VISUAL ACUITY WITH BRIEF STIMULI

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INTRODUCTION

ALTHOUGH the visual acuity of the eye has been often investigated, it has not yet been examined very fully in conditions of limited exposure time. The only known previous investigations in this field are those of Graham and Cook (1937), and Niven and Brown (1944), apart from a similar investigation on the somewhat analogous problem of intensity discrimination at short exposure times by Graham and Kemp (1935). The experiments here described aimed at increasing the intensity range beyond those of previous observations. They are all concerned with exposures of less than one second. The work can still only be regarded as incomplete; many more sets of observations with many more observers would be necessary before any accurate picture could be drawn of the variation of visual acuity under the various limiting factors which can be imposed, and over the whole possible range of exposure times. Meanwhile it is hoped that these results will facilitate the arrangement of further work.

The experiments fall into two parts; in which differing test objects were used:

(a) A double-star type of test object, with dark adaptation.
(b) A grating type of test object with low light-adaptation.

In both cases the object is bright on a dark-field, the contrast being effectively "minus one".

THE DOUBLE-STAR OBJECT

A consideration will be given later of the relative merits and drawbacks of this type of test object. It consists of a pair of circular holes each 0.59 mm. in diameter drilled in a thin opaque screen, with a third hole of 0.83 mm. diameter mid-between the other two. This third hole could be exposed when the other two were obscured, and vice versa, by means of a movable shutter in front of the plate. This was to provide an "alternative presentation" to the double-star presented by the other two holes, namely a single "star" of area equal to the sum of the areas of the other two (in order to avoid the photometric factor in the interpretation of any observation). The double-star distances (centre to centre)

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were made to subtend angles at the observing eye ranging from 3 mins. of arc down to 1 min. of arc. The latter separation of the holes was always horizontal. The exposure of the light behind it was made by a calibrated Compur shutter, having speeds ranging from 1/2 to 1/300th sec. The light source was a filament lamp, maintained at constant amperage, giving the test object, regarded as a source, a maximum effective brightness (*i.e.*, allowing for filters, etc.) of 58.15 candles/sq. ft. of test object, or $6.2 \times 10^{-2}$ stilb. Intensity control below this maximum brightness was by means of a calibrated pair of Nicol prisms.

The observer’s position was 20 feet from the test object, except for the observations for test objects subtending below 2 mins. of arc, for which the distance was increased; this was admittedly a possible source of criticism in that an unnecessary variable was thus introduced into the otherwise constant conditions of the experiment. The time available to the observer (K) did not, however, permit of the construction of the various additional test objects which would have been desirable. The observations were made with the right eye, using an artificial pupil of 2.5 mm. diameter and his required spectacle lens correction (-0.5D). The left eye was blacked out by means of an eyeshield. The observer’s head was kept steady by means of a dental clamp. The spectral composition of the light source was limited by means of a yellow-green filter. To facilitate fixation of the eye upon the desired spot a dimly illuminated ring, the diameter of which subtended about 2’ in the visual field, was exhibited, the eye being fixated on the centre of this. The image of the ring was projected into the plane of the test object by an unsilvered mirror, a gap in which allowed the unhindered observation of the object. An exacting effort at fixation was required; moreover it appeared that the observer’s ability to fixate varied from day to day; so much so that on certain days, despite apparent good health and willingness on his part, he was unable to control his fixation adequately. Work was discontinued if marked fatigue set in during a run of observations.

Observations were made in groups of ten flashes, each consisting of six double-star flashes and four single-star flashes given in a random order by the operator at the test-object end of the apparatus. The observer was allowed to give a “not seen” signal and have the flash repeated if he desired. He thus gives ten actual answers of “double” or “single”.

For a given speed of flash and test object, sets of ten such flashes were made at various brightness levels, and a graphical interpolation was made to find the brightness level for which the probable “number right out of ten” would be six; this was regarded
as the brightness of the test object for the threshold of resolution,
at that particular speed.

