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THE EFFECT OF ILLUMINATION AND OTHER FACTORS ON THE ACUITY OF VISION

BY

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(1) *The scope of this investigation.*—(*a*) To find test objects and also methods of testing visual acuity which are applicable to a large number of observers simultaneously and which do not cause visual fatigue; (*b*) to ascertain by their means the effect of increasing the illumination on the perception of fine detail by observers with normal sight and also by those with defective vision; (*c*) to ascertain the effect of replacing daylight by artificial light derived from gas-filled lamps giving the same illumination, on the perception of fine detail; (*d*) to ascertain the effect, in the case of gas-filled lamps of replacing continuous light by flickering light giving the same illumination.

(2) *The test objects.*—The capital letters of the alphabet were selected as the principal test objects for two reasons: (*a*) because of the convenience of being able to use 26 designs of recognized shape and name; (*b*) in order to seek confirmation of the results obtained by previous observers, *viz.*: that the letters differ greatly in the ease with which they are recognized.

The capital letters, with one exception, lay inside a rectangle measuring 25 mm. from top to bottom and 20 mm. from side to side. The black lines forming the letters measured 5 mm. across. The exception was "I" which measured 5 mm. by 25 mm. Block letters (Green's tpye), drawn with Indian drawing ink, each on a separate piece of white millboard, were used. Other test objects were also employed :—(*a*) the test type devised by Hay; (*b*) that employed by Snellen; (*c*) the Snellen "E" test; and (*d*) a grating type of test object (Grid test).

(3) *The experimental technique.*—The experimental work was carried out in three ways: (*a*) by ascertaining the number of mistakes made in the recognition of the letters with prolonged observation, the letters subtending at the eye only a small angle (Method I); (*b*) by ascertaining the number of mistakes made with brief observation of letters subtending at the eye a considerable angle (Method II); (*c*) similar to (*a*) with the letters replaced by the Grid test object (Method III).

Method I.—The apparatus consisted of the letters, the light sources and two mirrors, one plane and the other convex. The rays of light on their way from the letters to the observer were reflected first by the plane mirror and then by the convex one. The latter presented a greatly diminished image of the letters to the observer. Thus within the length of a table of 1.8 metres it was possible to imitate the visual angle produced by a distance of 40 metres.

The letters were presented one at a time in an irregular order and the answers of the observers were recorded. In all the experiments the observer's eyes were shielded from the direct rays of the light source and were in adaptation with the intensity of light under investigation. The illumination of the test card was measured with the lumeter during each set of observations.

Method II.—The letters were exposed to the vision of the observer for a brief time interval by means of a tachistoscope. A fixation mark was provided prior to the exposure so that the observer knew where the letter would appear. The duration of the exposure for each individual part of the letter was 0.019 seconds.

Method III.—This was similar to Method I, but a grid test was employed instead of the letters. The grid test was placed so that its lines first made one angle with the horizontal and then another. The observer had to identify their direction correctly. With each illumination investigated the smallest visual angle was ascertained at which the observer reported correctly in more than 50 per cent. of the trials.

(4) *The measurement of the illumination.*—The illumination on the test letters was measured by means of a lumeter which had been calibrated by the National Physical Laboratory. Our best

thanks are due to them for this valuable assistance, and also for the loan of a standard Osram lamp with the aid of which we were able to re-standardize our lumeter from time to time.

The brightnesses quoted throughout this paper are those actually measured on the white cardboard surrounding the test object in use. The results are expressed in equivalent foot-candles.

(5) *The visual acuity of the observers.*—The acuity of the observers was determined by means of several different tests and under various conditions in order that we could have ample data on which to form the division between normal-sighted and defective observers. Tables I and II show that in bright daylight normal sighted observers can attain an acuity exceeding 2 (12/6 on Snellen's standard, the black lines forming the test objects subtending an angle at the eye of a half minute of arc). They show further that the value of three is sometimes attained in daylight (Snellen 18/6—angle, one-third minute). By artificial illumination (gas-filled lamps) of roughly the same intensity as the daylight, lower values were obtained.

