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THE PHYSICAL REVIEW.

THE BRIGHTNESS SENSIBILITY OF THE RETINA.[1]

BY JULIAN BLANCHARD.

THE eye is able to perceive with ease and comfort a very wide range of light intensities, a range extending over a billion times. It is able to do this because the sensibility of the retina automatically adjusts itself to the stimulus applied, its action being analogous to that of such a physical instrument as a galvanometer with a continuously variable shunt. In this analogy the current through the galvanometer corresponds to the light flux, the scale reading to the brightness sensation produced by the light and the derivative of the scale reading with respect to the current to the sensibility of the retina. The sensation of course cannot be measured directly, but it can be relatively determined by getting a measure of the sensibility at the corresponding stimulus. Since the sensibility is the derivative of the sensation, or scale reading, with respect to the stimulus, the sensation is conversely the integral of the sensibility with respect to the stimulus.

When light falls upon the retina the sensation produced depends upon a number of variables. It is a function of the intensity of the light flux, the length of time it has been acting (before equilibrium is reached), the wave-length, the area and part of the retina affected and the physiological condition of the eye determined by its previous treatment. It would be a difficult matter to determine this general brightness sensation function, but by holding certain factors constant it is easy to obtain a number of limited relations.

The principal object of this investigation is to measure the brightness sensibility of the retina under certain definite conditions. There are three different ways of doing this, or rather three different sorts of sensibility, which are as follows: (1) *Threshold Sensibility*: This is measured by the least brightness that the eye can see. It is proportional to the reciprocal of the least perceptible brightness instantaneously

[1] Communication No. 45 from the Research Laboratory of the Eastman Kodak Company.

substituted for that at which the sensibility is desired and to which the eye has been previously adapted. (2) *Contrast Sensibility*: This is sensibility to brightness difference, or contrast, and is sometimes called photometric sensibility. The reciprocal of the least perceptible difference in brightness between two adjacent fields is taken as proportional to the sensibility at the brightness being used. Of the same nature as this is flicker sensibility, but this will not be considered. (3) *Glare Sensibility*: This is measured by the reciprocal of the brightness that just appears glaring with the eye previously adapted to any given field brightness. It gives an indication of the ability of the retina to stand an overload.

In this paper data will be given on each of these different kinds of sensibility, on the rate of dark adaptation, and on the equilibrium size of the pupil for different field brightnesses.

The literature on visual sensitometry is extremely varied and is too extensive to be reviewed here. Some of the best work that has been done on contrast sensibility is that of König and Brodhun,[1] while Nagel and his pupils[2] have made use of the threshold method in various ways, particularly in measuring the rate of adaptation. In this laboratory Dr. P. G. Nutting has used the threshold method in an improved manner and some preliminary results have been published.[3] In the present work both the contrast and threshold methods are used with the Nutting type of sensitometer.

Apparatus. Method of Measurement.

The apparatus used in these experiments is the same as that described by Nutting[4] with some alterations. It may be called a visual sensitometer. It consists of a matte white board B (Fig. 1) about 60 cm. square with an opal glass window T in the center, 3 cm. square, which is illuminated from behind to any desired intensity. For this purpose there is a Nernst filament N focused by a lens L on a slit S, and sliding in metal ways over this slit is an accurately calibrated absorbing wedge W for controlling the intensity. This small square is termed the test spot. Means are provided for moving the wedge by the observer sitting in

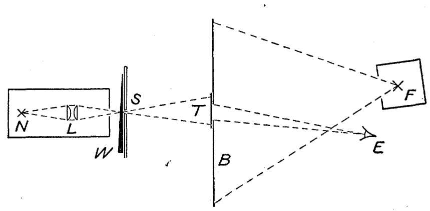

Fig. 1.
The Visual Sensitometer.

[1] A. König, Ges. Abh., pp. 115, 135.
[2] Cf. Helmholtz, Phys. Optik, 3d Ed., Vol. 2, p. 264.
[3] Trans. Ill. Eng. Soc., Vol. 11, p. 1.
[4] Loc. cit.

front of the board and for recording its position. The board is illuminated to any desired intensity by means of a lamp F inclosed in a box to the rear of the observer, the illumination being altered in steps by means of neutrally dyed gelatine filters of known transmission placed over the opening in the box. This is called the sensitizing field, or the pre-adaptation field. When using high candle power lamps which glow for a considerable time after the current is cut off, the field was darkened by operating a moving curtain camera shutter in the opening of the box.

The wedge W was made by coating a plate of plane glass with a thin layer of neutrally dyed gelatine uniformly increasing in thickness from one end towards the other. Two such wedges, separately calibrated, were placed together with the gelatine faces inside to avoid injury. The density increased from 0.95 one centimeter from the thin end by about 0.4 per centimeter of length, the calibration being carried to a density of 7.5. (Optical density is defined as the logarithm of the opacity, or the logarithm of the reciprocal of the transmission.) The calibration of the wedge for white light is given in Table I. Although very nearly

TABLE I.

Calibration of Absorbing Wedge.

Cm.	1	2	3	4	5	6	7	8	9
Density	0.95	1.36	1.77	2.16	2.59	3.02	3.46	3.92	4.39
Cm.				10	11	12	13	14	15
Density				4.86	5.34	5.85	6.33	6.85	7.43

non-selective it was not exactly so and it was therefore calibrated for each of the colors used.