The results thus obtained may best be given in graphical form,
by plotting \( \log a \times t \), that is the \( \log \) of "visual angle times time of flash",
against \( \log \) brightness. These are given in Fig. 1. A
number of observations were also made up to 6° away from the
fovea; the results, though rather few in number, were similar to

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Fig. 1.}
\end{figure}

those of Fig. 1. They indicated a gradual decrease in visual acuity
at angles up to 1° off-fovea, after which the decrease becomes
much more rapid. Fixation is clearly the chief uncertainty. Thus,
other factors remaining constant, it appears that the variation of
flash visual acuity with distance from the fovea over this range
is likely to be similar to that of normal long-term visual acuity;
more observations would be necessary before any precise conclu-
sions are possible.

Referring to Fig. 1 it will be noticed that the limiting visual
angle falls a little below 1.3 minutes; it was never found, however, to fall as low as 1.1 minutes for any level of the brightness. Resolution is poorer at high brightness levels presumably owing to an "over exposure" or glare effect, as will be discussed below,

![Graph showing relationship between log energy of flash and log time of exposure.](image)

**FIG. 2.**

but in the intermediate levels the limit is presumably set by the imperfections of the optical image or by the retinal grain.

If the above results are used to plot curves (Fig. 2) of log (brightness times time) i.e., log "energy of flash" against log
"time" for given visual angles, it appears that there is an approach to reciprocity between brightness and time for the 2 min. and 3 min. objects for stimulus durations up to about 0.04 seconds, but this is not the case for the smaller angles. These results do not include those of the glare region.

The optimum acuity seemed unexpectedly good for a flash exposure, and suggests that movements of the retinal image in ordinary acuity observations do not play a major part in determining the limit.

THE GRATING OBJECT

The main intention of this set of observations was not only to repeat some of the observations (using, however, a different object) but at the same time to extend the range of brightness of test object as far as possible. The first results above (Fig. 1) extended up to a high-brightness value where visual acuity appeared to be decreasing due to the "glare" effect of the bright test object against the dark background. When attempts were first made with the higher brightnesses, the star type of test object being still used, it was found that the observer could (after a little experience) learn to judge whether the flash showed a double or single star by the apparent outline of the glare patch; the patch due to a single star had more pronounced "spikes" than that due to a double star, the latter being particularly lacking in these glare "spikes" at the sides of the patch. Even without considering the precise mechanism by which such a difference in appearance could occur, it seemed manifest that it represented an additional complication in the test which is not only undesirable, but also liable to give very misleading results, since for one thing it involves a judgment of the overall width of the glare patch, which is greater than the angular subtense of the double stars themselves.

Consideration was therefore given to the possible alternatives to the double-star test object, a decision being made in favour of the Foucault grating. This could be made continuously variable in angular subtense by rotating it about an axis parallel to the bars, and, moreover, this variation itself could be used to provide an alternative presentation (which should not be resolvable) merely by rotating the grating to an angular subtense below that which can be resolved by the eye. The grating is, of course, viewed through an aperture of constant angular width*. It was expected (and found true) that the "shape of glare patch"

*It was considered desirable to avoid the type of test object whose orientation has to be judged (such as that used by Niven and Brown, 1944) because of the possibility that the astigmatism of the eye (which is very difficult to correct completely) might require a much greater number of observations to obtain a satisfactory statistical analysis.
criterion would not be applicable here. The well-known possible
drawback of the grating (i.e., the possibility of reappearance of
an image on the retina with reversed (but very feeble) contrast
after an initial disappearance with increasing rotation) need
hardly be feared in these experiments, unless the imperfections
of the eye play the major part in limiting acuity, and the elemen-
tary image has certain special characteristics. Other apparent
advantages and disadvantages over the double-star test object
arose because the grating has a considerably larger area than the
double-star. Advantages may be noted as follows:

(1) Any small unevenness in manufacture or in cleanliness of
the test object itself, or in the eye (such as "muscae volitantes"
or blood cells on the retina) would probably have less effect on
the result as a whole.

(2) It was found easier to tell whether fixation was adequate
with a grating flash. This point will be discussed in more detail
in a subsequent section.

