Mean. |
| 0.80 | 0.075 | 37.3 | 36.4 | 62.5 | 73.4 | 45.4 | 93.9 | 34.2 | (94.8) | 39.9 | 52.7 |
| | 0.170 | 28.0 | 27.8 | 47.4 | 58.0 | 37.5 | 93.3 | 29.2 | (82.0) | 31.6 | 43.6 |
| | 0.300 | 21.8 | 23.5 | 41.7 | 46.4 | 33.5 | 89.8 | 25.5 | (67.8) | 26.4 | 37.2 |
| 0.99 | 0.075 | | | | | | | | 55.7 | | |
| | 0.170 | | | | | | | | 46.9 | | |
| | 0.300 | | | | | | | | 39.2 | | |
| 2.41 | 0.075 | 3.81 | 3.34 | 6.63 | 5.19 | 5.40 | 10.1 | 3.89 | 9.08 | 4.26 | 5.35 |
| | 0.170 | 3.37 | 2.82 | 4.81 | 4.58 | 4.72 | 8.58 | 3.72 | 7.13 | 3.80 | 4.56 |
| | 0.300 | 3.08 | 2.74 | 4.39 | 3.93 | 3.97 | 7.69 | 3.39 | 6.15 | 3.40 | 4.08 |
| 16.02 | 0.075 | 1.14 | 0.95 | 1.68 | 1.23 | 1.42 | 1.37 | 1.02 | 1.55 | 1.25 | 1.27 |
| | 0.170 | 1.08 | 0.85 | 1.37 | 1.07 | 1.32 | 1.25 | 0.96 | 1.37 | 1.08 | 1.14 |
| | 0.300 | 0.98 | 0.71 | 1.16 | 1.04 | 1.20 | 1.28 | 0.90 | 1.24 | 0.98 | 1.04 |

### TABLE V.

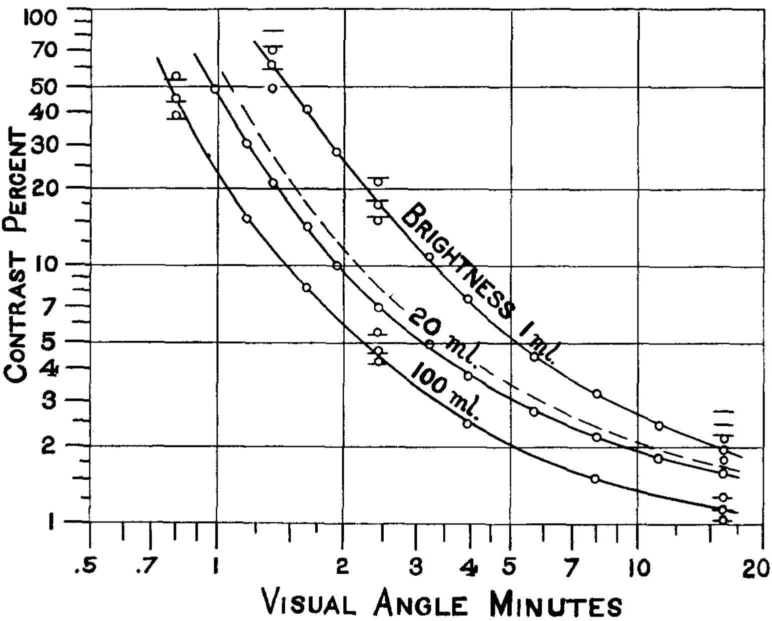
*Mean Percentage Contrast for Three Exposure-times.*

Values which have been interpolated or extrapolated are given in parentheses.