In making an observation on threshold sensibility the procedure is as follows. The eye at E, 35 cm. in front of the test spot, is fully adapted to the sensitizing field being used, the field is flashed off and by repeated trials the wedge is set so that the test spot is just visible immediately after extinguishing the field. Or if the threshold is desired at any subsequent time the wedge is moved along so that the test spot is just visible all the while, the position of the wedge being recorded at definite intervals of time as marked off by a sounder. In order to make the determination of the instantaneous threshold easier a white card was held in front of the test spot and at the instant of extinguishing the field this was quickly moved away and back again, giving an exposure of a small fraction of a second in which to decide whether or not the spot was visible. The brightness of the field and of the test spot was measured by means of a portable brightness photometer (modified Beck "lumeter"), recalibrated to read directly in millilamberts over a range from 0.02 to 2 and provided with decimal filters for reading as high as 2,000 ml. The very small intensities, below the range of the instrument, were calculated from the known density of absorbing screen used to cut down a measured higher intensity. In order to obtain the highest field brightnesses the lamp F was focused on a small region around the test spot and viewed through a bright tin-lined tube to enlarge the field of brightness. Since this necessitated using only one eye the other measurements were also made with monocular vision.

In all of this work the unit of brightness used is the "lambert," or millilambert, which is 0.001 lambert. It has been officially adopted by the Illuminating Engineering Society and is defined in the 1915 Report of the Committee on Nomenclature and Standards[1] as "the brightness of a perfectly diffusing surface radiating or reflecting one lumen per square centimeter," that is, in accordance with Lambert's cosine law. A perfectly diffusing surface emitting one lumen per square foot will have a brightness of one foot-candle, which is equal to 1.076 millilamberts. A brightness of ten meter-candles is equal to one millilambert. The lambert is to be preferred as a unit of brightness since the foot-candle and the meter-candle are also generally used as units of illumination.

Threshold Sensibility.

In the manner described above the instantaneous threshold was

Table II.

Instantaneous Threshold for Different Field Brightnesses.
All values are in millilamberts.

White.		Blue.		Green.		Yellow.		Red.	
Log B.	Log T.	Log B.	Log T.	Log B.	Log T.	Log B.	Log T.	Log B.	Log T.
− 6.15	− 5.85	− 7.26	− 6.72	− 6.85	− 6.40	− 5.70	− 5.35	− 4.83	− 4.26
− 5.95	− 5.80	− 6.96	− 6.66	− 6.60	− 6.35	− 5.45	− 5.33	− 4.68	− 4.20
− 5.80	− 5.72	− 6.61	− 6.61	− 6.31	− 6.32	− 5.28	− 5.23	− 4.36	− 4.08
− 5.65	− 5.73	− 6.26	− 6.49	− 6.02	− 6.22	− 4.98	− 5.17	− 4.06	− 4.01
− 5.35	− 5.60	− 5.72	− 6.24	− 5.12	− 5.65	− 4.65	− 5.00	− 3.48	− 3.74
− 5.05	− 5.44	− 4.77	− 5.69	− 4.20	− 5.18	− 3.70	− 4.40	− 2.92	− 3.42
− 4.15	− 4.92	− 3.87	− 5.01	− 3.30	− 4.56	− 2.70	− 3.93	− 2.26	− 3.10
− 3.20	− 4.35	− 2.92	− 4.17	− 2.40	− 3.95	− 2.20	− 3.50	− 1.40	− 2.60
− 2.30	− 3.52	− 2.11	− 3.56	− 1.57	− 3.05	− 1.75	− 3.15	− 0.80	− 2.40
− 1.35	− 2.80	− 1.71	− 3.26	− 1.24	− 2.72	− 1.15	− 2.70	− 0.18	− 2.00
− 0.40	− 2.28	− 1.11	− 2.76	− 0.67	− 2.33	− 0.17	− 2.12	0.37	− 1.70
0.55	− 1.75	− 0.58	− 2.39	0.26	− 1.98	0.10	− 1.90	1.00	− 1.37
1.50	− 1.02	− 0.18	− 2.29	1.03	− 1.64	0.80	− 1.75	1.30	− 1.33
2.00	− 0.75	0.42	− 2.01	1.32	− 1.50	1.10	− 1.52	1.56	− 1.12
2.40	− 0.37	0.66	− 1.86	1.62	− 1.20	1.41	− 1.25	1.81	− 0.97
2.97	0.29	0.97	− 1.61	1.91	− 0.93			2.12	− 0.78
3.30	0.71	1.34	− 1.36						

[1] Trans. Ill. Eng. Soc., Vol. 10, 1915, p. 642.

determined for fields varying in brightness from the highest obtainable (about 2 lamberts for white) down to the threshold itself, with white light and with blue, green, yellow and red. The data are given in Table II. and the curves in Figs. 2 and 6. On account of the great range of values involved it is necessary to plot logarithms of the variables. It is to be noted that − log threshold is proportional to log sensibility, since the reciprocal of the threshold is taken as proportional to sensibility. In Fig. 2 the individual points determining the curves are omitted to avoid

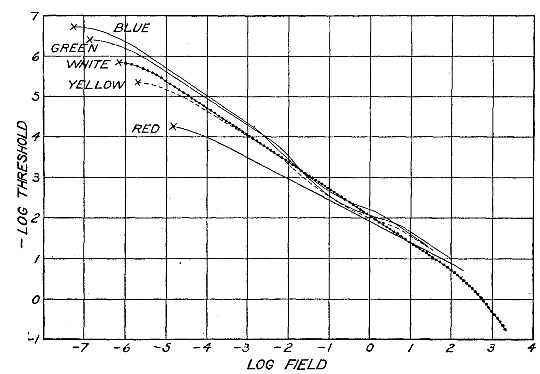

Fig. 2.