There are, however, certain drawbacks and difficulties:

(1) As will be explained, it was decided to introduce a dimly
illuminated background. The area of the test object itself forms
an appreciable and important part of this background which it is
difficult to illuminate. This difficulty was overcome for practical
purposes by making the bars of the grating white and illumina-
ting them to such a brightness that this region appears (during
adaptation) to be of the same even brightness as the rest of
the background.

(2) At high brightness the after-images were more trouble-
some; but it was found that the observer could, by careful
training, learn to decide whether he had resolved the actual flash
or merely the after-image. There is, however, some degree of
uncertainty in this connection. A longer time had to be allowed
between flashes at these high brightnesses.

(3) Since a larger area of the shutter is used, its efficiency
becomes important, as, especially at shorter exposures, a shutter
of the type used tends to give a longer exposure at the centre
relative to the periphery. This was found in fact to cause the
threshold brightness to vary slightly over the area of the test
object, so for example at the low-brightness threshold the
observer was resolving only the central part of the grating, and
vice versa at high brightness.

(4) In order to keep the intensity of the flash constant irre-
spective of the angular subtense, the area of the flash is kept
constant and hence the number of lines varies. There is
experimental evidence that with a small number of lines in a
grating the visual acuity varies slightly with this number of
lines; hence on this score it would be desirable not to allow the effective number of lines to go much below a minimum of say six.

(5) A large area of the fovea is involved. A compromise has to be made in this respect, especially if it is the aim to investigate the variation of flash acuity over the retina. The angular subtenses of the fields are given below.

Other significant changes in the apparatus as compared with the star experiments were as follows:

(1) The maximum effective brightness of the test object was much increased by using a "Point-o-lite" lamp, neutral density filters in place of the Nicol prisms, and a lens to concentrate the light so that the observer had the condition of "Maxwellian views". The maximum possible background brightness for the dark lines of the grating was 4,240 candles/sq. ft., i.e., 4.56 stilb.

(2) The observer's position was kept at the distance of 20 feet from the test object throughout the observations.

(3) A wide adapting field of brightness 0.0051 equivalent foot-candles, i.e., $1.5 \times 10^{-6}$ stilb. was employed.

Preliminary Investigation

In these experiments it was usual to fix two of the variables, viz., time of exposure ($t$) and brightness of the test object, and find the angle through which the grating needed to be turned from the full-on position in order to obtain a 50 per cent. chance of resolution of the grating. Two gratings were required to cover the full range. The fixed area of the test object subtended about 11 minutes in the field of view.

It was found possible for the operator to obtain the required setting of the grating by "bracketing" above and below the desired position in steadily decreasing steps, until after sufficient flashes (about 40 on average) the position had been obtained, generally to a repeatable accuracy of about 1°.

The steps were not always made alternately above and below the desired position, but were occasionally mixed, to ensure that the observer was not tending automatically to give responses of "resolved" and "not resolved" alternately.

The results obtained in this set of observations were intended to be exploratory. They are given in graphical form in Fig. 3. Each curve relates to the stated time of exposure; some of the limiting angles are entered on the diagram.

The abscissae are the logs of the field brightness in candles/sq. ft. The observer (G.H.) required a -1D correcting lens, agreeing with his normal spectacle prescription. He reports resolution at very small limiting angles, sometimes even lower than 0.75 min., and this general level of resolution ( <1 min.) persists over a range
of brightnesses having a ratio of 10,000 to 1. The limiting angle formed with a grating might be expected to be smaller, on statistical grounds, than that found with a double-star. The kinks in the left-hand branches of his curves are noteworthy, but it would be difficult to say whether optical aberration or retinal grain is the limiting factor in the flat parts of the curves.

**FULLER INVESTIGATION**

The consistency of the exploratory observations made, indicated the possibility of allowing the observer himself to set the grating by suitably arranged remote control, and so arrive at the desired position much in the same way as setting a pointer on a scale. This scheme was adopted for further work, the "observer" being able to increase or decrease the angle of the grating by means of an electric motor. He was not able, of course, to read the actual value of the grating angle during such an observation, although he could judge by the sound of the motor itself roughly by how much he was increasing or decreasing this angle.

