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THE PHOTOMETRIC EVALUATION OF FLASHING LIGHT SOURCES IN RELATION TO THEIR CONSPICUITY.

by

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ABSTRACT.

Different aspects of conspicuity when signals are operated under practical conditions are considered and a review is given of previous work relevant to the study of flashing lights. The present study is chiefly concerned with the variation of the threshold across the central retina, the influence of field size and flash duration upon this threshold and the fixed light equivalent of flashing lights. A three-beam optical system allowing such investigations is described.

The main conslusions are:

A slightly greater degree of temporal summation occurs in the periphery than at the fovea, the central region of which, about 30' in diameter, may have properties very different from the rest. Points on the retina giving the same threshold under one set of observing conditions may give similar thresholds under widely differing conditions. The Riccò area of complete spatial summation is less than 2' of arc at the fovea in the light-adapted eye. With increase in the flash duration, the transition from Bloch summation (It = constant) to constant threshold is relatively sharp under all conditions, certain discrepancies among the results of previous investigations being ascribable to imprecise fixation.

A method is described whereby retinal locations where blood vessels may interfere with visual measurements may be avoided.

Other experiments indicate that, during the course of dark adaptation, the Bloch summation time rapidly attains its maximum

value; in peripheral vision, the size of the receptive fields goes on increasing over more prolonged periods. Some investigations are described in which the apparent intensity of a flash may exceed that of a similar steady light. In further experiments, certain effects of changes in frequency and the dark interval between flashes, group flashing, placing the flashing light in a small dark surround within a larger conditioning field of high luminance have been studied.

Lines are indicated along which quantitative relationships may be sought for between:

a) the threshold,

b) the apparent intensity of flashing lights,

c) the critical fusion frequency,

d) the rise and fall of the visual response.

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CHAPTER I

CONSPICUITY

Introduction

Flashing lights have been extensively used in the field of aids to maritime and aerial navigation and are coming into wider use for general signalling purposes because of their economy, ease of identification and conspicuity. Were it not for the flashing characteristic which reduces operating costs, especially with battery operated lamps, the expense of operating a system using large numbers of light signals would be excessive and in remote places the problem of operating danger signals would be very difficult. As such, any possible change leading to improved operation and greater economy requires consideration, but as the detector of the flashing signal is invariably the unaided eye, an understanding of the response of the visual system in general and to flashing lights in particular is essential for their proper design and efficient use. The temporal pattern which gives an extra dimension to the flashing signal as a means of coding information is also responsible for certain characteristics of the visual response particular to intermittent or transient stimulation. Typical of the questions one must answer in setting up a new flashing signal are what are the optimum duration and pattern of the flash and how must the signal be situated in relation to its surround.

Conspicuity

The dictionary definition of Conspicuity is the property of being "clearly visible, obvious or striking to the eye". Though it seems highly desirable to establish a scale of conspicuities for light signals, it must be borne in mind that one is here dealing with a psychological magnitude and such a scale would involve relating this psychological magnitude to the physical stimulus. Any natural construct relates quantities defined in terms of the operations used to denote and measure them and conversely the definitions of these quantities imply the method used in their measurement. It is not easy to define conspicuity uniquely in this manner and this would appear to have led to some confusion now and again. As an example, one may quote from the paper of Toulmin-Smith and Green on the Fixed Light Equivalent of Flashing Lights (1933):

> "The useful range of a lighthouse, as distinguished from the range at which it is on the threshold of visibility, may therefore be defined as the range at which the light can be kept under continuous observation by foveal vision and at which the flashing character can be identified.
>
> As a preliminary step towards the establishment of a method of estimating this range for any given light, a decision must be reached as to the minimum illumination required for <u>adequate conspicuity</u>. Since the ability to see a distant light depends

on the illumination produced at the observer's eye, conspicuity may be conveniently expressed in candles/mile^2 and denoted by the symbol Ec.

....

According to Blondel and Rey the threshold value of Ec may be as low as 0.13, and it may be anticipated that when the conspicuity of the light is raised to over three times the threshold, i.e., when the character of the light is readable, the diminution in apparent intensity due to flashing will not be the same as for a light which is only just visible......

The method employed was to view alternately a fixed light of known conspicuity and a flashing light of the same intensity. The intensity of the flashing source was then increased till the conspicuity of the flashing light appeared to be the same as that of the fixed light. The fixed light equivalent of the flashing light was calculated from the increase in intensity of the flashing light required to obtain a balance ..... As it was desired to obtain curves at definite conspicuity levels the question arose as to whether a point source is equally visible when seen with one or both eyes .....

When the observer has defective eyesight the conspicuity for both eyes is that of the better eye .....

No difficulty was experienced in obtaining fairly consistent readings at low conspicuities, but above 1 candle/mile^2 the readings became less accurate .....

Fig. 5 shows the fixed light equivalents for conspicuities from 0.2 to 4.0 candle/mile^2 together with the curve for threshold visibility given by the Blondel Rey law. It is satisfactory to note that the results obtained in these tests for a conspicuity in the neighbourhood of the threshold, are in remarkably close agreement with the formula given by Blondel and Rey."

When the authors mention "adequate conspicuity" it would seem that the word is used in the dictionary sense, and their meaning is rendered more precise by the definition of the useful range of a lighthouse. Expressing conspicuity in terms of candles/mile^2 would attempt at establishing a scale of conspicuity by equating the psychological magnitude to the physical stimulus, but this unfortunately leads to the term "conspicuity" being indiscriminately used for the actual intensity, or the apparent intensity as measured by direct visual photometric comparison or the illumination produced at the observer's eye. Incidentally the meanings attached to "fixed light equivalent" and "apparent intensity" in the text and in the legends of certain diagrams in this paper (Fig. 1) are slightly ambiguous - Projector (1957) has used "effective intensity ratio" instead of "apparent intensity" when quoting these data.

The earliest definition of "conspicuity" one finds in the literature is possibly that of Stiles, Bennett and Green (1937): The signal value of a light when it is above the threshold. Recent suggestions have been "readiness of visibility", "attention getting power of a light" and "impact intensity of a light stimulus". These definitions stress the dependence of conspicuity on the sensation response evoked within the observer under the impact of a given energetic configuration and would imply that it is measurable on a suitable scale. Now Stevens (1961) postulates that at the sensation level, discrimination can be mediated by either of two processes (a) additive, (b) substitutive:

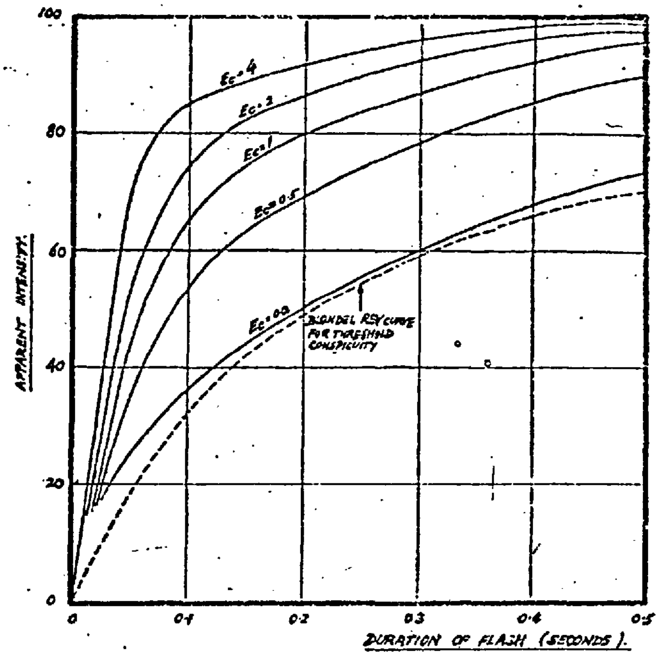


FIG. 1.—Fixed light equivalents at different conspicuity levels.

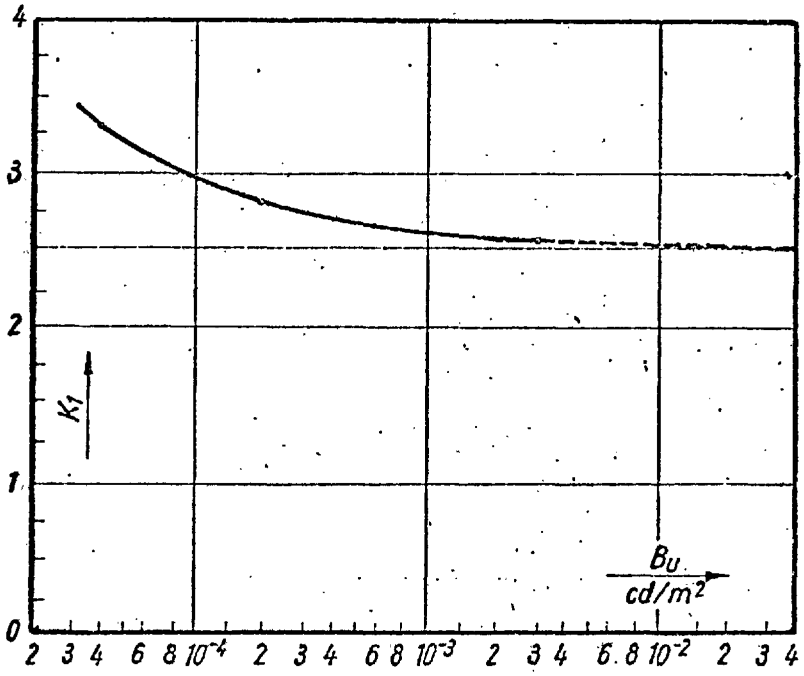


Fig 2. Conspicuity factor K, for various surrounding luminances B_U

(Adrian and Jainski)

> "A basic distinction can be made between two types of sensory continua, prothetic and metathetic. The distinction rests on a set of functional criteria, but it is useful to think of the prothetic continua as those concerned with how much (intensity) and the metathetic continua as those concerned with what and where (quality). At the physiological level, many prothetic continua (loudness, brightness and so forth) involve the addition of excitation to excitation, whereas some of the metathetic continua (pitch, apparent azimuth, inclination) involve the substitution of excitation for excitation."

One can clearly alter conspicuity through a change in either prothetic contrast (change in intensity of signal relative to background) or metathetic contrast (change in colour of source, flash pattern, motion, nature of background, etc.) or again a combination of both. It seems generally easier to set up psychological scales for prothetic than for metathetic continua. The complexity of the situations met with in practice often precludes a detailed analysis within a limited time - research then may limit itself to one particular configuration or a solution is arrived at by rule of thumb. Certain phenomena however are common to many problems, and some situations are less complex - in such cases it does not seem too unrealistic to suppose that some simple rules of direct application may be arrived at. Some of the conditions under which light signals are used may first be considered.

Plenty of research has been done in the field of maritime navigation where flashing lights have long been in use. Maritime lights operate from a few dozen metres to extreme limits of observation, of the order of 100 kilometres or so, when the light is a point source below the resolving power of the eye and near to the threshold. None the less, the mariner often has relatively simple and favourable conditions of observation. The light signal may appear against a fairly uniform background, ships move comparatively slowly and keep at good distance from obstructions to allow sufficient time for observation, pilot houses are dimly lit to facilitate night observation and the observer who is accidentally dazzled has plenty of time for recovery. When a ship is on course the bearing of the navigational aid sought for is approximately known and this restricts the search to the proximity of the visual axis. The necessity of taking a bearing or of recognising the colour and pattern of a signal require foveal observation so that in an analysis scotopic phenomena and variations with retinal location may be generally ignored. Thus background brightnesses have little influence on the photopic threshold up to about 0.01 cd. m^{-2}, explaining the great stability of the threshold under navigational conditions. Again adaptation is rapid in the brightness range from the photopic threshold up to about 6000 trolands, and with major flashing aids, flashes occur at intervals of several seconds allowing adequate recovery in the event of a disturbance of the visual sensitivity by another light in the visual field.

