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THE FOVEAL ABSOLUTE VISUAL THRESHOLD FOR SHORT FLASHES AND SMALL FIELDS

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It has been argued (Bouman & van der Velden, 1948; Bouman & Walraven, 1957) that the condition for the detection of a brief foveal stimulus is the absorption of two quanta within any small area of the fovea, it being left undetermined whether the required small area is a single cone or a small group of cones. The present paper, by examining foveal frequency-of-seeing curves, disproves this hypothesis and proves that if there are independent units in the central fovea such that the excitation of any one suffices for vision, then at least 5 quanta must be absorbed within an independent unit to excite it.

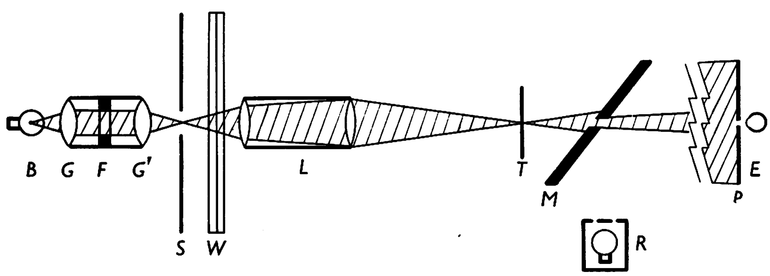

Fig. 1. Diagram of the apparatus for measuring foveal visual thresholds. The path of the light rays is indicated by cross-hatching. For the dimensions and a full explanation of the lettering, see text.

METHODS

Apparatus. The apparatus is shown diagrammatically in Fig. 1. The filament of a 12 V 24 W bulb B is placed at the focus of a gunsight lens G, and a second identical lens G' forms an image of the filament in the plane of a pendulum shutter S. Between the two lenses, where the light beam is parallel, an interference filter F transmits a narrow band of wavelengths. Neutral density wedges W control the light intensity, and a third lens system L forms an image of the filament at T. The test object T consists of a brass plate with a small hole mounted on a large plate and accurately centred. The test object is viewed through an artificial pupil P, 114·6 cm from it. The subject's head is held steady by means of a dental impression which can be adjusted so that the eye E is placed close to the artificial pupil.

Fixation is regulated by four dim red points R reflected in a mirror M set at 45° to the axis of the apparatus. The test object T is seen through a hole in this mirror. The subject maintains fixation on the centre of the square formed by the fixation points.

In the experiments described in this paper the filter used was a Schott interference filter with maximum transmission at 550 mμ and half width 19 mμ, the test object subtended 1 minute of arc at the artificial pupil, and the flash from the opening in the pendulum shutter had an effective time of 1·2 msec.

Calibrations. The wedges *W* were calibrated for optical density in light transmitted by *F* by comparison with sector disks.

The Schott interference filter was individually calibrated by the makers and by the National Physical Laboratory for absolute spectral transmission.

The shutter was timed by photographing an oscilloscope trace derived from a photocell, and comparing with an electronic time marker. The shutter was fully open for 0·8 msec, the image of the filament falling entirely within the aperture, and the time for the edges of the aperture to cross the image was about 0·4 msec each, so that the effective time open was 1·2 msec.

The light transmitted by the filter was compared by using a Spectra Spot Brightness meter with the light transmitted by the same filter from a source calibrated for colour temperature and intensity by the National Physical Laboratory.

The absolute energy calibrations may be in error by as much as 0·1 log. unit (25 %). The relative values are much more accurate, and errors in these are negligible in comparison with the variability of response.

Experimental procedure. In each experiment 7 intensities were used, at intervals of 0·1 log. unit. These were presented to the subject in random order, and a 'blank', when the light was completely cut off without the subject's knowledge, was included with each set of 7 intensities. They were chosen so that the highest intensity was always seen and the lowest never seen, and as far as possible so that the 50 % point lay near the centre of the range. No subject responded to a blank in the experiments reported here. In preliminary experiments one of these subjects once did so, and another subject (not included here) persistently responded to one or two blanks out of twenty.

Subjects were dark-adapted in complete darkness for 15 min before each experiment.