Threshold Sensibility for Different Colors.

confusion. The deviations from the smooth curves are no greater than for white light shown in Fig. 6.

The data given are the average of results obtained on three different days, in most cases with several days intervening. In beginning a run it was customary to remain first in darkness about thirty minutes in order to bring the eye into about the same initial condition each time. Observations were made at the threshold first, proceeding to gradually higher intensities, the eye being adapted to each brightness for several minutes before threshold observations were made.

In order to express the results consistently in the same unit of brightness it is necessary to take into account the Purkinje phenomenon. If two fields of different color are illuminated to the same apparent brightness and both cut down by equal amounts the brightness will not decrease in the same ratio. For example, red will grow darker much faster than blue. But at very low intensities it is impossible to measure brightness by any photometric means, and without having a definite measure of the Purkinje effect for the different colors the only feasible way of expressing relative intensities is in fractions of a certain measured intensity above the brightness at which the effect sets in. In these experiments all the colors were measured photometrically at a brightness of 10 millilamberts, which is safely above the Purkinje effect, and the lower intensities calculated from a knowledge of the filter densities.

In working with the colors both the test spot and the field were colored. These colors were obtained by using filters over the corresponding light sources. The filters were chosen to give a fairly narrow spectral band without having too great a density and their transmission-wave-length curves are given in Fig. 3. In the case of yellow the ordinates have been multiplied by ten. For this color it was necessary to combine two filters, resulting in a rather high density.

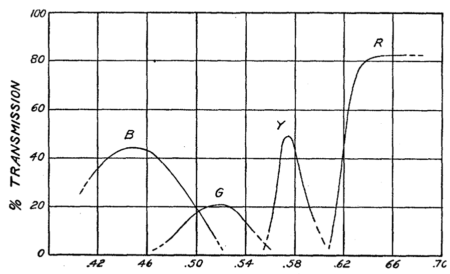

Fig. 3.

Relative Transmission of Color Filters.

The curve for white light is seen to be practically a straight line with the exception of the extreme intensities and may be represented over this portion by the equation,

$$\frac{T}{B} = \left(\frac{B}{B_0}\right)^{-n},$$

in which T is the test spot threshold for any field brightness B, B_0 the absolute field threshold and n a constant. From this, when $B = B_0$ the threshold T is equal to the field itself, although as seen from the curve the test spot threshold is greater than B_0. The reason for this is that the area of the test spot was smaller than the field and the peripheral regions of the retina are more sensitive than the foveal. The angular size of the fovea is between 2 and 3 degrees and the test spot subtended an angle of approximately 5 degrees. If the straight line is extended it will pass through the point where T is equal to the observed B_0.

The lower part of the curve begins to bend at about 100 ml. and in a region between this point and about 2,000 ml., that is, corresponding to bright interiors and outdoor daylight, the curve has a slope equal to unity, which means a constant, and minimum, ratio of T to B over this region. This is analogous to the well-known Fechner constant in contrast sensibility, in that case the least perceptible difference being a nearly constant fraction of the intensity over a much wider range of moderate and high intensities. (At the threshold this fraction is equal to unity and the minimum value is about 0.0175, which is Fechner's constant.) Beyond this region the ratio rises again and at blinding intensities it would approach unity, that is the instantaneous threshold would be equal to the sensitizing field itself, just as at the other end of the curve.

The equation may be written, taking logs,

$$\log T = (1 - n) \log B + n \log B_0,$$

so that n can be easily determined from the slope of the line. The value of n for white light is here equal to 0.33. The other constants are $B_0 = 0.00000071$ ml. (minimum field threshold), $T_0 = 0.0000014$ ml. (minimum test spot threshold), minimum $T/B = 0.0017$ (about one tenth the Fechner constant).

This curve shows at a glance the very wide range over which the eye can operate and the enormous change in its sensibility. The present experiments cover a range roughly from 10^{-6} to 10^3 millilamberts, one billion times, and over this range the sensibility as measured by the instantaneous threshold changes more than a million times.

The curves for the different colors are very similar to that for white, the instantaneous thresholds being nearly equal for moderate brightnesses and diverging most for the lowest brightnesses. This is apparently another manifestation of the Purkinje effect, the threshold being least for red and greatest for blue as measured by fractions of the same high intensity. All the color curves except red show a decided dip, indicating a depression of sensibility, in a region roughly between 0.01 and 1 ml., a region corresponding to about the average range of interior brightnesses at night.

For convenience of reference the four principal brightness levels that are encountered are indicated by the crosses in Figs. 5 and 6. These are exteriors at night, 0.001 ml., interiors at night, 0.1 ml., interiors in daylight, 10 ml., and exteriors in daylight, 1,000 ml. These are of course merely rough averages, each lower level being one per cent. of the next higher.

Contrast Sensibility.