| Minutes Visual Angle. | Exposure Time, Seconds. | Brightness, 1 ml. | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C. | M. | T. | Cm. | P. | Cl. | K. | W. | B. | Mean. |
| 1.17 | 0.075 | 85.5 | 81.9 | | | 92.9 | | 75.0 | | 86.9 | |
| | 0.170 | 68.2 | 70.8 | | | 88.8 | | 61.4 | | 72.2 | |
| | 0.300 | 58.0 | 56.8 | | | 68.9 | | 52.9 | | 59.1 | |
| 1.35 | 0.075 | (60.7) | (56.9) | 86.3 | (125.2) | (66.8) | (128.2) | (51.8) | (161.4) | (59.2) | 81.5 |
| | 0.170 | (48.4) | (48.1) | 65.7 | (118.7) | (59.3) | (127.4) | (43.0) | (157.4) | (49.2) | 71.0 |
| | 0.300 | (41.6) | (39.2) | 55.7 | (96.8) | (48.3) | (98.2) | (37.2) | (115.1) | (40.6) | 57.8 |
| 1.63 | 0.075 | | | | | | 77.4 | | 91.9 | | |
| | 0.170 | | | | | | 70.3 | | 81.1 | | |
| | 0.300 | | | | | | 56.2 | | 64.4 | | |
| 2.41 | 0.075 | 18.4 | 16.3 | 26.0 | 34.6 | 21.0 | 31.0 | 14.6 | 33.0 | 15.8 | 22.3 |
| | 0.170 | 14.8 | 12.9 | 22.1 | 28.4 | 15.2 | 24.3 | 12.8 | 25.0 | 13.3 | 17.9 |
| | 0.300 | 13.2 | 11.1 | 19.4 | 21.8 | 14.4 | 20.8 | 11.3 | 22.7 | 11.2 | 15.6 |
| 16.02 | 0.075 | 2.50 | 2.17 | 3.71 | 2.58 | 2.62 | 3.64 | 2.23 | 3.30 | 2.31 | 2.73 |
| | 0.170 | 2.28 | 1.95 | 3.32 | 2.37 | 2.28 | 3.15 | 2.16 | 3.01 | 2.03 | 2.46 |
| | 0.300 | 1.91 | 1.69 | 3.06 | 2.23 | 2.17 | 3.04 | 1.90 | 2.63 | 1.82 | 2.22 |

The mean values given in the tables are plotted in Fig. 3,[3] in which the three curves drawn in solid lines represent the data from Tables I to III inclusive. The curve in broken lines represents the values for 10 ml., the ordinates having been interpolated by Lagrange's formula from those of the

FIG. 3.




VISUAL ANGLE-CONTRAST RELATION.

The data indicated by the circles on the three curves were taken with an exposure-time of 0.170 sec. Those indicated by the groups of three short horizontal lines were taken at another time with exposure-times of 0.075, 0.170 and 0.300 seconds respectively, from above downward. The group of three circles indicates the result when the three are shifted downward so that the middle one coincides with the original datum plotted on the curve and representing identical conditions.

other three. Each group of three short horizontal lines shows the corresponding values from the time series for 75, 170 and 300 $\sigma$ respectively, from above downward. The middle line of the three in each group (for 170 $\sigma$) should, of course, check with the corresponding datum from the size-contrast set, and does check satisfactorily in four cases out of the six, as shown by the relation of the middle line to the middle

[3] In Figs. 3 to 7, inclusive, the numerals give the actual values of the designated quantities, which are logarithmically plotted throughout.

one of the three circles. The reason for the two discrepant values has not been determined. Both occur at the 1 ml. brightness-level, and are part of the last portion of the work done. In any event, the data show consistently the variation to be expected as the duration of exposure is changed between 75 and 300 $\sigma$. The three small circles represent the same data, shifted vertically in the plot until the middle one coincides with the value obtained in the size-contrast set.

What is especially to be noted is the nearly parallel course of the two size-contrast curves for 100 and 20 ml., and the fact that for 1 ml. brightness-level the curve departs rather widely from the other two in the high-contrast, small-size region (upper left of the plot), while approaching the others rather closely at the other end, which represents the larger, low-contrast phase of vision, in which the perception of small brightness-differences is more important than the resolution of fine detail in the object. The significance of this will become clearer as the other figures are considered. In passing it may be remarked that for a small, high-contrast object, a tenfold change in brightness is offset by nearly equal factors in visual angle or in contrast, over the whole range between 1 and 100 ml. Thus, by scaling from the plot, it appears that a drop in brightness, either from 100 to 10 ml., or from 10 to 1 ml., is offset by an increase in visual angle by a factor of about 1.45, or by a factor of about 2.3 in contrast. This is only true in the region toward the left of the plot, for objects having visual angles of 1′ to 2′, and seen in contrasts of 10 to 50 per cent. according to circumstances. On the other hand, with objects of 5′ to 16′ visual angle, and seen in contrasts of 2 per cent., more or less, the equivalent factor in visual angle is greater in dropping from 100 to 10 ml. than in the step-down from 10 to 1 ml. The two factors are here 2.1 and 1.45. The corresponding factors in contrast are 1.5 and 1.3 for this region.