Difficulties arise when interfering light sources hinder the sighting of a navigational aid, or certain navigational aids themselves or ships' lights hinder the sighting of other aids in the vicinity. In urban areas glare may be caused by public or private lights and automobile headlights may be troublesome when a road follows a navigation channel rather closely. Port entrance lights, direction and other lights along the axis of a channel are the main dazzling beacon lights as the level of the bridge may reach that of the lights, but as only foveal vision need be considered, the navigator will only be troubled by glare if the navigates with the help of aids in the immediate vicinity of other lights in a navigation channel. An interesting aspect is that under certain viewing conditions the presence of other background lights may provide a frame of reference against which the flashing signal may be sighted - otherwise there is actual danger of a faint signal consisting of short flashes separated by long intervals being lost against a uniform background when considerable scanning may be again required for its location. Interest is now growing in the detection of flashing signals against a wider range of background luminances as in daytime such lights are being increasingly used in both inland and maritime waterways and lighthouses are more often operated under conditions of bad visibility.

Rail and road conditions also necessitate flashed lights being used by day and night under widely different conditions of ambient illumination. Though viewing is generally restricted to a zone near the horizontal plane, the first flash may not be actually seen but merely awakens the attention of the observer who then adjusts his direction of view to bring successive flashes nearer to the visual axis for more precise perception. Under such circumstances the dynamic conditions and the environment as well as the degree of concentration of the observer may markedly influence the perception of a signal. In arrays of flashing lights, the spatial distribution and the time randomisation seem significant; thus a pattern of lights flashing in synchronism may appear highly conspicuous. Though road signals are usually of ample point brilliance, they may suddenlly appear at almost any point in the visual field, often against a distracting background of movement, street lights and other signals, and the motorist may be exptected to react immediately. The speed of motor traffic leads to rapid changes in the angular subtense of light sources and too bright a source in close proximity of a vehicle may be a potential source of irritation to the driver. The glare of headlamps is a troublesome problem for which no satisfactory solution seems as yet in view. On the other hand one may comment on the non-visibility of traffic signals when the sun is low on the horizon or under high levels of daylight illumination as met with in the tropics.

The pilot of an aircraft must pick up information from signal lights under the most diverse and rapidly varying conditions and failure of the proprioceptive mechanism under the accelerations encountered in aviation may render more difficult the search for a target even when its direction is approximately known. Guiding lights of aerodrome taxiways are used under all weather conditions and their design involves problems of conspicuity and recognition. There are numerous lights, fixed and flashing, with which aviation lights may be confused: white warning signals on aircraft may escape detection against a background of stars and a car headlight may be mistaken for an airway beacon. The use of red signals has been advocated, but such are not easily perceived by peripheral vision. Warning signals may appear almost anywhere in the field of view though collisions between aircraft and stationary objects involve relatively smaller viewing angles (10° to 15°) than collisions between aircraft flying on converging paths when detection at the extreme periphery of the visual field may be necessary. It is incorrect to assume that the state of adaptation of the eye is determined by the illumination of the background against which the signal is perceived; the effect of lights within the cabin, panel lights, etc., must be taken into account. The design of flashing signals for supersonic aircraft poses special problems owing to the very high speeds involved. Further, signals may appear against backgrounds varying from darkness to sunlight falling on snow or a bank of fog. Table 1 conveys an idea of the various background luminances against which signals may have to be detected under conditions of aerial and maritime navigation:

TABLE 1

Values of luminances met with in practice.

(a) The sun at zenith seen from the earth, mean.	1.65×10^9 cd. m^{-2}
(b) Daytime conditions.	
Clear sky near horizon, about noon, according to Middleton	10^4 cd. m^{-2}.
Overcast sky near horizon, about noon, according to Middleton	10^3 "
Grey sky near horizon, about noon, according to Middleton	10^2 "
Clear sky at noon, according to Langmuir and Westendorp (1931)	10^4 "
Glaring white clouds, according to Schönwald, quoted by P. Jainski (1960)	10^4 "
White clouds, according to Schönwald, quoted by P. Jainski (1960)	3×10^3 "
Grey white clouds, according to Schönwald, quoted by P. Jainski (1960)	10^3 "
Grey clouds, according to Schönwald, quoted by P. Jainski (1960)	3×10^2 "
Ocean, town, woods, seen from the air, according to Stiles, Bennett, Green (1937)	650 "
Fields and ploughed lands, seen from the air, according to Stiles, Bennett, Green (1937)	1400 "

continued/...

Dry sand, seen from the air, according to Stiles, Bennett, Green (1937)	2700	cd. m^{-2}.
Fog surface or snow, seen from the air, according to Stiles, Bennett, Green 1937)	1.4×10^{4}	"

(c) Sunset conditions

Overcast sky at sunset, near horizon, according to Middleton, quoted by P. Blaise (1960a)	10	"
Clear sky, 15 min. after sunset, according to Middleton, quoted by P. Blaise (1960a)	1	"
Clear sky, 30 Min. after sunset, according to Middleton, quoted by P. Blaise (1960a)	10^{-1}	"
Nightfall, according to Sch"onwald, quoted by P. Jainski (1960a)	10^{2}	"

(d) Night conditions

Starlit sky, according to Langmuir and Westendorp (1931)	5.5×10^{-4}	"
Moonlit sky, according to Langmuir and Westendorp (1931)	2.2×10^{-2}	"
Full moonlight on snow, according to Langmuir and Westendorp (1931)	7.5×10^{-2}	"
Sky by full moon, according to Middleton, quoted by P. Blaise (1960a)	10^{-2}	"
Clear moonless sky, according to Middleton, quoted by P. Blaise (1960a)	10^{-3}	"
Overcast moonless sky, according to Middleton quoted by P. Blaise (1960a)	10^{-4}	"
Sky luminance at night in Baltic Sea, according to W. Adrian and H.D. Hohnbaum (1965)	3.8×10^{-5} to 3×10^{2}	"

The preceding paragraphs illustrate the diversity of conditions met with in modern traffic and emphasise two different aspects of conspicuity. Guiding signals from which a navigator takes his bearings are generally approximately known in position and sufficient time may be available to search for them. Such signals may be of long range and of low apparent intensity near the range limit, but they must be readily recognised and correctly identified. Reliability of identification seems then to be the most important criterion of conspicuity. Danger or warning signals on the other hand are often of sudden appearance and must force themselves upon the observer's attention wherever they happen to appear in the field of view, and the time for their detection may be severely limited. In this case, reaction time as measured from the onset of the stimulus may be a more satisfactory criterion of conspicuity. Whereas for guide lights, correct identification may depend largely on metathetic contrast, in the case of warning signals prothetic contrast would be the more important factor. Cases may arise in practice however where both aspects are of comparable importance.

The following methods have been used or put forward at some time or other for the measurement of conspicuity:

1. Measuring the eccentricity with the visual axis at which a flashing light disappears - by varying the angle of presentation or presenting the sources at a series of definite angles - and taking this angle as a measure of conspicuity.

2. Measuring the level of background luminance against which a flashing light is just visible.

3. Comparing directly sources of different flash character and asking the observer to state which of the sources appears most conspicuous. A subjective scale of conspicuity may thus be set up by observer classification into different categories or estimation of the magnitude of his subjective impression.

4. Measuring the increment in a given parameter producing a just noticeable difference in conspicuity and setting up a scale thereby.

5. Measuring the reaction time when the observer is asked to perform some simple task. The validity of push-button response as a measure of anything has at times been questioned; in certain cases it is likely that the results may reflect the difficulty of the response and not that of detection of the signal.

6. Using the probability of detection of a signal within a given time limit as a measure of the conspicuity.

7. Using the fixed light equivalent as a measure of the conspicuity.

Of these methods, 1 and 2 essentially reduce to threshold measurements at different retinal locations and under different conditions. The threshold has been the most widely used measure of the visual response and is possibly the most accurate.

It sets a lower limit for detectability making possible the determination of the effective range of a signal and is a useful guide to the variation in perception across the visual field. One must exercise caution though in generalising conclusions derived from threshold experiments to conditions where signals appear well above threshold and under different metathetic contrast. In practice adequate conspicuity may often be achieved by allowing for a safety margin above the measured threshold. Adrian and Jainski (1960) have defined the "conspicuity factor" as the ratio of the threshold when the observer is not aware of the position of the stimulus to the threshold when the position is known. Simulating the conditions on a ship's bridge at night they have experimentally obtained values ranging from 2.5 to 3.3 for this factor (fig. 2). Using a "disturbing light" of 3.7° angular subtense and 0.14 cd. m^{-2} luminance to simulate illuminated instruments on the bridge, they detected no change in the conspicuity factor though the disturbing field produced discomfort which passed off as the surround luminance was raised. Earlier, Roper and Howard (1938) had determined the value 4.0 for the conspicuity factor for the visual conditions prevailing for the driver of a motor vehicle, but road conditions must have altered considerably since then!

Subjective scales of conspicuity would depend on the observer estimating an apparent intensity relative to some standard set by himself or the experimenter. The scale most directly related to the input-output function of the sensory system would appear to be the magnitude scale, whereas the j.n.d. scale describes the variation of resolving power with stimulus magnitude. According to Stevens (1961) these scales are not linearly related to each other or to the category scale which is "at best an interval scale on which the zero-point is arbitrary" and "not even a good interval scale as it is non-linearly related to the ratio scale of apparent magnitude".

It is doubtful whether conspicuity scales may be set up by measuring reaction time or probability of detection within a given time. Such measurements may become meaningless at high stimulus intensities when there is certainty of detection within a negligible time interval. However, signals must be operated economically and must be conspicuous without being too obtrusive or interfering unduly with the detection of other signals, and within this range of operation these measurements may give valuable information about signal performance and help us decide which of two signals is the better one. It would appear therefore that if conspicuity be defined in terms of subjective brightness or apparent intensity, a scale of conspicuities may be arrived at similar in many respects to the "brill scale" proposed by Wright (1941). The term "absolute conspicuity" may be applied to conspicuity measured on such a scale. It is suggested that the term "relative conspicuity" or "contrast conspicuity" be used when we imply reliability of identification against a heterogeneous background of other fixed and flashing lights and the expression "conspicuity as measured by reaction time" or simply "reaction time conspicuity" be used when reaction time measurement is the basis of comparison. Though it does not seem so far possible to set up subjective scales of conspicuity based on these definitions, they may express more clearly what we think we have in mind when in practice we decide that a signal has adequate conspicuity either through "the certainty of its being identified" or "its being responded to within a limited time interval from the moment of its appearance".

CHAPTER II

CERTAIN ASPECTS OF THE VISUAL RESPONSE AND OTHER CONSIDERATIONS

The present chapter aims at a brief review of certain aspects of existing knowledge relevant to the study of flashing lights. Topics requiring a more detailed discussion are considered elsewhere in the text.

The Photometry of Flashing Light Signals.