A means was also provided for the observer to set and to release the shutter. The latter step was considered a desirable improvement in any case, since the observer, able to release the shutter in his own time, would be likely to be in a more consistent state.
of readiness. With the old method, despite the preparatory word "ready" from the operator, there was still a possibility that there was more or less "tenseness" during the short period of expectation.

The shutter was released by means of a solenoid actuated by a press button on the observer's table.

The results obtained in this set of observations by D.D. are in graphical form in Fig. 4. He had some trouble to determine his best correcting lens for the size of artificial pupil, which was -3.5 D.Sph. His normal correction was -3.25 D/ -1 D Cyl. Ax 90°, and a certain small amount of irregular astigmatism seems to be indicated.

The fixed area of the test object seen by the observer subtended about 7.5 minutes. It was reduced from the previous observations in the hope of obtaining greater accuracy by reducing the area of the fovea used, even though the number of lines fell to a value of 3 when the grating was most nearly full on, i.e., considerably below the desirable minimum in these extreme cases. It will be noticed at once that D.D. finds limits for the smallest angle of resolution, about double those found by G.H. It is thus possible
that the residual aberrations of D.D.'s eye are controlling the limit. Although the observer did not persist in observations when feeling perceptibly tired or unwell, he found that there was quite a high proportion of observing days when his performance was less than the optimum. There was sometimes a barely perceptible deterioration, but there were occasions when the observer had difficulty even in resolving a 3 min. subtense test object flashed for 1/10th sec. at optimum brightness. It appeared that the mechanism by which the performance was lowered was that fixation became inadequate. This was manifest, particularly in the grating experiments, as a kind of "comet's tail" on the main flash. For the very reason that lack of fixation could almost invariably be so detected, it is felt reasonably certain that fixation was at all other times adequate.

Any observations exhibiting a perceptible deterioration from the normal level of consistency were disregarded, and if such observations were more than isolated cases, the set of observations was discontinued.

The effects of improvement with practice were certainly present in the "star" observations, and they are very hard to separate in assessing the results. In the preliminary grating investigation, the observer took about a month to settle down, then a comparatively rapid complete set of observations was made in about two weeks. Thus it was hoped that such improvement, though doubtless still present, was not very marked.

In the fuller grating investigation, repeats of many observations were continually made until the observer was found to have arrived at a sufficiently static condition. The order of the final set of observations was varied, in order to prevent any remaining tendency from distorting the curves as a whole.

THEORETICAL DISCUSSION

It is well understood that visual resolution (acuity) is intimately related to intensity discrimination, since the aberrations of the optical system of the eye, diffraction, irradiation and other causes produce a degradation of the contrast of the retinal image which is more severe, the smaller the detail (Selwyn and Tearle, 1946). The finite size of the elements of the retinal mosaic is another factor capable of limiting acuity under certain conditions. In this connection it was thought that the slight involuntary movements of the eye recently confirmed by Lord and Wright (1949) might play a profound part in sustained vision. Flash stimuli should simplify the conditions here. (As mentioned above the experiments suggest that such movements are not of much importance.) There are some circumstances, certainly in regard to scotopic
thresholds, where the quantum characteristics of weak stimuli have to be taken into account, but no theory can progress far without a discussion of the effects in the eye and associated neural structures since, for example, visual acuity has an obvious significance in flash conditions, and even in after-images, when the perception of resolution may occur when the stimulus has ceased. The theoretical considerations given below are largely confined to photo-chemical considerations; in view of the known complexity of the visual process and the electrical phenomena of the discharges in the optic nerve fibres, some apology seems to be necessary for such a restriction, and for the very speculative application of the theory to deal with the phenomena of brief flashes.

There is weighty evidence to show that the first reaction in the process of scotopic vision is the absorption of light by the chromophore groups of the rhodopsin or similar molecules which are supposed to be associated with protein layers in the outer segments of the retinal rods.