It is to be noted here, that since any object is visible by reason of the fact that its brightness (light-intensity) is more or less different from that of its immediate background, there are necessarily not less than two photometric variables involved in any visible object. In the present case, the object is the less of the two, that is, it is darker than its background, and it is either very small in extent, or only very slightly darker than the ground. The latter may then be considered as representing the brightness-level (or general intensity) to which the eye is exposed and adapted, and is so considered here. Instead of specifying the brightness of the object itself as the second intensity-variable, it has been found convenient to specify it as implied in the percentage contrast, which is the brightness-difference between the ground and the object referred to the former as the base. The brightness of ground and the brightness of object are therefore completely stated by implication in the two variables used:—percentage brightness-difference or contrast; and brightness-level. The former already appears as the ordinate in Fig. 3, while the different brightness-levels are indicated by the three separate curves. These three may be imagined as plotted in different planes in the third (depth) dimension in which case (using logarithm of brightness-level as the corresponding coördinate) the plot comes to look like the

FIG. 4*a*.

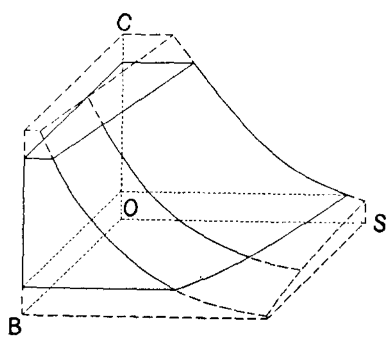
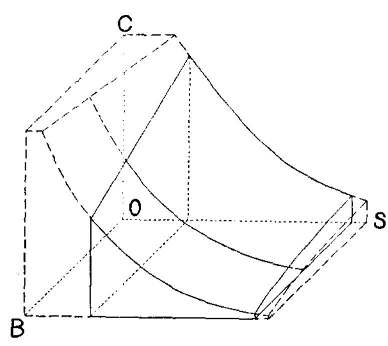


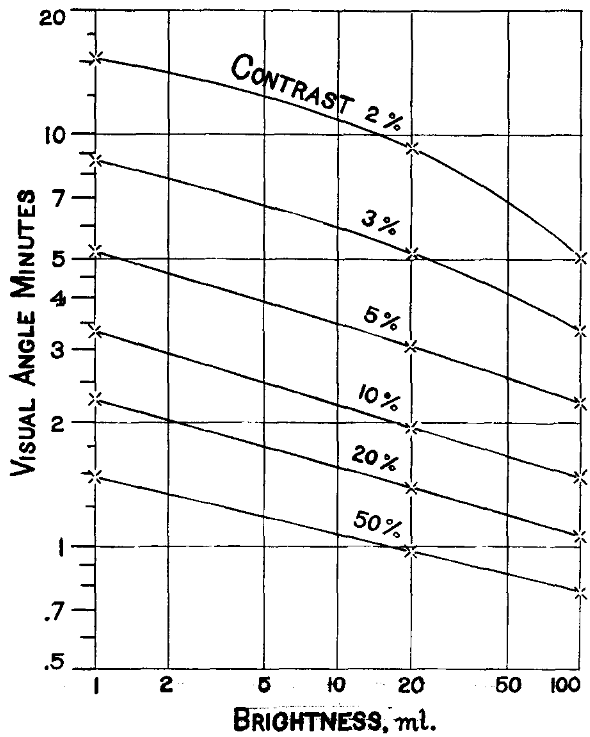

FIG. 4*b*.




The general form of the surface in which lie the data for 0.170 sec. exposure-time. *a*, indicating the relation to the whole of the curves of Fig. 5. *b*, the same, Fig. 6.

solid figure represented by (full and) broken lines in Figs. 4*a* and 4*b*, the curved surface of which represents the threshold condition for vision in terms of three variables:—visual angle (left to right), percentage contrast (vertically) and brightness-level (from behind forward), for a constant time of exposure of 170 $\sigma$. This surface can be conceived as raised or lowered, as the time is decreased to 75 $\sigma$ or increased to 300 $\sigma$, to the extent indicated by the corresponding data stated in Tables IV and V, and plotted in Fig. 3.

FIG. 5.