The least difference in brightness between two fields that the eye can perceive depends not only upon the brightness of the fields but also upon such factors as their areas and configuration, the previous adaptation of the eye and the time of adaptation to the fields contrasted. With the visual sensitometer contrast sensibility is easily measured with these factors under control. In the experiments as carried out the two fields were obtained by covering the upper half of the test square previously described with a strip of neutral gray gelatine of a certain density, thus affording a fixed contrast between this and the lower half depending upon the transmission of the film. The method of procedure is to adapt the eye to a certain sensitizing field brightness, flash off the field and then by moving the wedge adjust the test spot brightness until the difference between the two halves is just perceptible after any time desired. In this way time-contrast curves for white light were obtained for several different contrasts, the results appearing in Table III. and

Table III.

Time and Brightness to Detect Fixed Contrasts.

Eye initially adapted to 0.1 ml.
Values are log brightness of brighter field, in millilamberts.

Contrast..........	.0.	.39.	.67.	.87.	.97.
0 seconds........	− 2.80	− 2.63	− 2.40	− 2.10	− 1.20
1 "	− 3.47	− 3.36	− 3.00	− 2.46	− 1.57
2 "	− 3.82	− 3.58	− 3.13	− 2.49	− 1.67
5 "	− 4.30	− 3.74	− 3.22	− 2.48	− 1.69
10 "	− 4.49	− 3.85	− 3.21	− 2.55	− 1.59
20 "	− 4.60	− 3.97	− 3.33	− 2.54	− 1.63
40 "	− 4.89	− 4.06	− 3.46	− 2.67	− 1.73
60 "	− 5.03	− 4.23	− 3.48	− 2.73	− 1.78

Fig. 4. The maximum contrast was secured by using an opaque strip, in which case the actual threshold was determined, and the minimum by means of a thin film of clear celluloid having a transmission of approximately 0.97. The size of the fields was 3 cm. × 1.5 cm. viewed at a distance of 35 cm. (5 degrees × 2.5 degrees), and the brightness of sensitizing field was 0.1 ml. One eye only was used, with natural pupil. The curves are plotted with the brighter of the two contrasted fields as ordinates and show at what brightness a given contrast can just be perceived at any time up to one minute after extinguishing the sensitizing field. It is seen that when the contrast is very small the minimum brightness for it to be perceived does not change much with the time after the first few seconds, but with large contrasts the time factor is very important.

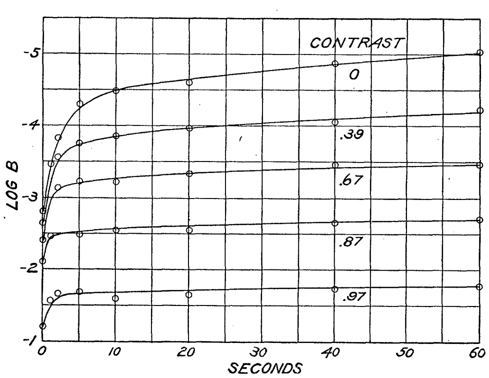

Fig. 4.

Time and Brightness to Detect Fixed Contrasts.

It is easy to obtain from these results the "Fechner fraction," which is the ratio of the least perceptible difference to the brightness at which it is measured. According to Fechner's law this is a constant over a wide range of moderate and high intensities, but it increases for both extremes. The difference has been generally expressed as a fraction of the lower intensity but it seems more logical to include the increment in the denominator of the fraction, since otherwise the ratio at the absolute threshold is meaningless. Theoretically at the threshold the least perceptible difference is the threshold itself, thus making the ratio here equal to unity. This ratio can be obtained from the above results by merely taking a cross-section of the curves at any given time. The Fechner fraction, $\triangle B/B$, is equal to one minus the contrast ratio and this is plotted against the corresponding value of log B, where B is the higher brightness. A series of such curves is given in Fig. 5 for times of 0, 2, 10 and 60 seconds after extinguishing the sensitizing field, which shows very clearly the effect of time of adaptation and brightness on sensibility to contrast.

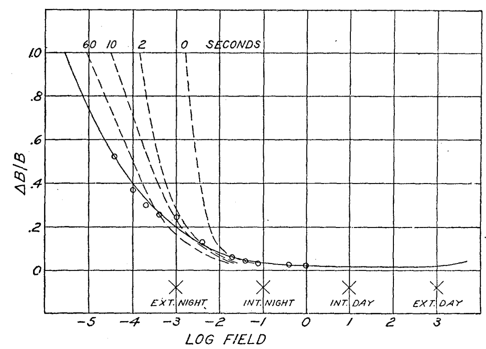

Fig. 5.

Fechner's Fraction.

The Work of König and Brodhun.

König's work (in collaboration with Brodhun) has already been referred to. He determined the least perceptible difference over a very wide range of intensities for white light and for several different wavelengths. His results, however, are deprived of some practical value on account of the uncertainty of his unit of brightness. This he states was the brightness of a magnesium oxide surface illuminated normally by 0.1 sq. cm. of freezing platinum at a distance of one meter and parallel to it. Since this light source is 0.1 the Violle standard, approximately 23 candle power, and since the reflecting power of magnesium oxide is 85 per cent.,[1] this gives as his unit a brightness of 0.20 millilambert. This value, however, is obviously much too high.

For comparison with the results on contrast given above and for obtaining another estimate of König's unit, a partial repetition of his sensibility curve for white light was made on a photometer bench. Two color-matched lamps of about the same candle power were mounted on the bench and by moving the photometer head back and forth the least perceptible difference in brightness between the two halves of the field

[1] Nutting, Jones and Elliott, Trans. Ill. Eng. Soc., Vol. 9, p. 593.

was determined. The low intensities were secured by screening with neutral filters of known density. This is not the same form of apparatus as used by König, although the principle is the same. In his arrangement the contrasted fields were secured by the use of polarized light and crossed nicols. In computing the Fechner fraction König used the ratio of the least difference to the lower intensity and his results have therefore been recalculated using the higher intensity instead, for the reason stated above. His data are given in Table IV., along with the

TABLE IV.