All photometric measurements ultimately refer to a standard light source which is internationally defined and set up by the various National Standardising Laboratories. The essential judgment the observer is called upon to make is of the equality of luminance of two geometrically similar fields, one of which is illuminated by a test lamp and the other by a suitable comparison lamp. If both sources being compared emit radiation of the same spectral composition in the visible region of the spectrum, the equation of the visual sensation necessarily implies equation of the radiant energy flux from the two fields, irrespective of the spectral sensitivity of the observer's eye. But luminous flux is radiant energy flux weighted by its effectiveness in stimulating the eye, and with spectrally different sources, the subjective impression of equal brightness need not correspond to equality of the physical energy flux. In fact, the observer may often have to establish a luminosity match in presence of a residual colour difference and this illustrates the essentially visual character of brightness matching. It is assumed that the observer can isolate in his mind the luminosity attribute (a sensation belonging to the class of prothetic continua) from the colour attribute (..... metathetic continua). The task is not easy - the various devices by which the difficulty can be overcome form the subject of heterochromatic photometry - but presumably it is legitimate and meaningful. The results may depend on the retinal location and the field size used, the state of adaptation of the observer and other characteristics of his visual response. Moreover, observer variations will occur to some extent. Hence photometrists have come to base all specifications on measurements with fields of prescribed size and brightness and refer the final results to an imaginary standard observer having a visual sensitivity averaged for a large number of observers.

Unfortunately, in the photometry of light signals, the standard conditions laid down by the photometrist can hardly be satisfied. Distant lights may subtend such a small angle at the eye as to be effectively punctual, and may not produce sufficient illumination on a photometer screen to permit measurement. There is a greater interest in the subjective intensities when these signals are viewed directly and the only significant procedure would appear to be comparison with a small standard source under similar conditions of observation. A decision has to be made about the proper viewing conditions. The apparent intensity of a small source may show considerable variations with eccentricity from the visual axis and one may choose to carry out measurements at the most sensitive position in the visual field or to approximate as closely as possible to the conditions under which the light will be seen in practice. At low levels of illumination, the primary function of the retina seems to be the detection of light and not the discrimination of detail and this is assisted by the spatial summation processes occurring within the eye; this necessitates the test and the comparison source to be as nearly as possible of the same angular size. So far it has been assumed that the photometric property measured has been the candle power, but it may not be desirable to incorporate this in the specification of a distant signal unless the distance of this signal from the observer and the transmission characteristics of the intervening media be known. It may be more relevant to specify the illumination produced by the source in the plane of the observer's pupil or the retinal illumination if the source is of finite area. The particular unit used will depend on the magnitude of the source and what one is primarily interested in.

Whereas ordinary photometry involves the measurement of light falling continuously on the retina, especially during the observation of a uniform extended field, when we are considering intermittent and transient phenomena the growth and decay of the visual response cannot be ignored. The photometry of flashing lights is necessarily affected by the terminal processes at onset and cessation of stimulation and one must examine carefully what the photometric procedures mean in this case.

There is no parallel in vision to the measurement of the photographic efficiency of a flash. In a standard experiment the surface illuminated by a flashing light is matched in luminosity against a surface under continuous illumination. The judgment of equality is not easy but one can generally tell when one half of the field is brighter than the other half or vice versa. We are here accepting the possibility of equating the transient luminosity sensation produced by a flash with the continuous sensation produced by a steady source. As the visual sensation varies during the perception of the flash, the equality setting may be in respect of an average or maximum sensation, though for flashes longer than about 0.1 second it seems likely that the observer continuously readjusts his criterion and equality is in respect of the sensation towards the end of the response. There is no possibility of prolonged comparison between the two surfaces and the match may to some extent be a memory match -

in fact in the experiments of Toulmin-Smith and Green (1933) and in certain experiments of Blondel and Rey (1911, 1912), the test and comparison flashes are presented alternately so that a memory match is necessarily involved. The equation of the luminosity sensation no longer implies equation of the luminous flux as the course of the response bears no simple relation to that of the physical radiation. The specification of the visual response to a flash in terms of "apparent lumens," etc., is understandable enough as it gives a measure of the visual effectiveness of the flashing light as compared with that of a steady source, though it may be debatable whether this is a legitimate use of photometric quantities. Confusion is not likely to arise however if one recognises the distinction between the physical and psycho-physical aspects of the problem, which has been reviewed by Wright (1949) in his examination of the basic ideas and concepts of visual photometry.

The Effective Intensity or Fixed Light Equivalent of Flashing Lights

From the preceding it would appear that the effective intensity or fixed light equivalent of a flashing light may be defined as the intensity of the steady source which matches for luminosity sensation the flashing light. This fixed light equivalent will vary with the experimental conditions and the equality setting may not be accurate especially for observations well above the threshold - Projector (1957) is of opinion that the concept should be avoided at high levels of illumination - and it is doubtful whether it gives any measure of conspicuity. However, it may serve as a useful basis for the comparison of flashing lights with different characteristics. In the limiting case, all flashing lights which are at threshold under a given set of observing conditions may be considered equivalent, though this equivalence may fail with a change in background intensity or retinal location.

The variations of the threshold and the effective intensity with changes in the characteristics of the test source and the background have occupied the attention of many experimenters though certain aspects of the problem are as yet not fully understood. Talbot (1834) had already concluded that the effective intensity was proportional to the flash duration and Swan (1849) put forward the same idea. A clearer formulation was given by Bloch (1885) and Charpentier (1887). Bloch believed that he had established that the quantity of light required to produce a threshold sensation was fairly constant and depended on the product "intensity x flash duration,"

$$It = \text{constant} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Charpentier, working with lights above the threshold, verified Bloch's law within certain limits and concluded that the reciprocal relationship held only for flashes of duration less than 0·1 second, longer stimuli behaving like steady lights (Fig. 3). MacDougall (1904), whose remarkable series of experiments are too often overlooked, extended this summation time to 0·2 second. Helmholtz and Brücke (1866), Exner (1868), Allard (1872), Bidwell (1894) also studied the phenomena, but the most thorough suprathreshold investigations were probably those of Broca and Sulzer (1902-1904).

Helmholtz, Brücke and Exner had already noted that as the duration of a flash well above the threshold was increased the luminosity sensation went through a maximum which was more rapidly attained at high intensities. Their methods were however open to criticism and Charpentier trying similar experiments failed to observe the effect as his intensities were not sufficiently high and his equipment did not permit a sudden exposure of the test field. Broca and Sulzer compared the apparent intensity of a flash with that of a steady light in a photometric match between two contiguous fields and showed that, except for very faint sources, the apparent luminance L_a rises at first linearly, exceeds the steady value L, attains a maximum equal to kL for a certain flash duration t_m and falls back more gradually to the value L (Fig. 4). The initial gradient of the curves and the value of k increased with the luminance of the test field and were greater for blue than for white or other coloured light.

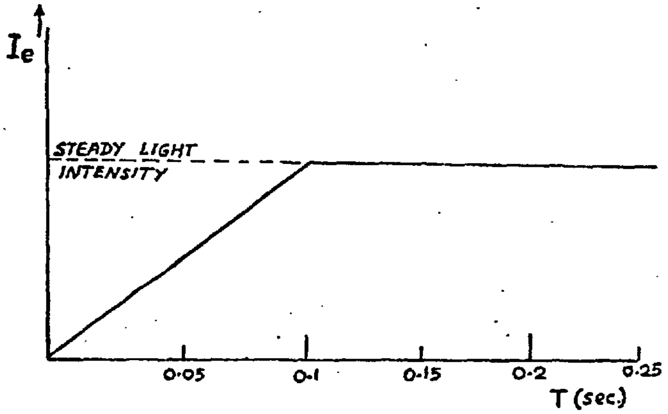


Fig. 3. Variation of apparent intensity with flash duration according to Charpentier.

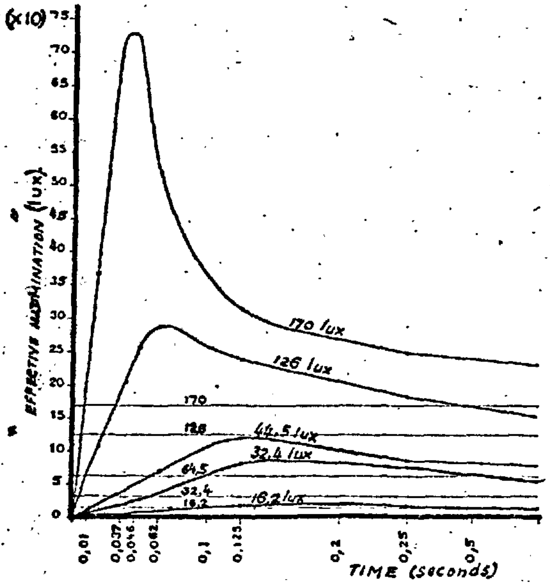


Fig. 4. Curves of Broca and Sulzer showing the variation of apparent intensity with flash duration for different luminances of the test field.

This "pre-equilibrium oscillation" in the visual response was studied further by Büchner (1907), Bills (1920), Kleitman and Piéron (1925), Stainton (1928), Juricic (1952), using similar methods to the above. Bills' results are essentially the same as those of Broca and Sulzer. The measurement of t_m being difficult, Kleitman and Piéron preferred to determine the equilibrium time t_e at which L_a first attains the value L before going to the maximum and their results approximately satifies the relationship

$$\frac{1}{t_e} = a \log L + b \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

They also claim that the rate of rise is higher for peripheral than for foveal vision though this may be ambiguous as their brightness levels are all expressed in multiples of the threshold brightness as determined for each condition. Büchner and Stainton have drawn attention to the possible occurrence of a second overshooting effect (Fig. 5) and Stainton finds that in moderate light adaptation the rate of rise is higher than for dark adaptation. Piéron's experiments with coloured flashes contradict earlier observations, and Stainton concludes that there is no peculiar characteristic distinguishing various spectral regions and that the rise in the visual sensation is primarily a function of intensity and not of wavelength.

More recently, Raab (1962) has used a method of direct magnitude estimation and Raab and Osman (1962), Katz (1964), Naus (1967) have compared a test flash of variable duration with a standard flash, using both monocular and binocular matching techniques, and co-beginning and co-terminating methods of presentation. Overshooting is observed in direct magnitude estimation, but in the comparison of two flashes with coincident onsets the effect is not observed, pointing to some artefact of the experimental technique which may bias the outcome. Katz obtains similar curves in uniocular and binocular experiments though the effect may be more marked under binocular viewing conditions. Lassalle (1947) has put forward a photochemical theory to account for the Broca Sulzer phenomenon but according to Boynton and Kandel (1957), Alpern and Barr (1962) the correct explanation can hardly be photochemical. In fact, apart from the fact that observers generally agree that the rate of rise of the apparent intensity increases with luminance, there seems to be very little agreement about anything at all!

In the Broca Sulzer experiments the apparent intensity of a flash only approaches the steady value for durations greater than one or two seconds. Certain experiments of Ribière (1908) seemed to indicate that a slow fall of the threshold went on indefinitely with increase in exposure

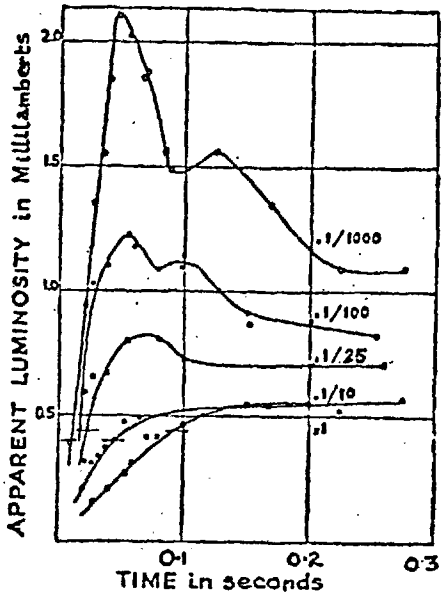


Fig. 5. Curves of build-up of the luminous sensation at 5 levels of brightness (from Stainton). Smallest brightness designated by 1, highest by 1/1000.