TABLE I.—VISUAL ACUITY (HAY'S TEST).

Daylight.

(About 100 equivalent foot-candles.)

	Hay.	E.	Snellen.
R.J.L. (A)	2	2	2
„ (B)	2.4	2.4	2.4
H.H.	2.4	3	3
H.B.	2	3	3

Artificial Light.

(About 80 equivalent foot-candles.)

	Hay.	E.	Snellen.
R.J.L. (A)	2	1.5	1.3
„ (B)	2.3	2.4	2.3
H.H.	2	2.4	2

(A) = without correcting glasses.
(B) = with correcting glasses.

TABLE II.—VISUAL ACUITY (HAY'S TEST).

(Normal-sighted observers.)

Artificial Light.

(About 80 equivalent foot-candles.)

	1st set.	2nd set (distance increased).
A.S.	1.4	—
W.F.	1.4	—
C.B.	1.4	1.6
W.H.	1.3	1.8
A.R.	1.7	—
V.S.	1.4	1.7
E.H.	1.4	1.6
E.B.	—	1.8

In Table III are given the visual acuities of the observers with defective vision. It will be seen that these range from 0.2 to 1.2 (6/30 to 6/5 Snellen). We took the line of demarcation at 6/5 instead of 6/6 as we felt that 6/6 is too low a standard for normal sight. An observer with an acuity higher than 1.2 is therefore considered normal. The inclusion of A.W. with observers with defective vision is due to his obtaining 0.5 with one eye and not better than 1.2 with the other.

Table IV gives the values for two normal sighted observers rendered defective by means of spectacles.

TABLE III.—VISUAL ACUITY (HAY'S TEST).
(Defective sighted observers.)
Artificial Light.
(About 80 equivalent foot-candles.)

	R.E.	L.E.
A.G.S. - - - -	0.2	0.6
F.C.B. - - - -	0.8	1.1
P.F. - - - -	0.5	0.6
A.W. - - - -	0.5	1.2

TABLE IV.—VISUAL ACUITY.
(Normal sighted observers made artificially defective.)

Observer.		Brightness in equivalent foot-candles.	Test Type.		
			Hay.	E.	Snellen.
R.J.L. - -	No error	80	2.3	2.4	2.3
	Small error [1]	40	1.1	0.9	1.1
	Large error [2]	40	0.9	0.9	0.9
H.H. - -	No error	80	2.0	2.4	2.0
	Small error [1]	40	1.1	0.9	1.1
	Large error [2]	40	1.1	0.9	0.9

[1] R.E. $\frac{+\ 0.5\ \text{D. sph.}}{-\ 1.0\ \text{D. cyl.}\quad 135^\circ}$ L.E $\frac{+\ 0.5\ \text{D. sph.}}{-\ 1.0\ \text{D. cyl.}\quad 45^\circ}$

[2] R.E. $\frac{+\ 1.0\ \text{D. sph.}}{-\ 2.0\ \text{D. cyl.}\quad 135^\circ}$ L.E. $\frac{+\ 1.0\ \text{D. sph.}}{-\ 2.0\ \text{D. cyl.}\quad 45^\circ}$

(6) The effect of intensity of illumination on the number of mistakes per alphabet in the recognition of the test letters by normal sighted observers is shown in Table V.

TABLE V.—METHOD I.

Brightness in equivalent foot-candles	6	40	70	200	600
H.H. Number of alphabets	2	2	—	—	4
Mistakes per alphabet	21.5	13.5	—	—	7
R.J.L. Number of alphabets	2	2	6	6	4
Mistakes per alphabet	19.5	13.5	7.2	6.8	4

Visual angle, 0.47 minutes. Total number of alphabets, 28. (R.J.L. wore glasses.)

METHOD II.

(Time of exposure = 0.019 sec.)

Intensity in equivalent foot-candles	4.5	30	80	550
Mistakes per alphabet	2.4	1.3	1.7	1.3

Visual angle = 3.4 minutes. 25 alphabets at each intensity. Total number of observers=9. (Table II.)