Least Perceptible Difference for Different Field Brightnesses.
All values are in millilamberts.

From König's Data.			Photometer Bench Method.		
Log B.	$\Delta B/B$.	Log ΔB.	Log B.	$\Delta B/B$.	Log ΔB.
3.60	0.0346	2.14	− 0.01	0.021	− 1.69
3.30	.0266	1.72	− 0.41	.025	− 2.01
2.90	.0260	1.31	− 1.11	.032	− 2.60
2.60	.0191	0.88	− 1.41	.042	− 2.79
2.30	.0170	0 53	− 1.71	.060	− 2.93
1.90	.0172	0.14	− 2.41	.131	− 3.29
1.60	.0173	− 0.16	− 3.05	.246	− 3.66
1.30	.0176	− 0.45	− 3.41	.254	− 4.01
0.90	.0178	− 0.85	− 3.71	.302	− 4.23
0.60	.0175	− 1.16	− 4.02	.372	− 4.45
0.30	.0188	− 1.43	− 4.41	.521	− 4.69
− 0.10	.0217	− 1.76			
− 0.40	.0290	− 1.99			
− 0.70	.0314	− 2.20			
− 1.10	.0380	− 2.52			
− 1.40	.0455	− 2.74			
− 1.70	.0560	− 2.95			
− 2.10	.0860	− 3.17			
− 2.40	.110	− 3.36			
− 2.70	.159	− 3.50			
− 3.10	.220	− 3.76			
− 3.40	.274	− 3.96			
− 3.70	.326	− 4.19			
− 4.10	.410	− 4.49			
− 5.54	(1.00)	(− 5.54)			

results of the writer, in millilamberts. The latter are plotted in Fig. 5 as circles, whereas the full line curve is that of König after his values of B have been multiplied by a factor which will bring his curve into as close coincidence as possible with that of the writer. This factor is 0.0040, so that if the contrast sensibility of each observer is approximately the same König's unit of brightness is about 0.0040 millilambert.

König's results were obtained with the eye screened from all light during the test except that of the fields compared, no mention being made of the previous adaptation or the time involved. His contrasted fields were two rectangles, each with apparent sides of 3 degrees and $4\frac{1}{3}$ degrees at the eye, viewed through the natural pupil (presumably, not stated). In the present experiments the fields had apparent sides of 2.5 degrees and 5 degrees, viewed through the natural pupil with the eye continuously screened from all other light, and in the sensitometer the fields were also this size and viewed through the natural pupil. If all conditions are the same the results should be identical with the different forms of apparatus. In Fig. 5 it appears that the sensitometer curves are nearly coincident with the König and photometer bench curves for all adaptation times at the highest intensities used and approach the latter for all intensities as the adaptation time increases. The adaptation time for König's low intensities was probably an hour or more.

As stated in the beginning the reciprocal of the least perceptible brightness difference may be taken as a measure of retinal sensibility (contrast sensibility) and the logarithm of this quantity is plotted in Fig. 6 against the logarithm of the field brightness (the brighter of the two fields). The circles represent the data of König and the crosses the check results of the writer taken on the photometer bench (Table IV.). It is significant that this gives a nearly linear relation of the same general character and range as the threshold method.

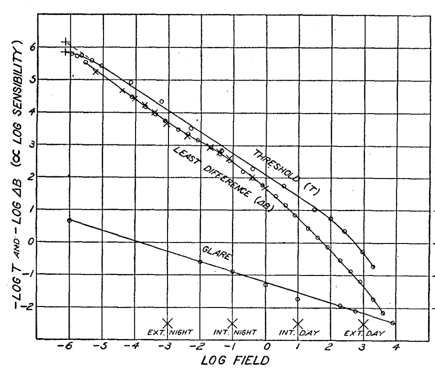

Fig. 6.

Threshold, Contrast and Glare Sensibliity.

Glare Sensibility.

In addition to threshold and contrast sensibility there is a third sort which is not as precisely defined or measured. This is glare sensibility, which is of considerable importance in illuminating engineering. When the eye is adapted to a certain brightness and is then suddenly exposed to a much greater brightness the latter may be called "glaring" if it is uncomfortable and instinctively avoided by the eye. This judgment will naturally depend largely upon the criterion adopted by the observer and different observers may be expected to disagree rather widely. Measurements were made in the following manner with the use of the visual sensitometer. A small mirror was fastened over the test spot so as to reflect into the eye at E (Fig. 1) an image of the opal glass window in the field lighting box F, this constituting the glare source. The angle subtended at the eye by the glare spot was approximately 4.0 degrees. The sensitizing board B was illuminated by means of other lights placed to the rear of the observer. With the eye adapted to a given field brightness the glare lamp F was snapped on and by trial the smallest brightness that was considered glaring was determined. With this apparatus measurements were made with fields from the threshold up to 200 ml. and the highest fields and glare intensities were obtained by using sunlight on white paper and through diffusing window glass with the aid of suitable mirror arrangements. The results of three observers, including the writer, are given in Table V. and the average of all three

TABLE V.