The position of the eye in relation to the artificial pupil was determined by means of the effect of chromatic aberration. The fixation points were first arranged so that the field, illuminated through a *red* filter, appeared accurately in the middle of them. The red filter was then replaced by the filter 550 mμ, used in the experiments, and the dental impression moved until this appeared accurately in the middle of the fixation points. This is not necessarily the ideal position for obtaining the minimum cone threshold having regard to the Stiles–Crawford effect. There was no evidence that any of the subjects had pupils asymmetrically placed, and a check for F.M. showed that a movement of 1 mm to either side of the central position had no sensible effect on the threshold.

RESULTS

Exposure time. Preliminary experiments showed that summation was virtually complete (Bloch's Law) for exposure times up to 100 msec. For pairs of flashes the energy increased for separations over about 20 msec. The exposure time used, 1·2 msec, almost certainly gives the minimum energy required for vision under the conditions used.

Size of field. The field used subtended 1 minute at the eye. When viewed through a 2 mm artificial pupil it appeared as a slightly blurred spot. Through a 1 mm pupil it appeared as a sharply defined circle with, if it was bright enough, faint interference rings round it. With smaller pupils this interference pattern was enlarged. The use of a correcting lens did not improve the definition of the image, even with a 2 mm pupil, except for one subject who was markedly myopic.

Preliminary experiments showed that the threshold was slightly lower with the 1 mm than with the 2 mm pupil for three subjects and slightly higher for two, the difference being about 0·1 log. unit in each case. It was concluded that:

(*a*) The retinal image formed when using a 1 mm pupil is probably nearly that which would be calculated from the diffraction pattern. The Airy disk in this case has a diameter of about 5 minutes, and the effective diameter of the image, to the point at which the intensity is less than 50 % of the maximum, about 3 minutes.

(*b*) This image is almost the smallest which can be produced by an external light source when the eye is used in the ordinary way.

(*c*) There is no reason to suppose that the light acting on the retina at threshold represents the least energy necessary for vision in the sense of Ricco's Law; if it were possible to stimulate smaller retinal areas, the threshold energy might be less.

Threshold measurements. Threshold energies and frequency-of-seeing curves were obtained for seven subjects. Each experiment consisted of 20 flashes at each of 7 intensity levels, plus 20 blanks. No blank was reported as 'seen' by any of the subjects. The threshold values were determined by the method of Hartline & McDonald (Pirenne, Marriott & O'Doherty, 1955).

Table 1 shows the full results of each experiment, with the threshold value in quanta, and the value of the parameter n'. The significance of this parameter is discussed below. The frequency-of-seeing curves were generally steeper than those obtained by Hecht, Shlaer & Pirenne (1942) for peripheral vision.

The subjective colour of the flash was not systematically recorded. Usually it appeared colourless when it was only just detected, and greenish when it looked fairly bright; occasionally it appeared definitely red. These findings are in good qualitative agreement with those of Bouman & Walraven (1957).

The peripheral threshold of subject F.M., measured with the same apparatus at 24° temporal, was 348 quanta (550 mμ). This corresponds to 165 quanta (507 mμ) for scotopic vision, which agrees fairly well with previous determinations on this subject.

TABLE 1. Density steps

Subject	0·8	0·7	0·6	0·5	0·4	0·3	0·2	0·1	0	Threshold	n'
T.G.	0	0	3	12	14	20	20			542	19 (6, 36)
L.G.		0	0	2	13	20	20	20		652	67 (15, 156)
F.M.	0	1	6	9	16	19	20			530	13 (5, 23)
T.P.-M.	0	2	4	14	18	20	20			494	19 (7, 37)
A.S.		0	1	0	7	18	20	20		715	26 (11, 45)
J.S.		1	2	7	15	17	20	20		595	12 (5, 23)
D.T.	0	2	5	13	19	20	20			494	20 (7, 37)
J.T.*			0	2	2	9	17	20	20	879	17 (7, 31)
D.W.		1	2	8	17	17	20	20		555	21 (8, 40)
Mean value										606	17 (14, 21)

* With correcting lens (−2·5D). No correction made for light loss due to this lens.