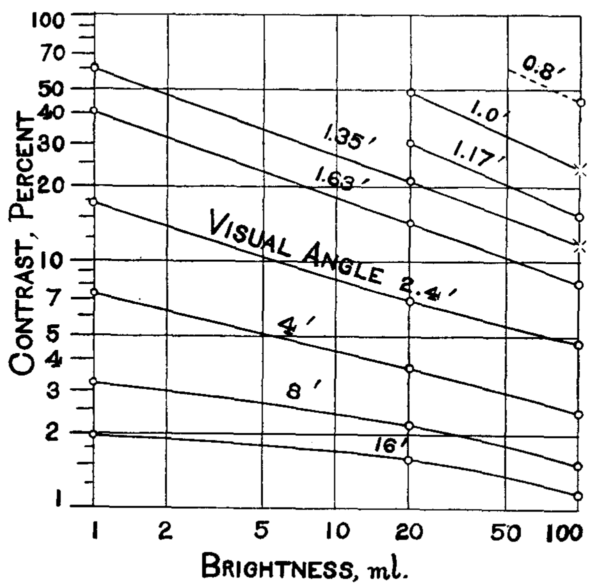



The visual angle-brightness relation for various grades of contrast between the test-object and its ground. Exposure-time 0.170 sec.

In Fig. 5, the angular size of the test-object is plotted, against brightness-level as the abscissa, with separate curves for various grades of contrast. The values plotted are graphically interpolated from Fig. 3, and the separate curves are successive horizontal sections of the curved surface, projected on the horizontal plane, of which the extreme ones are shown in Fig. 4*a* in solid lines. The marked curvature shown in the plot for the contrast-values of 2 and 3 per cent. as opposed to the comparative straightness of the other curves, corresponds to the deviation of the curve for 1 ml. brightness referred to in discussing Fig. 3.

In Fig. 6, the original data are again plotted with brightness-level as the abscissa. The ordinates are the mean contrast values of Tables I, II, and III, and a separate curve is plotted for each size of test-object used. Here the curves are to be looked upon as vertical sections of the

FIG. 6.




Contrast-brightness relation for objects seen under various visual angles. Exposure-time 0.170 sec.

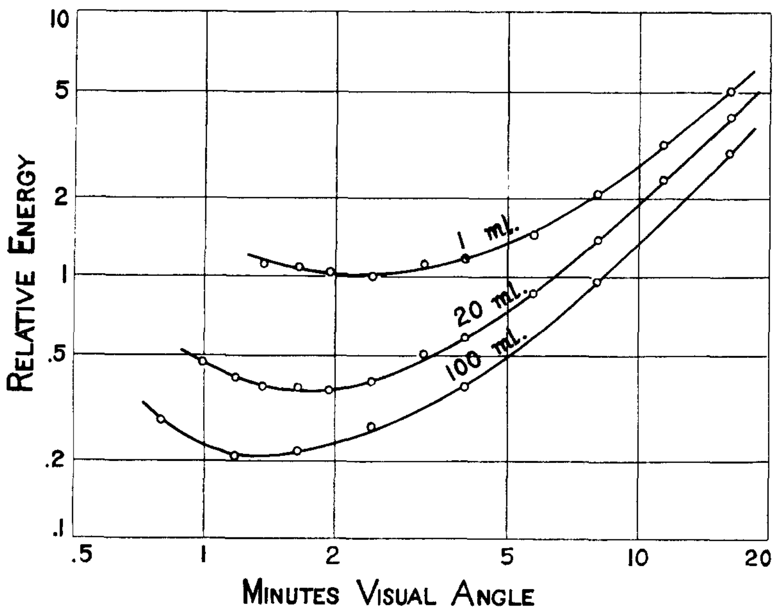
surface, as indicated in Fig. 4*b*, parallel to and projected on the *CB* plane. Corresponding to the deviation of the 1 ml. curve of Fig. 3 from the other two, we note again from Fig. 6 that the curves for the 8′ and the 16′ test-object curve strongly downward, while the other curves are not far from straight.

The range of time used, 75 to 300 $\sigma$, was selected as representing what previous work has shown to be about the normal range of pause in the eye-movements in the familiar operation of reading, in which the eyes move rather rapidly and do not linger unduly in fixation upon any point. The aim has been to extend the range of the other three variables of the visual object, contrast, size and brightness-level, and to establish their relationships beyond the range used in any prior work. All of these variables have been investigated in their various phases, sometimes over wide ranges, as for example, the work of Koenig on visual acuity and on brightness discrimination. Other earlier work has largely been comparatively fragmentary, extending over restricted ranges only, and has been done with various techniques which make the results non-intercomparable. The intermediate gaps have never been filled, nor the whole result stated as a function of three or more variables.