METHOD II.

(Time of exposure=0.019 sec.)

Intensity in equivalent foot-candles	4.5	25	80
Mistakes per alphabet	9.4	4.4	2.8

Visual angle=1.7 minutes. 17.5 alphabets at each intensity. Total number of observers=7. (Table II.)

The two different methods give results which show that, as the illumination is increased above 4.5 equivalent foot-candles, there is a decrease in the number of mistakes made per alphabet, not only for the two observers H.H. and R.J.L., but also for the eight observers whose initials are recorded in the visual acuity Table II.

(7) Table VI shows that four observers with defective vision gave similar results.

TABLE VI. METHOD II.

(Time of exposure = 0.019 sec.)

Brightness in equivalent foot-candles	4.5	30	80	550
Mistakes per alphabet	7.3	4.4	3.5	3

15 alphabets at each intensity.

Total number of observers = 4. (Table III.)

That two normal sighted observers given defective vision by the aid of glasses behave in a similar manner is shown in Table VII.

TABLE VII.

The effect of illumination on the visual acuity of two observers with artificially produced defective vision (worse than 6/5 normal vision).

METHOD I.

(Visual angle 0.915 minutes.)

(a) R.E. $\frac{+\ 0.5\text{ D. sph.}}{-\ 1.0\text{ D. cyl.}\quad 135°}$ L.E. $\frac{+\ 0.5\text{ D. sph.}}{-\ 1.0\text{ D. cyl.}\quad 45°}$

Brightness in equivalent foot-candles	1.2	3.5	9.8	45	1700
H.H.	22°	16*	14.5*	3°	4°
R.L.	25°	18.5*	15*	9°	3°

*Two alphabets per observer at each intensity.
°One alphabet per observer at each intensity.

(b) R.E. $\frac{+\ 1.0\text{ D. sph.}}{-\ 2.0\text{ D. cyl.}\quad 135°}$ L.E. $\frac{+\ 1.0\text{ D. sph.}}{-\ 2.0\text{ D. cyl.}\quad 45°}$

Brightness in equivalent foot-candles	1.2	3.5	9.8	45	1700
H.H.	25°	19*	14*	10°	16°
R.L.	24°	21*	23.5*	17°	20°

*Two alphabets per observer at each intensity.
°One alphabet per observer at each intensity.

R.L. wore glasses.

These variations in the number of mistakes made in the recognition of the test letters are due to a change in the visual acuity of the eye with change in intensity.

A similar effect is obtained when the distance between the observer and the test letters is varied, the illumination being kept constant, as the following table shows.

TABLE VIII.

The effect of visual angle on the number of mistakes made by normal sighted observers in recognizing the test letters.

Brightness = 6 equivalent foot-candles.—Method I.

Visual angle in minutes		0.86	0.62	0.47
H.H.	Number of alphabets	6	6	2
	Mistakes per alphabet	3.5	14.2	21
R.J.L.	Number of alphabets	18	6	2
	Mistakes per alphabet	2.8	12.3	19.5

(R.J.L. wore glasses.)

*Bright daylight.—Method I**

Visual angle in minutes		0.46	0.41	0.34	0.28
H.H.	Number of alphabets	5	5	5	5
	Mistakes per alphabet	3.4	7.2	13.8	16.4
H.B.O.	Number of alphabets	5	5	5	5
	Mistakes per alphabet	2.6	3.4	6.4	16.8

*Hartridge and Owen. *Brit. Jl. of Ophthal.*, Vol. VI, p. 543.

(8) *The effects of illumination on visual acuity.*—Two questions arise :

(*a*) Is a similar effect to be observed for one of the varieties of test used in physical optics, for instance the grating test, in which alternate black and white bars of equal width have to be resolved by the eye?

(*b*) Is it possible to obtain direct data for the relationship between intensity and resolving power?

The answers to both these questions are given in Table IX, where the relationship between illumination and visual angle is given for a grating test object for two observers.

TABLE IX.