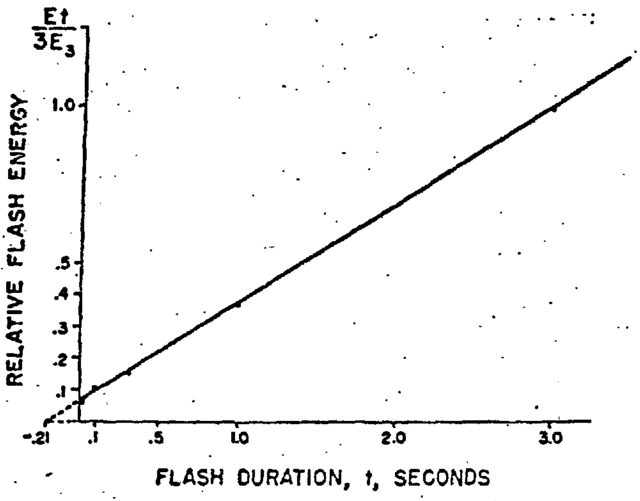


Figure 6. Ratio of test flash energy required for threshold excitation to energy of a threshold flash of 3 seconds duration as a function of test flash duration. (Blondel and Rey).

time. Blondel and Rey (1911, 1912) found it difficult to agree with Charpentier (Fig 3) about the sharp break in the threshold curve - "natura non fecit angulos". It appeared a priori to them that to detect a point source just at threshold, one should search for an infinite time as the eye could not remain fixated upon the target long enough to detect it. Whereas Bloch's law (eq.1) is a rectangular hyperbola with the co-ordinate axes as asymptotes, Blondel and Rey argued that if Eo be the illumination produced at the eye by a point source at absolute threshold, then the threshold illumination E for a flash of duration t should satisfy the relation

$$(E - E_o)\, t = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

and they set out to test their hypothesis.

The Blondel-Rey law has played such an important role in the design of flashing signals that it seems worth while considering their experiments in some detail. Using central fixation they presented flashes of square wave-form at a repetition rate of one every 3 seconds to their observers to avoid interaction between successive flashes. The stimuli were of 1' to 4' angular subtense in Blondel's apparatus and sufficiently small in Rey's apparatus to be considered point sources. A method of successive comparison was used in which brief flashes were compared with flashes of 0.03 and 0.3 sec and longer flashes with flashes of 3 sec. duration, the following durations being used:

0.001, 0.003, 0.01, 0.03, 0.1. 0.3, 1, 3 seconds

Equality of two flashes was obtained by either successive or simultaneous comparison and it was noted that the impression of simultaneity depended on the flashes co-terminating. Blondel used both alternate and simultaneous presentation whereas in Rey's experiments the observer receded from the sources which were adjusted in intensity until they disappeared together - Rey found that as one approached the sources again the shorter flash appeared to be the more intense. The mean of their observations for 17 observers is given in fig. 6 where the ordinate of a point is the ratio of the energy of a threshold test flash of t sec. duration to that of a three second threshold flash. The intercept on the time axis is -0.21 second and the results may be represented by:

$$(E - E_o)\, t = 0.21\, E_o \quad \ldots\ldots\ldots\ldots \quad (4)$$

as predicted theoretically. It may be noted here that, owing to the inherent imprecision in such measurements, large variations are likely to occur among individual observations and that the authors attribute the good straight line fit to "un heureux hasard".

Eq. 4 may be written as

$$\frac{E_o}{E} = \frac{t}{a+t} \quad \ldots\ldots\ldots\ldots \quad (5)$$

and as at threshold intensity may be used interchangably with illumination

$$I_e \doteq \frac{It}{a+t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where I_e is the effective intensity of a flashing light of instantaneous intensity I and duration t. Values between 0.15 and 0.25 sec. have been obtained for the constant 'a' and the C.I.E. committee (1963) recommended that the value 0.2 sec. be adopted for the calculation of fixed light equivalents at threshold.

For the foveal threshold values from 0.11 to 0.39 mile-candles have been measured by various investigators, but it is accepted practice to utilise a practical limit somewhat above the absolute threshold obtainable under idealised viewing conditions. From the data of Table 2, excluding the results of Rey and Van Vloten which were based on observations of the visibility of neighbouring lights by lighthouse operatives and which were considered by Hampton and Holland (1933) as unreliable, the mean value for the practical limit is 0.34 mile-candle. At the Lighthouse Conference in Paris (1933) a practical visual threshold of 0.5 mile-candle or 2×10^{-7} lux was agreed upon; in the U.S.A. the value 0.67 sea mile-candle is used.

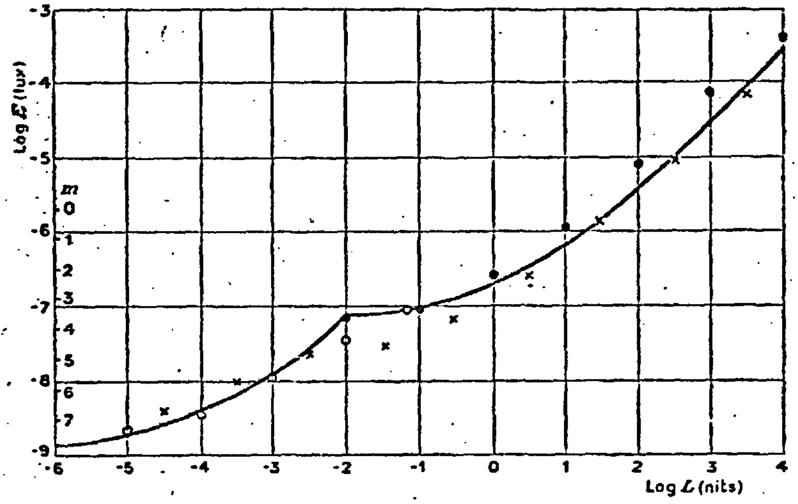


Fig. 7. Threshold E for a point source as a function of the background luminance L. (circles; Langmuir and Westendorp; dots: Green; crosses: Blackwell. The curve represents Hecht's formula.
m: stellar magnitude.)
(according to Legrand)

TABLE 2.

Foveal Thresholds, after Stiles, Bennett and Green (1937).

Investigator	Minimum eye ellumination in mile-candles. Foveal Threshold	Practical limit
Allard (1876)		0.26
Deutsche Seewarte Report		0.35
Blondel and Rey (1911)	0.13 to 0.26	
Patterson and Dudding (1912)		0.31
Rey (1913)		0.78
Gehlhof and Schering (1919)	0.36	
Van Vloten (1920)		0.78
Löhle (1927)	0.39, 0.28	
Toulmin-Smith and Green (1933)		0.425
Stiles and Crawford (1937)	0.11, 0.15	
Green (1935)	0.16	

In practice the threshold for a point source against a background of low luminance E is of greater interest than the absolute threshold. Knoll, Tousey and Hulburt (1946) determined this for five young observers viewing a source of 1' angular subtense and colour temperature 2360°K against a 20° background. Hecht (1947) showed that their results fitted very well the empirical formula

$$E = a\,(1 + b/\sqrt{L})^{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

where $a = 1.5 \times 10^{-9}$ lux $b = 4000$ cd.$^{-1}$ m^{2} for scotopic vision

and $a = 7 \times 10^{-8}$ lux $b = 0.4$ " " " photopic vision.

This curve is shown in Fig 7, where the data of Langmuir and Westendorp (1931), Green (1935), Blackwell (1946) are also plotted for comparison.

Toulmin-Smith and Green (1933) carried out experiments with a view towards finding a law that would allow the calculation of the effective intensity of a flashing light at the practical limit of range rather than at the absolute threshold. A test flash of variable intensity was compared with a fixed light producing a known illumination at the observer's eye by a method of alternate presentation. No difficulty was experienced in obtaining consistent readings at low illumination levels but above 1 mile-candle the observations were less accurate. Their results have been given in Fig 1 and from these the curve of Fig 8 was obtained by interpolation for the practical limit of 0·425 mile-candle, and this conforms to the equation.

$$I_e = \frac{1{\cdot}1\ It}{0{\cdot}15+t} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

For comparison a curve following the Blondel-Rey law is also shown as well as one derived from a simplified expression proposed earlier by Van Vloten (1930):

$$I_e = \frac{1{\cdot}4\ It}{0{\cdot}2+t} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Hampton (1934) found eq. 7 and 8 difficult to justify as it seemed essential that the apparent intensity of a long duration flash should approach that of a steady light. Treating the constant 'a' of eq. 6 as a function of the illumination E_c at the observer's eye he derived from Toulmin-Smith and Green's

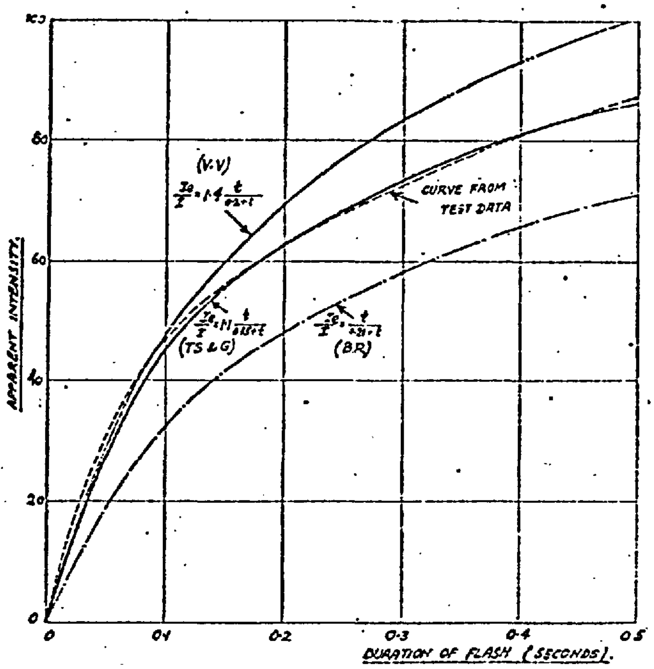


Fig. 8. Variation of effective intensity ratio with flash duration at the practical limit of range. (Toulmin-Smith and Green)

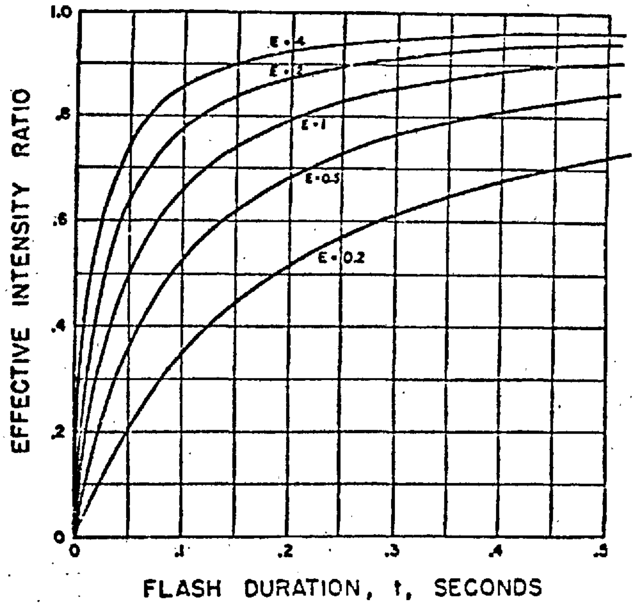


Figure 9. Representation of Toulmin-Smith and Green data (Fig. 1) as recast by Hampton in the form of the Blondel-Rey equation, with the value of *a* empirically determined from the data (equation 11).

results the relation

$$E_c\, a^{1.235} = 0.0255 \tag{10}$$

or $$\log a = \bar{2}.37 - 0.81 \log E_c \tag{10a}$$

so that $$I_e = \frac{It}{\left(\frac{0.0255}{E_c}\right)^{0.81} + t} \tag{11}$$

The family of curves derived from this equation fit the Toulmin-Smith and Green data fairly well (Fig 9). However the work of Schuil (1940) at an eye-illumination of 2 mile candles did not confirm the value of "a" or the increase in the fixed-light equivalent noted by Toulmin-Smith and Green. From experiments at supra threshold levels Luizov (1954) and Luizov and Bulanova (1957) have derived a relation which may be written as

$$\log a = \bar{2}.88 - 0.23 \log E_c \tag{10b}$$

More recently Hampton has given the modification

$$I_e = \frac{It}{a(1-nt) + t} \tag{11b}$$

to his original formula, and this gives better agreement with the data of Schuil. He has suggested that (1-nt) be treated as a "searching time factor".