The variations in the size of the visual object, with variations in contrast and brightness-level, depend upon more than one physiological factor. First to be considered is the geometric fidelity of the retinal image to the object from which it arises. This depends upon the perfectness of the refractive apparatus of the eye, in more ways than one. The irregularities of the refracting surfaces, their so-called spherical aberration, and the chromatic errors of the eye play a part. The size of the pupillary aperture, which is undoubtedly different at different brightness-levels, works in two ways: a larger pupil admits the refractive errors of the eye to a greater degree of effectiveness; while, on the other hand, a smaller pupil tends to blur the retinal image by reason of diffraction at the pupillary margin. One of the authors has been able to show, however, that with eyes of normal refractive power, these opposing tendencies just about balance each other, so that the acuity of vision is just about constant, provided the pupillary diameter remains within a range of 2.5 to 4 mm. as observed from the exterior of the eye. As that range represents the usual diameter of the pupil, under ordinary working intensities of light, it is doubtful if we need look for much variation from this cause, except that the pupil tends somewhat, by its variations, to counteract the differences in brightness-level.

At any rate, the degree of blurring of a retinal image which still permits an object to be seen in details separated by as little as one minute of visual angle, must become less and less significant as the extent of the object is increased, up to sixteen times this. In this region a different effect comes into play, namely, the interaction of the retinal end-organs. The fact that decreased brightness-difference may be compensated by increased size of the retinal image may no longer be explained by the hypothesis that the image is becoming relatively better defined, as in the case of the smallest objects. It is rather to be supposed that the retinal elements reinforce one another, so that the participation of a larger number, as the area increases, accomplishes the same result as before with a smaller stimulation of each element. Such reinforcement could be said to fail completely, if a point were reached at which further increase in the size of the object failed to decrease the contrast necessary for the threshold; but this condition was never reached within the limits of the present experimental range.

FIG. 7.




Energy of the test-object at the threshold, relative to brightness-level, at the three brightness levels used. Exposure-time 0.170 sec.

The relative energies involved at the threshold values of the stimulus are indicated in Fig. 7. The energy is negative, it is to be remarked, since the stimulus is of lower brightness than the field as a whole, and in each curve, the unit plotted is the energy received by the eye, during the exposure time of 0.170 seconds, from a square element of the background subtending 1 minute angle at the eye, and having the brightness of the screen. The minima of energy estimated from the curves in the figure, for 1, 20 and 100 ml. brightness-level, occur when the visual angle subtended by the object is 2.2, 1.8, and 1.3 minutes respectively, and are 1.00, 0.37 and 0.21 units referred to the respective brightness-levels as just indicated. When referred to a screen brightness of 1 ml. as the unit, these values become 1.00, 7.4 and 21 units respectively. Thus the minimal energy-value at 100 ml. is 21 times that at 1 ml., although relatively to the brightness to which the eye is attuned it is only 1/5 as great at the higher level as it is at the lower.

SUMMARY.

1. There are at least four variables which enter into the description of any visual object. Essentially, two of these are photometric, the brightness of the object and that of its ground respectively. The third is the size of the object, expressed in visual angle, and the fourth is the time during which the image of the object acts upon the retina.

2. These may conveniently be expressed as: (*a*) the brightness-level, closely approximated by the brightness of the background upon which a darker object is exposed when at its threshold value; (*b*) the contrast-ratio, which is the ratio of the difference between these two, to the background-brightness; (*c*) the visual angle under which the object is seen and (*d*) the exposure-time.

3. The aim of this work has been to investigate the interrelations of these, by a uniform method over wider ranges than has previously been done.

4. In general, within the limits of 1 to 100 ml. brightness, 0.8 to 16.0 minutes visual angle and 0.075 to 0.300 seconds exposure-time, measurements of the contrast-ratio necessary for vision at the threshold indicate that these four variables are mutually complementary; that is, a deficiency in one may be compensated by the augmentation of one or more of the other three.

5. The comparatively small advantage of increased brightness in the vision of large, low-contrast objects, obtained by

passing from 1 to 10 ml., would suggest that the optimum brightness for this phase of vision lies at a higher level than for the vision of small, high-contrast objects.

6. Taking the size (visual angle) of the test-stimulus into account, and the contrast-ratio, it is possible to compute relative energy values for the different conditions. At each of the three brightness-levels investigated, it was found that the energy-value passed through a minimum. At 1, 20 and 100 ml. respectively, the minimum occurred when the visual angle was 2.2, 1.8 and 1.3 minutes. The minimum energy is much greater at the higher brightness-levels, but by no means in proportion.