By Method III.—(Grid Test.)

H.H.	Illumination in equivalent foot-candles -	.14	.98	2.65	18.5	250	1400	2300
	Visual angle -	1.25	.88	.75	.63	.57	.58	.56
R.J.L.	Illumination in equivalent foot-candles-	.15	1.04	4.2	6.5	31	100	235
	Visual angle -	1.25	.84	.81	.72	.63	.59	.58
	———	710	2360	—	—	—	—	—
	———	.59	.65	—	—	—	—	—

It will be seen that there is good agreement between the values obtained by the two observers except at the highest intensity of all. Up to 100 foot-candles there is a steady rise in resolving power, but thereafter it either rises less rapidly or becomes level or even falls. The agreement between our results and those of König using the Snellen "E" test is very good. (See Fig. 1.)

(9) *The resolving power of the eye.*—The means at our disposal did not permit us to investigate this matter further. We sought instead the answer to two questions :

(*a*) Is the highest resolving power which we have obtained in these experiments greater than that to be expected from the optical properties of the eye media or the histological structure of the retina?

(*b*) Is the initial rise in the curve as the intensity increases due to the decrease in the size of the pupil which in its turn has the effect of diminishing aberrations, and is the subsequent fall due to a still further decrease in the pupil introducing diffraction effects, or to some other cause?

With regard to the first question, the highest visual acuity is found to correspond to a distance on the retina of 0.0049 mm.; that is, the distance from centre to centre of the images of the white strips of the grating. This value corresponds fairly well with those of other observers, namely, 0.0045 for a double star, 0.0046 for a chequer pattern, and 0.0036-46 for the grating. It is well above the optical limit obtained by Abbe's or Fraunhofer's formulae for the resolving power, namely, 0.0029; and above the average diameter of foveal cones, namely, 0.0032. It is clear that a considerable increase in resolving power above that found by us is quite possible. This possibility we propose to investigate at some future date.

With regard to the second question, we found that, even at the highest illumination which we used, the pupil was still quite large

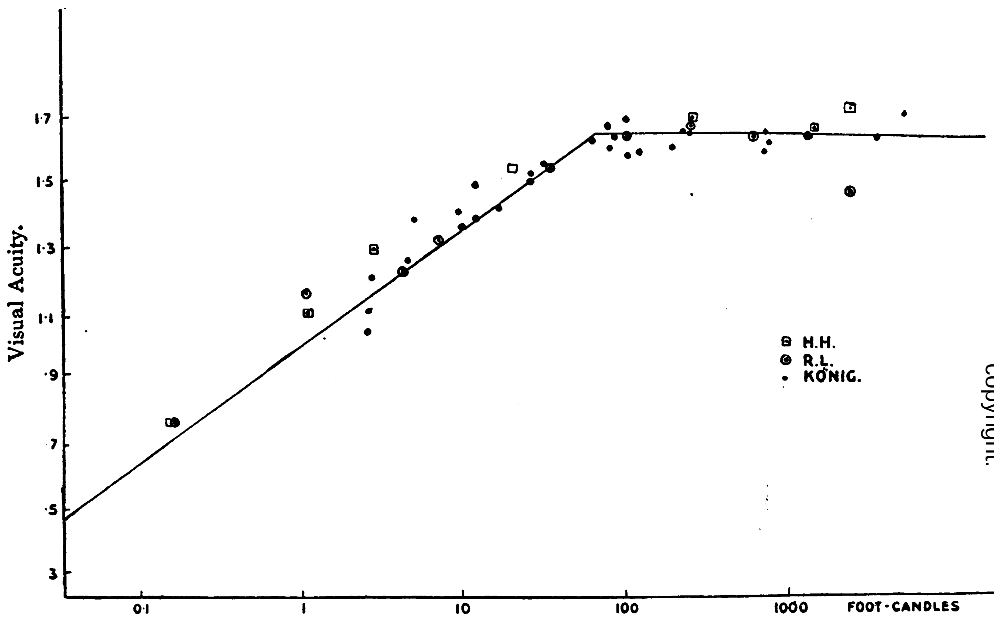

FIG. 1.

in diameter and that it varied but little with change of intensity. The change in resolving power would therefore appear not to be due to the change in diameter of the pupil. The cause must be sought elsewhere.