The main evidence for this conclusion is the close correspondence between the absorption coefficient for visual purple in solution and the spectral sensitivity of the dark-adapted parafoveal retina. No generally acceptable theory of the manner in which the initial photo-chemical change is transformed into the rhythmic nerve-pulses has yet, so far as we know, been proposed. In his well-known experiments with *Limulus*, Hartline (1935) has shown that though an interval of the order of 0.1 seconds may elapse between a flash stimulus and the onset of the nerve discharges (and this interval will be greater with diminishing stimuli) there is a good reciprocity between the duration and intensity of short stimuli, so that the number and frequency of the pulses are a function of the energy in the flash. This is an additional and important indication of the initial photo-chemical storage, and probably of fairly close conservation of the energy in passing through its different stages; if "leakage" occurs it must be of a very regular character. There is evidence to show that the absorption of as few as five quanta can give rise to a perception of light in the dark-adapted human retina and this again suggests a high degree of conservation of the photo-chemical energy.

Possibly, even the absorption of a single quantum by a rod receptor with the decomposition of a single molecule of the visual purple may give rise to a definite energy pulse in the associated neuron. The reason for the time delay, a long one when one considers the usual time scales of molecular reactions, is an interesting puzzle; it might indicate some diffusion or electro-phoresis of the excited molecules or ionic products of decomposition; it has also been suggested that an excited chromophore group may give
rise to a chain of secondary reactions leading to the excitation or decomposition of further molecules. Though our present suggestion is little more than speculation it seems possible that a rod with its presumably regular structure of protein and carotenoid molecules might act as a unit in which energy exchanges or ionic transfer can take place. The action of light would ionize some molecules and excite electrons to higher energy levels in others. Energy might then be stored in local electrostatic fields and mechanical strains; spontaneous energy exchanges between excited molecules may lead to further ionization and consequent polarization; a certain proportion of excited molecules will thus continually return to ground levels. Some of the properties of such a system, reciprocity for medium stimuli for example, would resemble those of a silver halide grain in a photographic plate. We return to this point below. The immediate point of importance is the probable conservative connection between the energy in the flash and the magnitude of the response in the nerve, in spite of the time delay. The above considerations are mainly related to rod vision, but there are many considerations, well-known and otherwise (Dartnall, 1948), which suggest that the initial phase in photopic vision is also photo-chemical, the sensitive substance still being rhodopsin; the relative spectral response being modified by the accumulation of decomposition products. This again is consistent with the Talbot-Plateau law and other phenomena of photopic vision. We therefore have some ground for discussing the photo-chemical actions in the present connection. Hecht (1935) and his collaborators have given much attention to the consequences of a theory of a simple photo-chemical system in which the decomposition products A, B, C, etc., of some initial substance S eventually re-combine to form S once again. This may be useful, insofar as it may serve to examine certain overriding effects and limits.

Let us assume that there is a rough proportionality between the limiting angle of resolution and the limiting fraction of discrimination dI/I. We may then discuss the probable limits of dI/I under flash conditions. Following Hecht (1935) let the original concentration of S be \( \sigma \) and the general concentration of the photo-products A, B, C, at any time t be \( x \). Then the magnitude of the visual effect is usually associated with \( x \). However, reconstitution of S is supposed to be a function of \( x \). The equation is:

\[
\frac{dx}{dt} = k_1 (a - x)^m - k_2 x^n
\]

where \( k_1 \) and \( k_2 \) are constants, and \( m \) and \( n \) represent the chemical order of the reaction, e.g., mono-molecular, bi-molecular, etc.,
Hecht (1935) applied this equation to deal with the steady states of full adaptation. Graham and Kemp (1935), in a modification of the theory, supposed that in a given critical time \( \Delta t \), during which storage might take place, the building up of a critical concentration difference \( \delta x \) is the criterion for the perception of a flash in which the stimulus is momentarily increased above the existing adaptation level. It is supposed that \( \Delta t \) is very short in comparison with the effective adaptation time. They thus obtain a further equation which is in agreement with the general features of their experimental results. Niven and Brown (1944), assuming that visual resolution is proportional to intensity discrimination, find their results on acuity can be represented in a similar way. In our work the adapting field has a small or negligible intensity, and the conditions of flash illumination require the formal integration of some equation such as that above. In order to study some general implications we may assume very simple numerical constants. Suppose \( k_1 = k_2 = m = n = a = 1 \).