The flash from most flashing signals is not abrupt. The instantaneous intensity may rise and fall gradually, varying appreciably during the flash. Some specifications for flashing lights have used the relation

$$I_e = \frac{I_{max}\, t}{a + t} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

where I_{max} is the maximum instantaneous intensity for evaluating the effective intensity, the value of 'a' being often adjusted to give reasonable agreement between the computed and observed values of I_e. Shortly after the publication of their original paper however Blondel and Rey (1911) gave an integral form of their equation which has been little used,

$$I_e = \frac{\int_{t1}^{t2} I\, dt}{0.21 + (t_2 - t_1)} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

where the numerator on the right hand side represents the light energy in the flash between the time limits of integration t_1 and t_2. The difficulty here seems to be the ambiguity in the choice of the time limits. It seemed illogical to Blondel and Rey to extend the integration to times when the instantaneous intensity of the flash was below the threshold for a steady light, and they suggested that the limits should be the times when the instantaneous intensity was equal to this threshold. When the specification for aircraft anti-collision lights was being drafted it was suggested that the limits be so chosen that I_e were a maximum. Douglas (1957), by an application of the calculus of variations, showed that the maximum effective intensity is obtained when the intensity at the beginning and the end of the interval of integration is equal to the effective intensity. He has further extended the method to the calculation of the intensity of a group of flashes separated by intervals of the order of 0.01 sec. or less, so that they appear as a single flash (Fig 10).

$$I_e = \frac{\int_{t_1}^{t_a} I\,dt + \int_{t_b}^{t_c} I\,dt + \int_{t_d}^{t_e} I\,dt + \int_{t_f}^{t_2} I\,dt}{a + t_2 - t_1} \quad \ldots\ldots\ldots\ldots (14)$$

Douglas' analysis neither proves nor disproves the validity of the integral form of the Blondel Rey equation, though the use of the maximum value of I_e may not be valid except when the light is at or near threshold.

The time taken to locate a flashing light and reaction time measurements.

Whereas in laboratory experiments the approximate position at which a flashing light is going to appear is often known to the observer, such may not be the case in actual practice. Langmuir and Westendorp (1931) carried out experiments to determine the time taken to locate a flashing light against a rectangular background of luminance 7×10^{-3} cd/sq. ft. and subtending 56° horizontally by 19° vertically at the observer's eye. The flash intensity was a constant multiple L of the threshold intensity appropriate for the observer and it would appear from the level of the background luminance used that the foveal threshold was implied. Their results could be

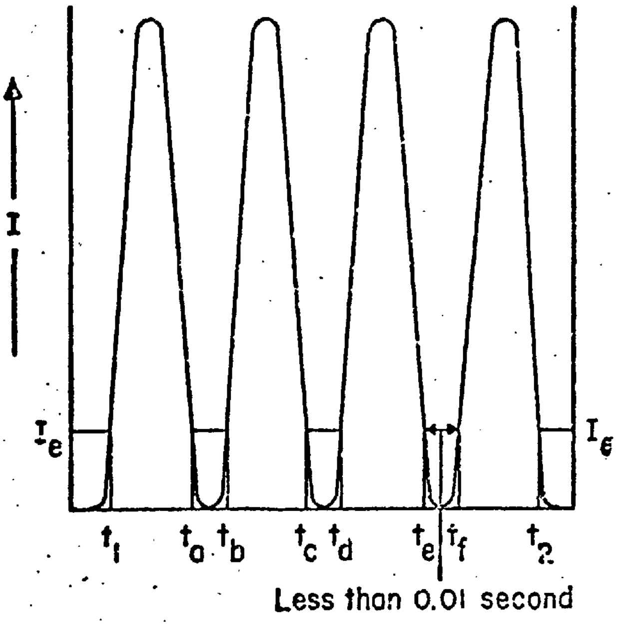


Fig 10. Illustrating the application of the method of calculation of Douglas to multiple flashes.

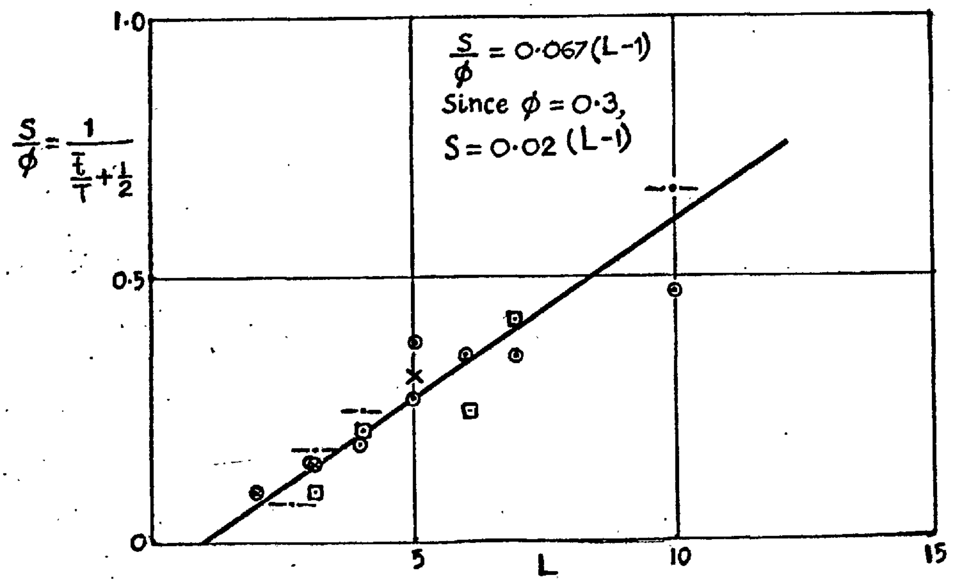


Fig. 11. The formula of Stiles, Bennett and Green fitted to the data of Langmuir and Westendorp.
(Stiles, Bennett and Green)

represented by the formula

$$(\bar{t}-0.5T)\ (L-1)^{3/2} = 67\ \phi\ T \ \ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

where $\bar{t}$ is the average finding time, T the period of a flash of short duration and ϕ the solid angle within which the signal is sought. They reasoned that since it takes a relatively long time to detect a flashing light only a few times brighter than at the threshold, there is a searching process during which the flash will not be perceived unless it is within a small area on which attention is being focused. For low intensity flashes the finding time should therefore be proportional to the flash period T and the solid angle ϕ.

Stiles, Bennett and Green (1937) have given the following analysis:

For a given L, suppose the flash is seen if it falls on a small foveal area corresponding to a small angle S in the visual field, S being a function of L which vanishes when $L=1$. The probability of first spotting the flash in time dt will be

$$(S/\phi)\ (dt/T) \quad \text{for } t \leq T$$

$$(1-S/\phi)(S/\phi)\ (dt/T) \quad \text{for } T \leq t \leq 2T$$

and generally $(1-S/\phi)^n\ (S/\phi)\ (dt/T)$ for $n\,T \leq t \leq (n+1)\,T$

The average finding time is given by

$$\bar{t} = \sum_{n=0}^{\infty} \int_{nT}^{(n+1)T} t\ (S/\phi T)\ (1-S/\phi)^{n}\ dt$$

or

$$\bar{t} = T\left(\frac{\phi}{S} - \frac{1}{2}\right) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

If $S > \phi$ the signal is certainly seen when it flashes and we replace ϕ/S by unity. Fitting this formula to Langmuir and Westendorp's data (Fig. 11) one obtains as a tolerable approximation

$$S = 0.02\,(L-1)$$

$$(\bar{t} + T/2)\,(L-1) = 50\,\phi\,T \quad \text{for } L \leqslant \frac{\phi - 0.02}{0.02}, \quad \ldots\ldots\ldots\ldots \quad (17a)$$

$$\bar{t} = T/2 \quad \text{for } L \geqslant \frac{\phi - 0.02}{0.02} \quad \ldots\ldots\ldots\ldots \quad (17b)$$

This assumes the correct searching process though the formula need not hold for T greater than 1 or 2 sec. The searching process does not seem likely to be valid at scotopic levels of illumination when the parafovea has a higher sensitivity than the fovea, but Langmuir and Westendorp claim that their formula is applicable to zero background brightness - there is a possibility that they used the extrafoveal threshold as the unit of intensity in such cases. Their results also indicate that for a flashing signal to be picked up within the first few flashes it must be at least about ten times the threshold intensity.

Berger and Cattell (1886) and Piéron (1921) studied the dependence of human reaction time on the brightness of a test stimulus appearing on a background of fixed luminance, Hovland (1936) and Steinman (1944) studied the effect of changing the surround brightness, Hall and von Kries (1879), Poffenberger

(1912), Lemmon and Geisinger (1936) investigated the relationship with retinal position. The early experiments of Hall and Von Kries and Poffenberger established the following relations:

1. With a light adapted eye reaction time is least for bright images falling on the fovea.
2. the nasal and the upper retina yield faster reaction times than the temporal and lower retina respectively.

Lemmon and Geisinger argued that in the dark adapted eye the peripheral retina should show faster reaction time than the fovea as it is more sensitive and their measurements at 0° and 45° with the visual axis tended to confirm this, though the results were not very clear-cut. Galifret and Piéron (1948) using bright stimuli and the dark-adapted eye obtained faster reactions to foveal stimulation. This apparent contradiction was resolved by Bartlett and Mcleod (1954) in their study of the effects of flash and field luminance on the reaction time. These investigators used the fovea and a region 11° 20' below the fovea and observed flashes of 20' angular subtense and 575ms duration against backgrounds of 0.0, 0.4 and 40 mL. Their results (fig 12) may generally be represented by an equation of the form

$$T = \frac{1}{B \log (I/Io)} + K \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

where B is a slope constant, I the flash luminance, I_o a limiting flash intensity at which the reaction time approaches infinity and K a limiting latency which the reaction time approaches at high intensities. They find that foveal I_o values are lower than those obtained in peripheral vision except for very dim fields and confirm Lemmon and Geisinger's findings that peripheral stimulation yields shorter reaction times for dim flashes, whereas for bright flashes foveal reactions are faster as reported by Galifret and Piéron. More recently, Rains (1963) using flashes of 4' angular subtense and 0.023 sec duration, has shown that for scotopic stimuli the faster reaction occured at 10°- 20° eccentricity and that the nasal side of the retina was superior to the temporal side in this respect. These results have led him to advance a hypothesis to account for his findings in terms of the densities of the retinal elements in the human eye. According to him, any stimulus exciting the cones only should give speeds of reaction paralleling the count of cone density in the retina and with flashes of large area and duration the differences between the fovea and the periphery should be less apparent because of the greater capability for summation of the periphery.