It is most probably due to an increase in the power of the retina to discriminate detail as the illumination is increased. This has been explained by Hecht as follows: The foveal cones obey the "all or nothing" law, for each one of them either gives its full response or none at all. They are not, however, equally sensitive to light. Thus an increase in the illumination of the retina will increase the number of active cones. If then, as seems very probable, visual acuity depends on the number of active cones per unit area, this should increase as the intensity increases. Also it will follow that at a certain level the last cone per unit area will receive adequate illumination and therefore no increase above this should bring about increased visual acuity. This deduction of Hecht's fits in with our data and explains the plateau which we found above 100 foot-candles.

(10) *The effects of flickering light on visual acuity.*—The increasing use of alternating current lighting raises the question: Is such a flickering light as good for visual purposes as a non-flickering source? So far as acuity is concerned the results appear to be identical (Table X).

TABLE X.

The effect of substituting flickering for continuous illumination on the visual acuity of two normal sighted observers (H. H. and R. J. L.)

Method I.

Brightness = 6 equivalent foot-candles.

	Flickering. (9 cycles per second.)	Continuous.
Visual Angle.	Mistakes per Alphabet.	
0.86′	3.1	2.8
0.62′	12.5	14.0
0.47′	17.3	16.5

Total number of alphabets = 40.

TABLE XI.

The effect of substituting flickering for continuous illumination on the visual acuity of two observers artificially made defective by glasses.

Method I.

Brightness - - - 3.5 equivalent foot candles.
Visual angle - - - 0.915 minutes.

	Flickering.	Continuous.
0.5 D. cyl. at right angles -	19.0	15.5
1.0 " " " - -	19.5	20.5

Total number of alphabets = 8.

Other comparisons between the results of flickering and non-flickering light have been published.*

The flickering light was produced by interrupting a direct current. A mercury interruptor was used which was driven by an electric motor. The number of interruptions per second could be altered at will. The current was on and off for approximately

*Hartridge, Lythgoe, and Matthews. *Brit. Jl. of Psychol.*, Vol. XVI, p. 293, 1926.

equal periods. In the above tests the rate of flicker was about nine cycles per second.

Summary

(1) An investigation was made on the effect of illumination on visual acuity (*a*) where the test objects subtended only a small angle and were viewed for a prolonged period, and (*b*) where the test objects subtended a considerable angle but were viewed for only a fraction of a second.

(2) By these methods we investigated the effect of intensity of illumination on visual acuity, (*a*) for normal sighted observers, (*b*) for normal sighted observers given defective vision by means of glasses, and (*c*) for observers with abnormal vision. In each case we found a clearly marked increase in visual acuity as the illumination was increased up to about 100 foot-candles. Beyond this intensity no further increase could be found.

(3) The range 1-100 foot-candles covers that ordinarily met with in artificial illumination. An increase in the intensity from 1 to 100 causes only a twofold increase in visual acuity.

(4) Artificial illumination of 2-4 foot-candles is most probably fully adequate for a variety of purposes.

For very fine work on the other hand, where the maximum visual acuity is required, an intensity of 100 foot-candles should be found adequate.

THE BEARING OF STEREOSCOPES ON THE RELATION BETWEEN CONVERGENCE AND ACCOMMODATION

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WHEN we look into any kind of stereoscope, how is the relation between our accommodation and convergence affected? Does the instrument enforce a squint during its use and, if so, of what kind, and how much? And what is the effect of pushing the pictures further away or drawing them nearer? Since stereoscopes are often used for muscle training, a study of this overlooked subject may be useful.

Our natural thought is that to push the pictures away lessens relative convergence and that to draw them up increases it. We shall see that exactly the reverse is the case, and that the effect of pushing the pictures away is to create relative convergence