DISCUSSION

Previous results

Few measurements have been made of the foveal absolute threshold for small fields and short exposures. Boswell (1908), in von Kries's laboratory, using light of 589 mμ, exposure times of 3·3, 5·0, 6·6 and 10·0 msec, and a field 0·88 minutes in diameter, found a mean threshold of $31{\cdot}6 \times 10^{-10}$ erg, with a minimum value at 5 msec of $23{\cdot}7 \times 10^{-10}$ erg. On the basis of the C.I.E. photopic visibility function, these correspond to 625 and 469 quanta of 555 mμ.

Bouman & van der Velden (1948), using 2·5 msec flashes and a field 2 minutes in diameter, found thresholds of 800 quanta for both 560 and 600 mμ, equivalent respectively to 790 and 467 quanta of 555 mμ on the basis of the C.I.E. photopic visibility function. Miller (1959), using 40 μsec flashes and a field 9 sec in diameter, found a threshold of 2440 quanta for light of 550 mμ.

Boswell's result agrees well with those reported here. Bouman & van der Velden's results also agree well, but it must be noted that in the same publication they give extremely low values for the peripheral threshold. Miller's value is outside our range of results.

Zanen & Jimenez (1962) found a mean threshold for fifteen subjects of 1600 quanta using light of 538 mμ, a 3 minute field and 0·5 msec flashes. These results may not be strictly comparable with those reported here, since the subjects were adapted to a 'dimly lit room (5 lux)', rather than to complete darkness.

Frequency-of-seeing curves under similar conditions have also been published by Bouman & van der Velden (1948) and Bouman & Walraven (1957). The former found much shallower curves than those reported here, but the latter agree well with the present findings.

Foveal and peripheral thresholds

The only valid basis for comparison of the present results with peripheral thresholds seems to be on the basis of minimum numbers of quanta *of the most efficient wave-lengths*. The average threshold obtained by these subjects, 606 quanta, is about five times the average value for the peripheral threshold (Hecht *et al.* 1942; Pirenne & Marriott, 1962).

Quantum fluctuations

The quantity n' is a convenient parameter to express the steepness of the frequency-of-seeing curves. If the condition for a response is that n or more quanta should act on the retina, n' is an estimate of the parameter n: n is then defined by the distribution function for the Poisson sum on p. 422.

The values of n' are given in Table 1 with their 95 % confidence limits. The accuracy of the estimate is very low; this is to be expected since, for practical reasons, a fairly large range of intensities was used and the curves were in general considerably steeper than those found for peripheral thresholds. In spite of the wide scatter of the results, there is no clear evidence that the frequency-of-seeing curves differ for these subjects. They could all have arisen from a curve with parameter about 20.

In peripheral vision the value of n' agrees quite closely with the number of quanta absorbed by the rod pigment (Hecht *et al.* 1942; Pirenne & Marriott, 1962). This led to the conclusion that in these experiments most of the uncertainty of seeing at the threshold was due to fluctuations in the actual numbers of quanta acting on the retina.