Log Field.	Log Glare.			
	P. R.	P. G. N.	J. B.	Mean.
− 6.0	1.45	0.78	1.81	1.35
− 2.0	2.64	2.65	2.50	2.60
− 1.0	2.74	2.78	3.18	2.90
0.0	3.30	3.30	3.30	3.30
1.0	3.70	3.76	3.62	3.72
2.30	3.87	3.85	4.00	3.91
2.76	4.09	4.11	4.06	4.09
3.91	4.18	4.16	5.02	4.45

plotted in Fig. 6, using the logarithms of the variables. It is seen that the curve is a straight line, the upper limit of which will naturally be where the field is equal to the glare itself. The relation may be represented by the equation

$$\log G = a \log B + \log c,$$

or

$$G = cB^a,$$

where G represents the glare brightness, B the field brightness, and a and c are constants. For the conditions here used $a = 0.32$, $c = 1{,}700$, so that for a given field brightness the brightness of a small area, such as a lamp globe or reflector, which will be considered glaring in the sense here defined may be roughly calculated by taking the cube root of the field brightness and multiplying by 1,700. It is to be expected that with a larger area a smaller brightness would be considered glaring, although no measurements were attempted with different areas.

The curves for the three different kinds of sensibilities are given for comparison in Fig. 6, the negative logarithms of the threshold, least difference and glare being plotted as ordinates since they are proportional to the logarithm of the respective sensibilities. It is observed that although the threshold and contrast methods give very similar results the range of sensibility by the glare method is very much smaller, being only about one thousand times. The latter is essentially different in nature from the other two, being based on a maximal reaction, whereas the former are both based on minimal reactions.

Rate of Adaptation.

The rate at which the eye increases in sensibility on going from light to darkness (dark adaptation) has been studied by Nagel and others.[1] In his experiments the observer entered a dark room from a daylight exterior and noted the time required to just see a given brightness. With the apparatus here employed it is possible to make measurements from the very instant of turning out the field light and it is easier to work under definite conditions. In these experiments the eye was adapted to a given sensitizing field and by adjusting the wedge the threshold was determined at the instant of turning off the field and at intervals of a

Table VI.

Rate of Dark Adaptation.

Values are − log threshold, in millilamberts.

Sensitizing Field, Ml.	White				Blue.	Green.	Yellow.	Red.
	0.1.	1.0.	10.	100.	0.1.			
0 secs.	2.79	2.20	1.60	0.90	2.82	2.69	2.61	2.32
1 "	3.82	2.99	2.30	1.66	3.92	4.08	3.84	2.69
2 "	4.13	3.27	2.53	2.00	4.36	4.39	4.17	2.98
5 "	4.50	3.79	3.08	2.46	4.91	4.82	4.41	3.37
10 "	4.75	4.15	3.54	2.64	5.27	5.11	4.65	3.57
20 "	4.96	4.51	3.94	2.88	5.53	5.26	4.78	3.65
40 "	5.16	4.82	4.31	3.20	5.68	5.43	5.02	3.73
60 "	5.32	5.06	4.61	3.84	5.81	5.56	5.09	3.80
2 mins.	5.52	5.22	4.83	4.12	6.00	5.70	5.24	3.92
5 "	5.68	5.52	5.22	4.76	6.23	5.80	5.39	4.02
10 "	5.70	5.68	5.59	5.38				
20 "	5.80	5.81	5.76	5.60				
30 "	5.91	5.86	5.83	5.77				
40 "	6.01	5.97	5.91	5.82				
50 "	5.98	6.02	5.94	5.90				
60 "	6.06	6.04	6.01	5.97				

[1] Op. cit.

few seconds or minutes thereafter. Results for white light with sensitizing fields of 0.1, 1, 10, and 100 ml., up to one hour's dark adaptation, are given in Table VI. and the curves in Fig. 7. Observations were made

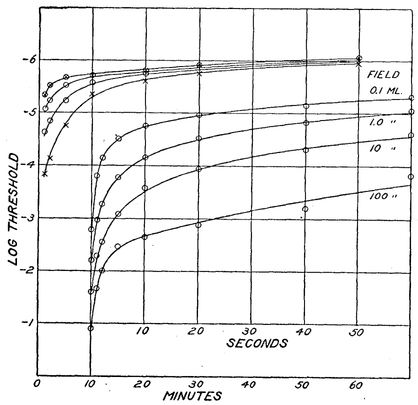

Fig. 7.

Rate of Dark Adaptation, White Light.

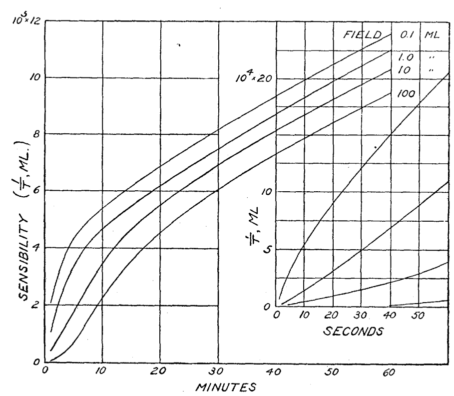

Fig. 8.

Rate of Dark Adaptation, White Light.

in this case with both eyes, natural pupil, test spot 3 cm. square at 35 cm. (visual angle 4.9 degrees). The results are the average of a number of trials made on different days.