The "attention getting effectiveness" of steady and of flashing lights has been compared by Gerathewohl (1953, 1954, 1957) by measuring the speed of response (reaction time conspicuity) when the observer was engaged in a complex task and did not know when to expect the signal to appear. In his

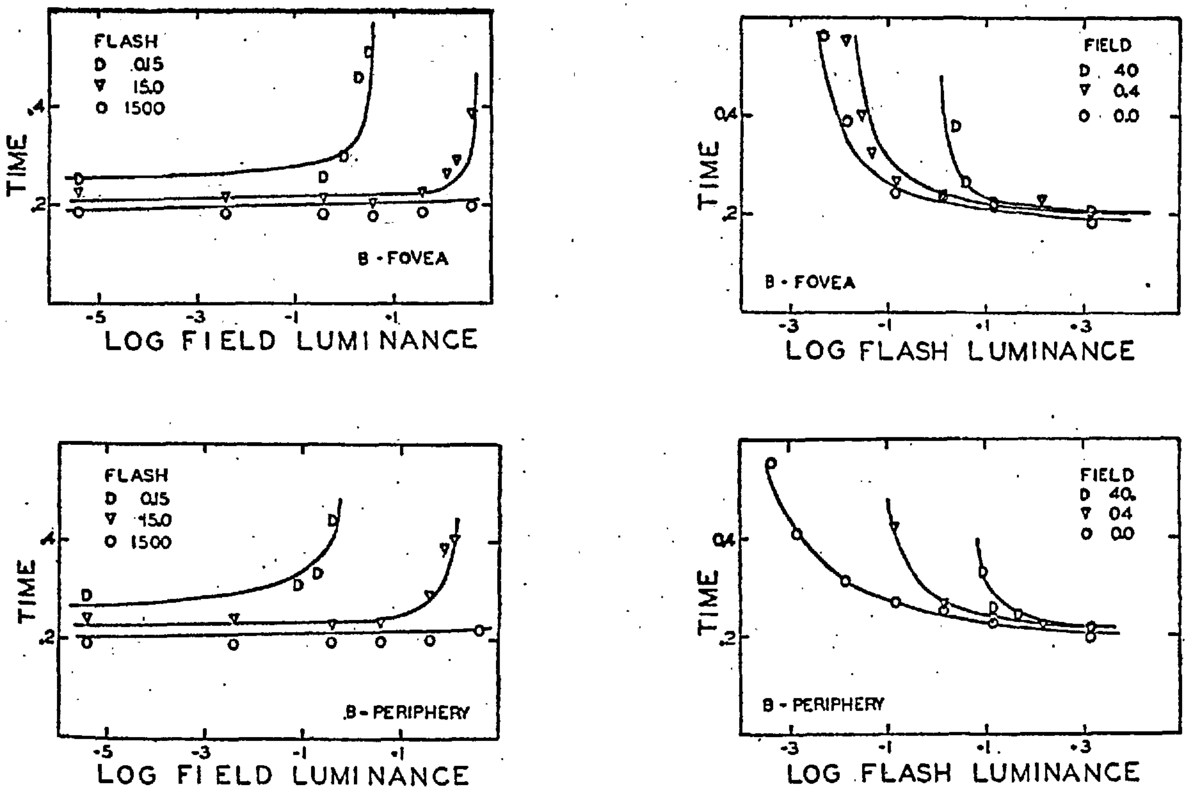


Fig. 12. Variation of reaction time (seconds) with field and flash luminance (mL) at the fovea (upper curves) and 11° 20' below the fovea (lower curves). (Bartlett and McLeod)

multiple complex reaction apparatus the test signal was located $15^{\circ}\ 30'$ above the visual axis on a screen of luminance about 2.6 ml. A second screen placed below the first carried distracting lights of various colours and luminances in the range 11.9 to 119.6 ml dotted around the fixation area. Two auditory distractions of different pitch were also used and the luminances of the steady signals were always matched by the luminances of the flashing signals. The observer had to respond in various ways to the distraction lights and auditory signals as well as to the test signal. All observers agreed that the task was complex and difficult and the sequence of signals unpredictable. His data for two series of experiments are given in Fig 13, the signal contrast value being defined by

$$\frac{L_2 - L_1}{L_1}$$

where L_2 = total luminance of the signal
L_1 = background luminance

The smaller values of T for both steady and flashing signals in the second series presumably indicate that the observers improved their ability to detect the signals with practice.

The results show that the comparative conspicuity of fixed and flashing lights as measured by reaction time differ markedly from the comparative visual effectiveness as measured by threshold or apparent brightness above the $\overset{h}{t}$reshold. Flashing lights have a higher threshold and a lower effective intensity than steady lights when not far above from the threshold, though at higher intensities they may appear brighter (Broca Sulzer effect). Gerathewohl finds however that for contrast ratios below 1.0 the response to a flashing light is faster than that to a steady light; at higher intensities there is very little difference between the reaction times, if anything the steady light evokes the quicker response. During the course of the experiments, no observer failed to respond to the flashing signals except at the lowest signal contrast used, but failure occurred with steady signals at all contrasts less than 1.0. For the lowest signal contrast the average response failures was 7.3 and 5.2 out of 15 presentations for steady lights but only 3.4 and 0.8 for flashing lights.

Using flash frequencies of $\frac{1}{3}$, 1, 3 c/s Gerathewohl also found that the change of reaction time with contrast was more pronounced at low frequency, and that at low contrast fast flashing lights give shorter reaction times than slow ones. On the other hand the effect of signal duration seemed to be only of marginal significance. Whereas at low frequencies an increase in flash duration increased the conspicuity, at higher frequencies the response to a 0.1 sec flash was quicker than for a 0.2 second flash. A similar observation had been made by Crumley and Atkinson (1954). The higher conspicuity of flashing signals at low contrast levels may be due to the

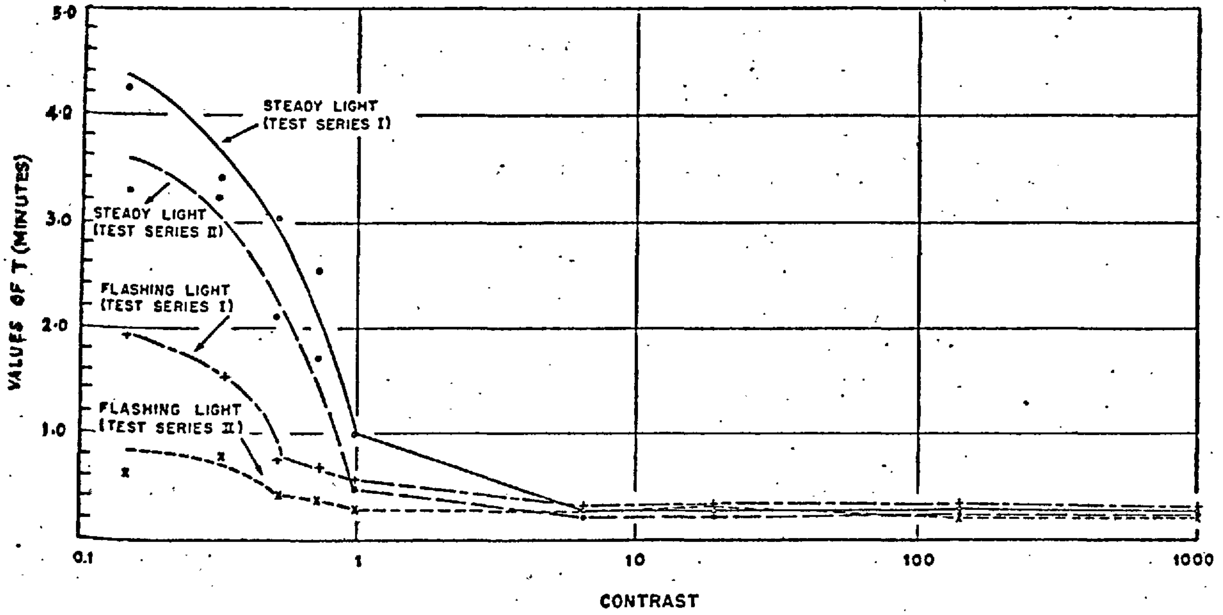


FIG. 13. Relationship between contrast and total response time (T).
(Gerathewohl)

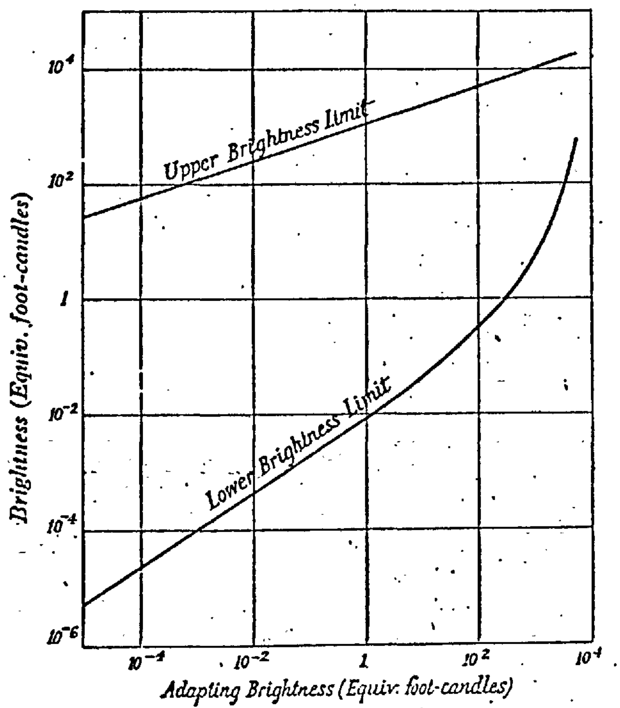


Fig. 14—Upper and lower brightness limits for various adaptation levels
(Nutting)

fact that detection may be dependent on the sequential variations in the nerve impulses at onset and cessation of stimulation - increasing the frequency then may give a greater probability of detection. Fol'b (1958, 1965) considers it well established that at threshold levels the conspicuity of flashing lights is considerably greater than that of fixed ones, though for stimulus intensities more than ten times above the threshold, the detectability of both kinds of signal is the same.