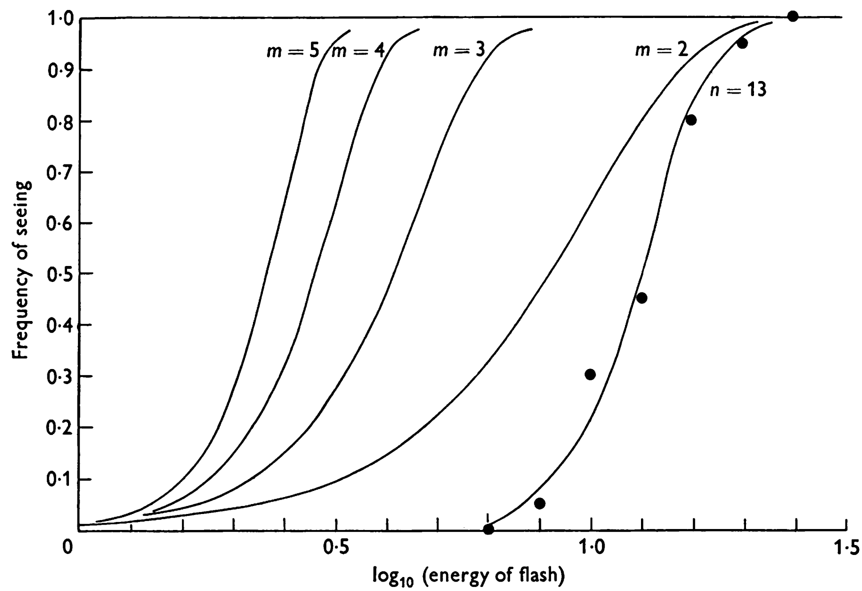

Fig. 2. The experimental results for one subject (F.M. in Table 1) are shown with the fitted Poisson sum for $n = 13$. The curve clearly gives an excellent fit. On the left the 'limiting curves' for $m = 2, 3, 4$, and 5 (see text) are plotted on an arbitrary abscissa scale. It is clear that the experimental points correspond to a steeper curve than those for $m = 2$ and 3, and agree reasonably well with $m = 4$. If all the results in Table 1 are considered as arising from the same theoretical curve, this curve must be steeper than that for $m = 4$.

This conclusion cannot be validly drawn for the foveal threshold. No reliable estimates are available for absorption by the cone pigments. It has been shown, however, that the parameter estimated by n' gives a lower limit to the mean number of acting quanta at threshold (Pirenne & Marriott, 1959). Further, Brindley (1954, 1963) has shown that, if the condition for a positive response is m acting quanta falling within a certain receptive area and summation time, then as the area and time of the stimulus increase the frequency-of-seeing curve tends to a limiting form.

The variance of this limiting curve (on a logarithmic basis) may be compared with the variance of the experimental results from which n' has been derived. This comparison shows that a value of n' of 3 or greater gives a steeper curve than can possibly be derived from $m = 2$, and thus excludes the 2-quanta theory even if the number of spatio-temporal units is very large. Likewise values of $n' \geqslant 6$, 11, and 16 exclude $m = 3$, 4, and 5 respectively.

Figure 2 shows the experimental results for one subject (F.M. in Table 1) with the fitted Poisson sum for $n = 13$. In the same figure, on an arbitrary abscissa scale, are shown the limiting curves for $m = 2$, 3, 4, and 5. The experimental results clearly fit a curve steeper than $m = 2$ or 3, and correspond roughly with $m = 4$.

The distribution functions of the Poisson sum and limiting curve may be written respectively:

$$F_n(x) = \sum_{r=n}^{\infty} \frac{e^{-x} x^r}{r!} \quad \text{and} \quad F_m(x) = 1 - \exp\left(\frac{-x^m}{N^{m-1} m!}\right),$$

where x is the number of acting quanta in each case and N is the number of units responding to m quanta. The means on a natural logarithmic scale, $\int_0^\infty \ln(x)\mathrm{d}F$, are

$$\digamma(n-1) \quad \text{and} \quad \left(1-\frac{1}{m}\right)\ln N + \frac{\ln m!}{m} - \frac{\gamma}{m}.$$

The variances are given by

$$\int_0^\infty (\ln x)^2 \, \mathrm{d}F - (\text{mean})^2,$$

and are

$$\Digamma(n-1) \quad \text{and} \quad \pi^2/6m^2.$$

A comparison of these two functions gives the results above. The digamma and trigamma functions are defined as the first and second derivatives of the ln factorial function, so that

$$\Digamma(z) = \frac{\mathrm{d}}{\mathrm{d}z}(\digamma(z)) = \frac{\mathrm{d}^2}{dz^2} \ln\Gamma(1+z).$$

For large values of n,

$$\digamma(n-1) \simeq \ln(n-1/2), \quad \Digamma(n-1) \simeq 1/(n-1/2);$$

these approximations are quite adequate for the values of n considered here.

Now the (weighted) mean value of n' (Table 1) is 17, with 95 % confidence limits of 14–21. The lower confidence limit therefore corresponds to a steeper curve than is consistent with $m = 2$, 3, or 4, and thus excludes any explanation based on the response of any one of a number of independent units responding to less than 5 quanta.

The frequency-of-seeing curves of Bouman & Walraven (1957) equally exclude the 2- and 3- quanta theories put forward by these authors.

SUMMARY

1. For 1·2 msec flashes of a 1 minute field foveal thresholds ranged from 494 to 879 quanta of light of 550 mμ.

2. The frequency-of-seeing curves were rather steeper than those found for similar experiments in the periphery. There was no reason to associate the variability directly with quantum fluctuations, but the steepness of the curves excludes simple 2-, 3- and 4- quanta theories of vision.

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