In Fig. 7 are plotted the logarithms of the threshold values and these curves show therefore the geometrical increase in the sensibility. The way in which the actual change occurs may be seen better in Fig. 8, where the reciprocal of the threshold, which is proportional to the sensibility, is plotted against the time, these values being taken from the smooth curves in Fig. 7. During the first minute of darkness the sensibility is rather small compared with the total rise and this period is shown on a larger scale in the inserted set of curves. It is seen that when the pre-adaptation field brightness is small the initial rise in sensibility is quite rapid, but with increasing field brightnesses the rise is more and more delayed. The sensibility is still increasing at the end of an hour and continues to rise slightly for several hours. The curves for all brightnesses of course eventually merge into one another.

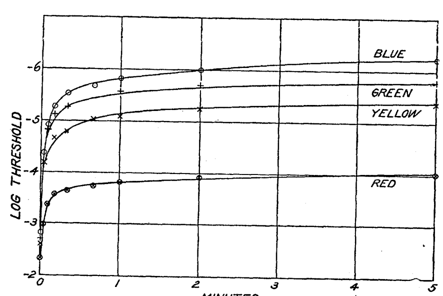

Fig. 9.

Rate of Dark Adaptation, Different Colors.

Similar adaptation curves for a period of five minutes only were taken for the colors blue, green, yellow and red, using the filters previously described. The results are shown in Table VI. and Fig. 9. The sensitizing field was the same color as the test spot and the brightness 0.1 ml. In each case. It is observed that the rise in sensibility is greatest and most rapid for blue and green, which are nearly equal, with red considerably lower and yellow intermediate. The threshold brightnesses in this series were all calculated from the wedge densities necessary to cut down an initial test spot brightness of 0.1 ml., as balanced against white, at which brightness the Purkinje effect is present to some extent.

Size of Pupil.

The amount of light flux falling upon the retina is directly proportiona to the area of the pupil, which in turn depends upon the brightness to which the eye is exposed. When in bright sunlight the pupil contracts as much as possible to protect the retina from the excessive brightness, and as the brightness diminishes it gradually enlarges and reaches a maximum in complete darkness. The average range is approximately from 2 to 8 millimeters. Several pupillometers have been devised for measuring the diameter but none of them are applicable for all brightnesses, especially for very low intensities. In order to determine the diameter throughout its entire range the method of flashlight photography was used. A large white cardboard was fastened in front of the camera with a hole in the center for the lens. The subject sitting in front of this was adapted to any brightness desired by means of a flood lamp to the rear, such as that used at F in Fig. 1. An extra long bellows camera was used so that with the subject close up an enlarged picture of the eye could be obtained, and a chin rest was used to keep the eye in focus. After adapting to the given brightness for at least five minutes the shutter was opened by an assistant and immediately the flash set off and the shutter quickly closed again. A white paper scale stuck on the face in the plane of and close to the pupil enabled the diameter to be accurately measured with the help of a pair of dividers. For the highest brightness used the whole apparatus was moved out of doors. With moderately bright sunlight on white paper a brightness of 2 lamberts was obtained, which is beyond the brightness which the eye can steadily view without discomfort.

When measuring the diameter of the pupil for any brightness it is necessary to take into account whether one or both eyes are open. If for instance the right pupil is being measured this will expand immediately upon closing the left eye and contract when it is opened again. When the left eye is closed it becomes dark adapted with a consequent expansion of the pupil and the right pupil sympathetically changes in the same direction and thus admits more light. This well-known effect can easily be observed by watching one's eye in a mirror as the other is suddenly opened and closed, the effect being most marked at moderate intensities. A series of measurements under both these conditions is

TABLE VII.

Diameter of Pupil.

Field Brightness, Ml.	Diam., Mm.	
	Both Eyes Open.	One Eye Closed.
0.0	7.4	7.5
0.00015	7.15	7.25
0.01	6.7	7.2
0.6	5.3	6.5
6.3	4.1	5.7
126.	2.6	3.3
355.	2.3	2.9
2,000.	2.0	2.0

given in Table VII. and the curves shown in Fig. 10. The two curves are practically coincident at both extremes and diverge most for brightnesses between 1 and 10 ml., the difference in this region being nearly 1.5 mm.

It is to be noted that the pupil thus measured is not the actual pupil but its image formed by the refracting media in front of it. The iris lies just in front of the lens, and since with different degrees of accommodation the refraction is altered on account of the change of curvature and displacement of the lens, the size of the image of the pupil changes with accommodation. For the eye accommodated to 25 cm. the ratio of the diameters of the image and actual pupil is 1.02, for the unaccommodated eye it is 1.14.[1] In the photographic experiments the white field viewed was about 35 cm. in front of the eye, so

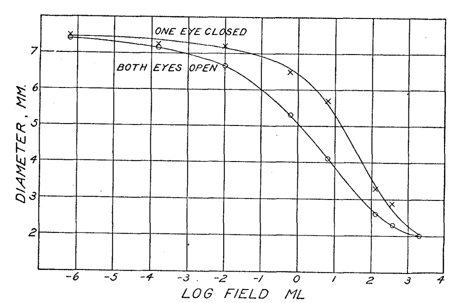

Fig. 10.

Diameter of Pupil for Different Field Brightnesses.

[1] See Helmholtz, Phys. Optik, 3d Ed., and P. G. Nutting, Outlines of Applied Optics, p. 117.

that the size of the pupil image thus measured may be taken as equal to that of the pupil itself, this error being less than that of diameter measurements.