When viewing a light signal against a background of other "noise" lights one has to select perceptual information from a background of other irrelevant but often similar sensory information. A. Crawford (1962, 1963) has investigated the effect on the reaction time of irrelevant lights amongst which an essential signal occurs. Four conditions were used:

	Signals.	Irrelevant lights.
(a)	Flashing	Steady
(b)	Steady	Steady
(c)	Flashing	Flashing
(d)	Steady	Flashing

Fig. 15 summarises his findings. Earlier experiments by Moore et al (1958) had not been able to decide between the greater effectiveness of a flashing or a steady light against a background

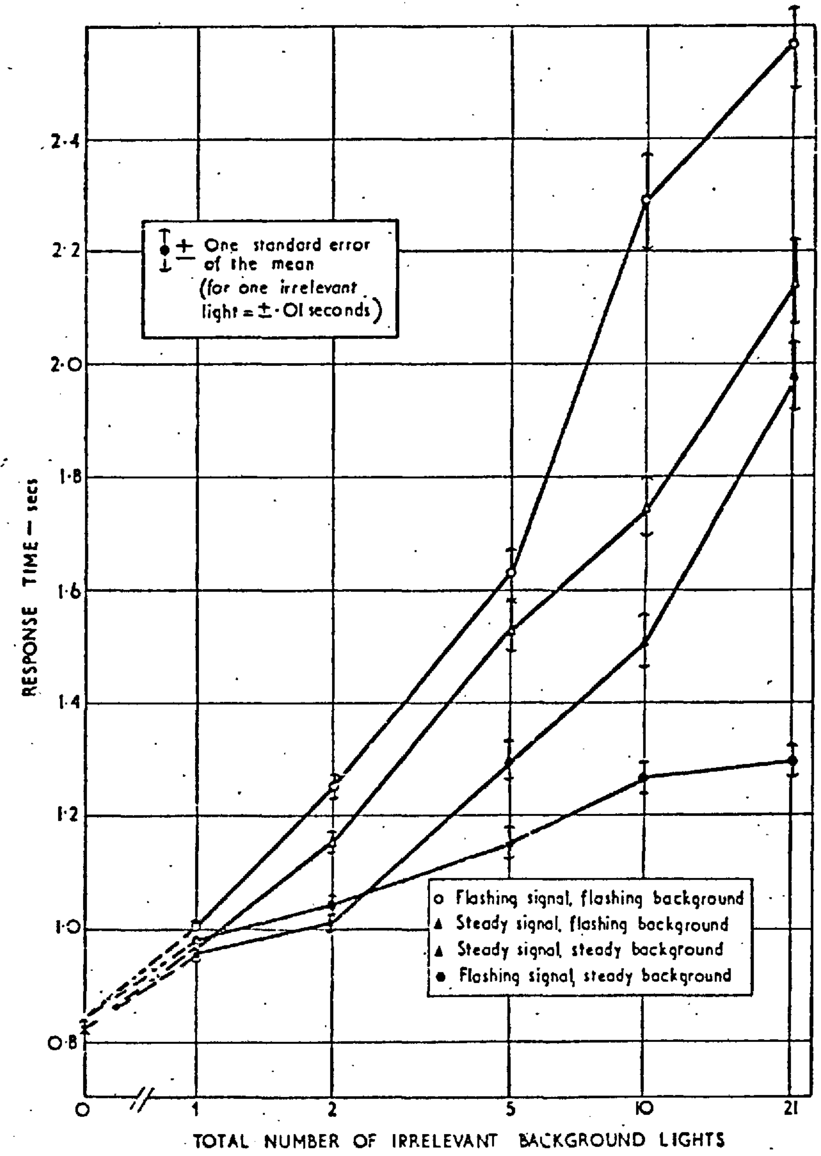


Figure 15. The effects on the response time of irrelevant background lights of different codings.

(A.CRAWFORD)

devoid of noise-lights, and the results of Crawford confirm this. The amount of "visual noise" appears as an important parameter in the effectiveness of free search and a background of flashing lights appears worse than one of steady lights even when the signal is steady. Further experiments using a mixture of steady and flashing noise lights indicated that steady signals are more effective than flashing signals if the proportion of flashing lights in the background exceeded about 1 in 10. The loss of effectiveness of the flashing signal was large when more than four irrelevant lights in the background were flashing. However a flashing light is easily recognised against a background of steady lights and this may be taken advantage of by flashing only signals of the highest importance, but signals should not be flashed if there is a danger of too many such signals appearing together in the field of view. In trying to explain what is the property of a flashing light that makes it a good signal but a bad background, Crawford suggests that, in the strategy for search, priority is given to the flashing light in deciding between the stimuli awaiting closer scrutiny and that this may be associated with the mechanism for the perception of a moving object which also has high priority. He also found that whenever there was a choice of recognising a signal by its colour or by its flashing, the flashing aspect was preferred.

Disturbing Lights and Glare effects.

The eye adapted to a given brightness level requires a certain time, which may vary from a few seconds to over half an hour, to attain optimum performance if it is suddenly subjected to a very different level of illumination. When there is an upward change in the illumination level, the inadequacy of the visual performance during the transitional phase of adaptation is often accompanied by an unpleasant feeling of shock, due in part to the spasms of the sphincter of the iris, and the effect is known as successive glare. Discomfort usually passes off after a while unless the second level of illumination is too high - Stiles (1952) places the discomfort level around 20,000 trolands. Successive glare has been extensively studied by Nutting (1920) and Fig. 14 which gives the just visible and blinding white intensities for various adaptation levels may be adapted to such problems. For luminances in cd m^{-2}. and filling a large part of the visual field, painful shock is estimated to occur if

$$L > 3500\, L_o^{0.32}$$

where L_o and L are the initial and final levels of luminance.

When, in addition to the signal being sought, the field contains bright light sources which produce a local illumination of the retina too high for the general adaptation level, simultaneous glare occurs, and the effect may vary from irritation and discomfort to serious disability and impairment of the visual function. The glare may produce degradation of image contrast due to scattered light, retinal inhibitory effects, bleaching of the photo-pigments and troublesome after-images. Fluctuations in the light-regulating and focusing mechanisms of the eye occur in the attempt to improve vision and lessen glare (Hopkinson, 1956) and these processes may lead to fatigue and psychological overloading of the visual system (Hartmann, 1963). The degree of disability produced by glare will depend on the retinal locations of the image and the glare source and the previous adaptational history of those parts of the retina. After removal of the glare source readaptation and recovery may start immediately or after a few seconds, there being wide differences among individuals in glare sensitivity and recovery (Simonson, 1958) (Fisher and Christie, 1965).

Two explanations have generally been advanced to account for glare; one in terms of entoptic stray light and deriving from the veiling appearance of glare, the other in terms of neural inhibition. The main arguments favouring the stray light explanation are that scattering by the ocular media can objectively be demonstrated and experiments like those of Boynton et al (1954) on excised eyes make it probable that there is enough scatter to justify the experimentally observed fall in visual performance. The masking influence of a glare source seems to be relatively independent of its position in the visual field - Stiles and Crawford (1937) have shown that neither the fovea nor the blind spot behave differently in this respect and their result is more readily explained in terms of scattering than nervous inhibition. However, according to Fry (1954), most of these experiments cannot completely stand the test of criticism and theoretical approaches have failed to give a satisfactory quantitative or even qualitative explanation of glare.

In favour of nervous interaction are the demonstrations by Schouten and Ornstein (1939) of the difference between the dynamic behaviour of glare and an ectoptic veiling luminance though Fry and Alpern (1953) repeating their experiment under more carefully controlled conditions could not reproduce their results. Again there is the neurophysiological evidence from experiments like those of Kuffler (1953), Barlow (1953), Glezer (1965), which point to the existence of inhibitive areas around a stimulated point. Vos (1962), in a detailed study of glare, has considered the scattering produced by the ocular media and in particular the fundus, the contribution of the Stiles-Crawford effect, and has shown that the brightness of the entoptic veil depended more on the plane of polarisation of the glare stimulus and its point of entrance at the pupil than on its intensity. He concludes from his investigations that most of the effects of glare can be accounted for in terms of the stray light hypothesis though he does not rule out the possibility of inhibition playing a relatively minor role.

Holladay (1927) first introduced the idea that the veiling luminance could be determined by finding the actual uniform field luminance producing the same rise in the threshold in absence of the glare source. Stiles and Crawford (1932) developed this method for measuring the condition of the retina irrespective of whether the modification corresponded to the effect of scattered light or to deeper physiological processes of neural interaction. Crawford (1947) applied it to the study of dark adaptation. If the glare source is small and produces an illuminance E at the observer's eye, and the background luminance is L, the equivalent background luminance β is given by

$$\beta = L + k \frac{E}{\theta^n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

where the test stimulus is located θ^o from the glare source, and k, n are constants (Holladay 1927, Stiles, 1929). The original experiments were performed with the natural pupil but little error is likely to be introduced by assuming the pupil to have the same size under glare and the equivalent field stimulus, so that one may write.

$$\beta' = L' + \frac{k}{\theta^n} L'_G \alpha_G \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

where β', L', G' are troland values and α_G the angular subtense

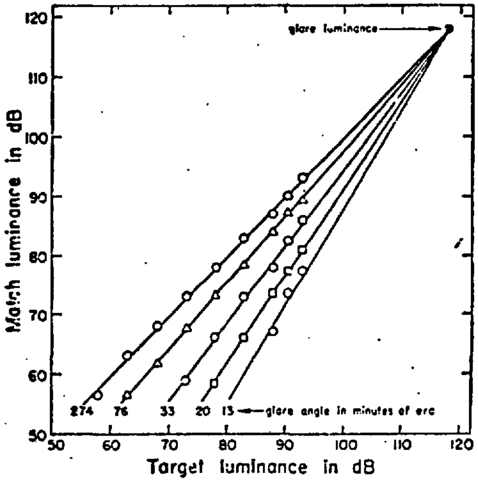


FIG. 16. Showing the luminance of the match field that equals the brightness of the target for various angles of glare.

In these logarithmic coordinates the presence of the glare source alters the slope, and hence the exponent, of the functions. The functions project to a common point, a value equal in luminance to that of the glare.

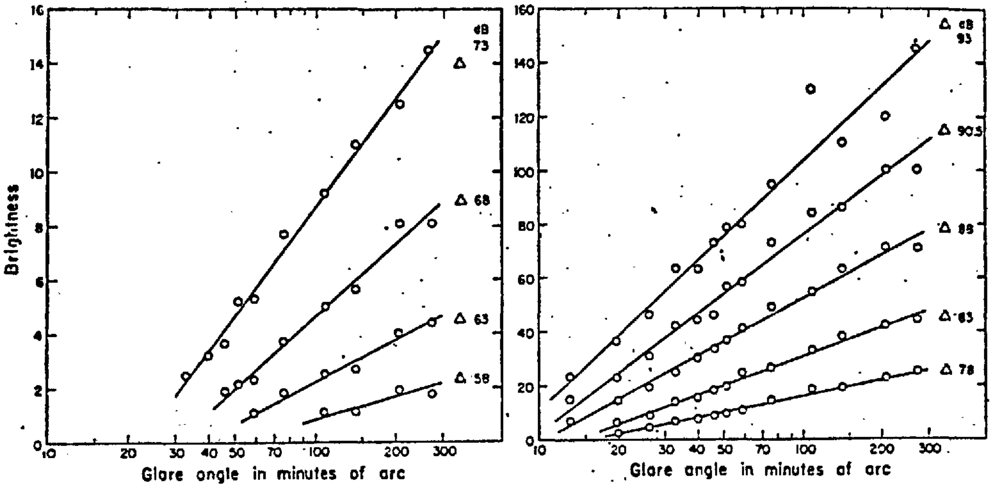


FIG. 17. Showing how the brightness of a target grows as the glare angle is increased. Brightness is plotted linearly, glare angle logarithmically. The parameter is the luminance of the target in dB. The triangles show the brightness of the match field when it was set equal to the target in the absence of glare.

of the glare source at the eye in steradians. For several glare sources the resultant equivalent background luminance is approximately additive:

$$\beta = L + k\left(\frac{E1}{\theta_1{}^n} + \frac{E2}{\theta_2{}^n} + \ldots\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (21)$$

Typical values for foveal vision with $0.5^\circ < \theta < 25^\circ$, $E = 10$ lm.m^{-2}, $L = 5$ cd.m^{-2} are $n=2$, $k=10$, but k increases to about 16 as the test stimulus is moved into the periphery. Fisher and Christie reported a dependence of n and k on the age of the observer and their results indicated the existence of a threshold below which glare effects were small, this threshold being higher for young people. This seems significant from the point of view of the stray light hypothesis as scattering at the cornea and the eye lens are known to increase with age.