Then

\[ x = I \left[ 1 - \exp \left\{ -t (1+I) \right\} \right] / (1+I) \]

In order to get a set of curves of such a type we have plotted (using common anti-logs)

\[ x = I \left[ 1 - \text{antilog} \left\{ -t (1+I) \right\} \right] / (1+I) \]

for different values of \( I \); see Fig. 5. Note that three sets of curves

![Fig. 5.](http://bjo.bmj.com/)

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appear, the relative value of I in each set having the ratios 5:10:20. The curves are relatively crowded for very small and for very large values of I, but are more widely spaced for intermediate values. If we assume that the limit of the discrimination fraction corresponds to a fixed value of $\delta x$ at the end of a flash-duration t, we shall have a relatively large value of $\delta I$ for a small value of I, but the fraction will diminish and thereafter increase with steadily rising values of I, the position of the minimum being a function of t; it tends towards larger values of I, the shorter the time.

A plot of relative values of $\log \frac{1}{\delta x} \cdot \frac{\delta I}{I} \cdot t$ against log I is shown by the curves of Fig. 6; they are derived from the last equation above.

Since we have assumed $\delta x$ a constant, the curves show relative values of the log of the product of the discrimination fraction and time against log I. There are some obvious resemblances between these curves and the experimental curves of the product of the log of limiting angle of acuity and time. The experimental acuity curves have, however, flattened minimal regions, suggesting that other factors are here setting a limit to the angular resolution. To put the essential point more briefly, the up-turn of the curves is to be expected on account of the temporary exhaustion of the light-sensitive material with flashes of high energy, so that differing stimuli cannot be distinguished. The photographic plate offers an analogy. Our experiments do not involve a previous adaptation to a ground-intensity I. If adaptation is secured, the up-turn would probably disappear.
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For the flashes of shorter duration there is clearly no general possibility of a movement of the image over the retina which might permit of a smaller limiting angle of visual resolution. The set of curves in Fig. 5 shows, of course, nothing of the over-shooting of the steady state characteristic of discharge-frequency and electroretinogram records, and the usual idea that the visual sensation in its early stages is a steady function of $x$ must be abandoned. Fig. 5 may be compared with Fig. 7 which represents very roughly

![Figure 7](image_url)
initial variation of $x$ due to photo-chemical action; the spontaneous discharge is not taken into account.

If indeed the above picture has any truth whatever, the initial visual photo-chemical effect would involve a very short time-scale in comparison with the very much longer periods for true photopic (much more so for scotopic) adaptation which may represent the reconstitution of chemically separated substances. If the main initial effect of the light is the electrical excitation of the ground-state molecules, the "reconstitution" term $k_x$ in our use of the equation might represent the return of the electrons to ground levels during the flash period, or some other leakage effect. It is possible that a re-constitution effect plays no important part in the short time intervals contemplated here. The value of $k_x$ would then be zero; the curves of Figs. 5 and 6 are changed, and the resemblance to the experimental curves is diminished, though some of the main features of the results are still explainable.

There is obviously room for a considerably greater amount of work on the subject of brief stimuli; we do not claim that our results are final but they offer suggestions for further investigations. They are not fully consistent with the theory put forward; for example if D.D.'s retinal image has poorer contrast than that of G.H., it would be expected that increasing intensity would produce the "over-exposure" effect at lower levels for D.D. than for the other observer, but this is not seen in the results. The difficulty of distinguishing resolution in the flash as against the after-image may be recalled. We feel as the result of these experiments that subjective observations of differing observers are most difficult to compare, owing to the different criteria which will be used even for the simpler observation tasks.

**Summary**

These experiments aim at increasing the range of intensities beyond those for which measurements of flash visual acuity have already been made. Double-star and Foucault-grating test objects were employed, with dark-adaptation and low light-adaptation respectively. The limiting angles of resolution were found to be small (often <1 minute) under medium intensity stimuli, and they do not suggest that eye-movements have any major effects in improving acuity. "Over-exposure" effects with high-intensity flashes are studied, and some possible connected physical and chemical processes in the retina are suggested for discussion.

**REFERENCES**