The diameter of the dark adapted pupil varies to some extent with different individuals. Steavenson[1] gives 8.5 mm. as the average of five subjects measured by him by the flashlight method. The limits of the writer are approximately 2 and 7.5 mm. The pupil is also constantly fluctuating over a small range even when the eye is subjected to a fixed brightness. Arrangements are being made to study these variations as well as the rate of opening and closing of the pupil when changing from one brightness level to another by taking a series of pictures with a motion picture camera.[2]

Since the range in diameter of the pupil is roughly from 2 to 8 mm., the ratio of the areas, and consequently the flux upon the retina, is 1 to 16. This means that from the highest endurable brightness to darkness the threshold sensibility increases about 16 times merely on account of the enlargement of the pupil. It has been seen that the total rise in sensibility is more than a million times, so that the increase due to pupil expansion is rather small in comparison with that due to processes going on in the retina itself.

The Flux Density at the Retina.

It is of interest to know the actual flux density at the retina for any given brightness viewed and corresponding size of pupil. This may be approximately calculated as follows.

Consider a small surface of area a_0 sq. mm. normal to the axis of the eye at a distance of u mm. and a brightness of I candles per sq. mm. Treating this surface as a point source of a_0I candlepower, the illumination at the pupil will be a_0I/u^2 lumens per sq. mm., and the flux through the pupil, of area S sq. mm., will be a_0IS/u^2 lumens. Since all of this flux falls on an area a_1 on the retina, the image of a_0 (the small absorption of the eye is here neglected), the flux density at the retina will be a_0IS/a_1u^2 lumens per sq. mm. But from geometrical optics we have $a_0/a_1 = u^2n^2/v^2$, where v is the back focal length of the eye and n is the index of refraction of the medium between the lens and the retina. Hence we have for the flux density, E, in lumens per sq. mm.,

$$E = ISn^2/v^2.$$

[1] Jour. British Astron. Assoc., Vol. 26, p. 303.

[2] Since this was written measurements of the dark adapted pupil for eight subjects have been made, the average being about 8 mm., with values ranging from 7 to 8.7 mm. These results, together with the data on rate of opening and closing, will be published shortly.

If the brightness of a_0 is given in millilamberts, B, instead of candles per sq. mm., then, since by definition 1 ml. $= 1/\pi \times 10^{-5}$ candles per sq. mm., we will have

$$E = 1/\pi \times 10^{-5} BSn^2/v^2.$$

Table VIII. gives a series of values of E for corresponding values of

TABLE VIII.

Field, Ml.	Diameter, Mm.		Effective Area.	Lumens per Sq. Mm.
	From Curve.	Effective.		
B.		D.	S.	E.
0.00001	7.30	8.17	52.2	7.0×10^{-12}
0.001	6.97	7.80	47.8	6.4×10^{-10}
0.01	6.65	7.44	43.4	5.8×10^{-9}
0.1	6.00	6.72	35.4	4.7×10^{-8}
1.0	5.06	5.66	25.1	3.3×10^{-7}
10.	3.86	4.32	14.6	1.9×10^{-6}
100.	2.72	3.04	7.25	9.7×10^{-6}
1,000.	2.08	2.32	4.23	5.6×10^{-5}
2,000.	2.00	2.24	3.94	1.1×10^{-4}

B and S, for the case with both eyes open. In the computations n is taken as 1.34, v is 20.7 mm. (focus for distant vision), and S is the area of the pupil image, in computing which the pupil diameters are taken from the smooth curve in Fig. 10 and multiplied by 1.14/1.02, for the reason previously explained.

For a given brightness of surface the value of E, and hence the apparent brightness to the eye, will change only slightly with the distance of the surface from the eye. For in the above expression for the flux density at the retina, on which the apparent brightness depends, E is directly proportional to S/v^2, or to the solid angle subtended at the image on the retina by the pupil image. On changing the accommodation for near and far objects both S and v^2 change only slightly and in the same direction, so that their ratio remains approximately constant. This independence of the so-called natural brightness upon the distance of the object viewed is borne out by experiment.

SUMMARY.

1. Three different kinds of retinal sensibility have been defined and a new form of apparatus for measuring the sensibility, called the visual sensitometer, has been described.

2. Threshold sensibility (the reciprocal of the least brightness perceptible) has been measured over a wide range of field intensities for white, blue, green, yellow and red light, and a linear relation (with exceptions over certain regions) found between log sensibility and log field brightness.

3. Contrast sensibility has been studied with reference to variations in contrast, brightness and time of adaptation. König's work on the least perceptible difference has been repeated over a limited range and his unit of brightness thereby determined to be approximately 0.0040 millilambert. Recalculating his results, the reciprocal of the least perceptible difference, another measure of retinal sensibility, has been plotted as a function of the field brightness. The curve closely resembles that for threshold sensibility.

4. The least brightness that appears glaring has been determined for all field brightnesses and a linear relation found between log glare and log field.

5. The rate of dark adaptation, with different initial sensitizing brightnesses, has been measured from the beginning of adaptation for white, blue, green, yellow and red light, with the natural pupil.

6. The diameter of the pupil has been measured by means of flashlight photography for different field brightnesses throughout its range, both for monocular and binocular vision, the limits for the writer being approximately 2 mm. and 7.5 mm.

7. From the results of the above measurements the flux density at the retina for a given field brightness and corresponding size of pupil has been calculated for the entire range of vision.

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