An obvious effect of glare is the decrease in the apparent brightness of luminous sources in the visual field provided their luminance is less than that of the glare source - brighter lights affect dimmer lights, but dimmer lights have little effect on brighter lights if at all. Stevens and Diamond (1965) set out to determine how a glare source inhibits the apparent brightness of a small target as the glare angle was varied. They used an intra ocular matching technique and found that at all target luminances the apparent brightness of the target was directly related to the logarithm of the glare angle.

For a given glare angle the apparent brightness increases as a power function of the luminance, the exponent being largest for small glare angles (Fig 16,17). According to them the apparent brightness varies with the glare angle according to the empirical relation

$$\psi = 0{\cdot}68\,\psi_{max}\ (\log \alpha - \log \alpha_t) \quad \ldots\ldots\ldots\ldots\ldots \quad (22)$$

where α_t is the threshold angle at which the target is first perceived.

Studies on the disturbing effect of coloured lights on the threshold of a white test stimulus viewed foveally indicate that the disturbing effect is independent of the colour of the glare source and depends only on the illumination it produces at the observer's eye (Stiles, Bennett and Green, 1937). The experiments of Arndt and Voit (1960) in which they measured the angle at which a given test stimulus showing a luminance contrast ratio 3:1 with the background in absence of the glare source was just visible in presence of the source confirm this (Fig 18). Vos (1962) concludes that glare is practically independent of the colour of the incident light and that this can be understood theoretically. In picking up a white light signal by the dark adapted extra foveal retina, however, a red light is less disturbing than a green or blue light of the same intensity (Stiles and Crawford 1934, Fol'b 1965). Experiments with electronic light flashes have shown that higher luminous intensities are permissible with flashing

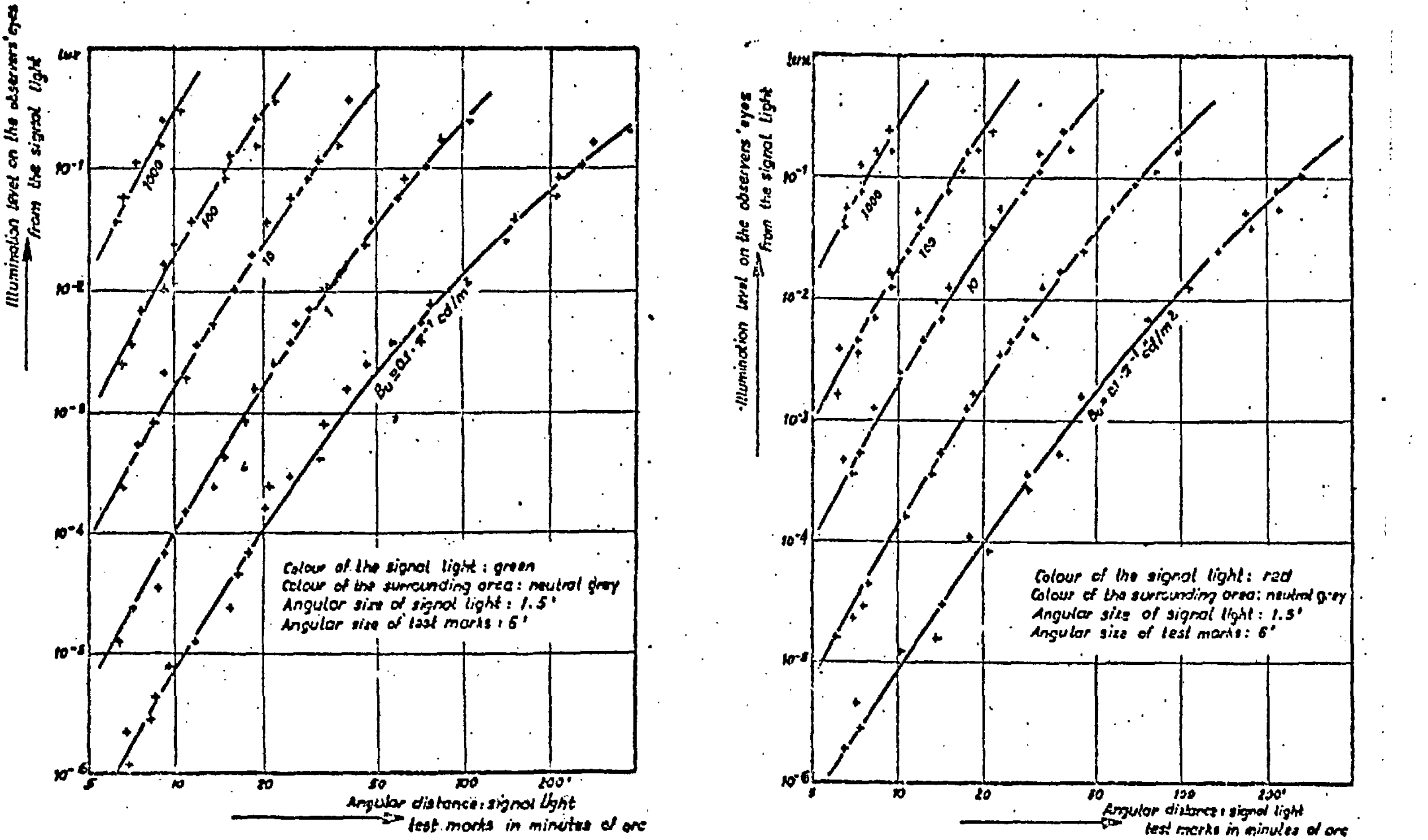


Fig. 18. Comparison of the glare effects of green and red signal lights. (Arndt and Voit)

lights than with steady lights from the point of view of glare effects. When continuous lights of 1000 cd. began to cause glare, flashing lights of 10,000 cd. were still free from glare (C.I.E., 1959).

The perception of the colour of a signal light.

It is often necessary that not only should a signal be detected, but that its colour should be correctly perceived. Now, although the sensitivity of the parafoveal retina is higher than that of the fovea in the dark-adapted state, except for red light, this gain in sensitivity is attended by a loss of colour perception. The minimum intensity of a light at which it can be recognised as being coloured is the chromatic or specific threshold, and the photochromatic interval is defined as the ratio of the chromatic threshold to the general or achromatic threshold for light perception. In foveal vision the colour impression persists almost to the level at which the test spot disappears, i.e. the photochromatic interval is not very different from unity throughout the spectrum. Actually, since the intensity of a stimulus must exceed slightly its threshold value for its attributes to be appreciated, a small photochromatic interval exists even at the fovea. This is greater for unsaturated colours, but even for highly saturated monochromatic radiations the foveal colour threshold may be about twice the achromatic threshold (Galifret and Pieron).

Owing to the photochromatic interval the chromatic threshold may not be greatly different in the fovea and the parafovea as can be seen from the following table:

Table 3.

Ratio (g) of the chromatic thresholds at the fovea and 5° eccentricity.

(according to Wentworth, quoted by Stiles, Bennett and Green 1937)

λ (nm.)	468	522	582	672
g	0•6	0•9	0•2	0•6

The higher chromatic threshold at 5° eccentricity shows that the advantage of parafoveal vision in dark adaptation is lost if the colour of a signal must be perceived.

Wald (1945) measured the energy threshold across the spectrum for 22 young subjects with a test spot of 1° angular diameter which was viewed for 40 ms. at the fovea and 8° eccentricity (Fig.19) Within certain approximations, the difference between the two curves gives the photochromatic interval, which under these conditions may exceed 100 for λ 550 nm. but almost disappears at the red end of the spectrum. These results should not be taken to apply too generally, as the curves may alter in shape and shift in position with different exposure times and field sizes, though it is conceivable that the photochromatic interval may be independent of the test spot size. No systematic data for the photochromatic ratio throughout the spectrum seem available for

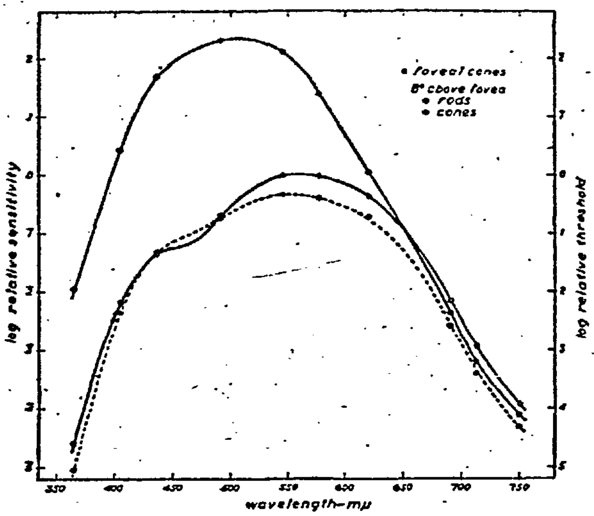


FIG. 19. Spectral sensitivities (1/threshold) of dark-adapted foveal cones, peripheral rods, and peripheral cones (broken line). All sensitivities are expressed relative to the maximum sensitivity of the fovea. The relative positions of these functions on the ordinates are therefore those observed in the eye. (Wald)

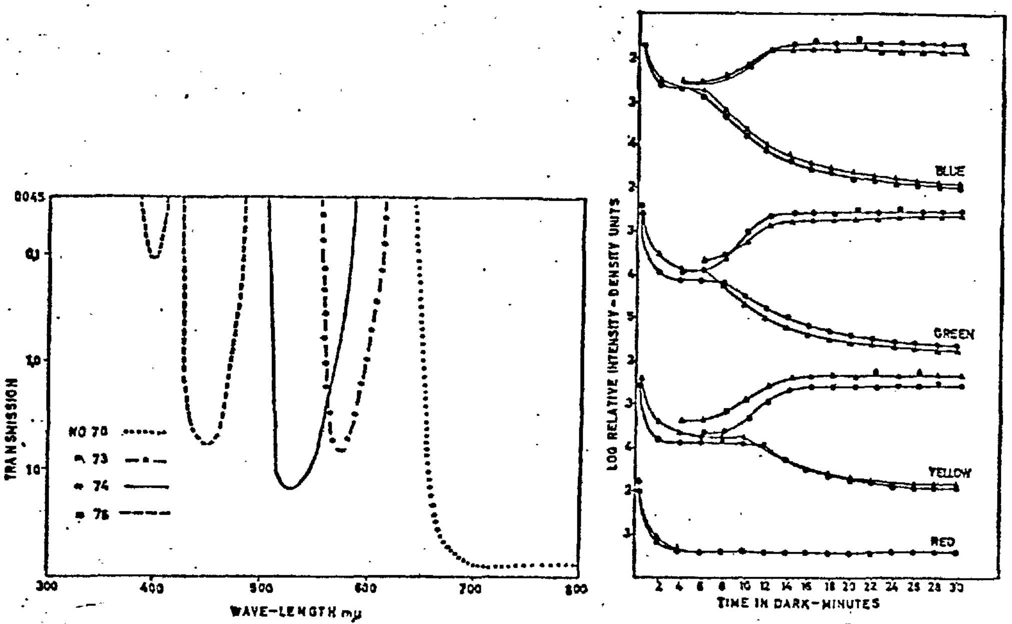


Fig. 20

(a)

(b)

(a) Transmittance curves for the four Kodak Wratten Filters used in the experiments.

(b) The absolute and the specific threshold during dark adaptation for colors of different spectral composition. Measurements were made with a testfield of one degree viewed six degrees nasal from the fixation point. The circles and the triangles represent the result for B. S. and U. S. respectively. (B.STABELL and U.STABELL) the important case of an effective point source.

The photochromatic ratio increases with eccentricity from the visual axis, as evidenced by the following data obtained with a test field of 76' angular subtense:

Table 4.

Variation of photochromatic ratio p with eccentricity α

(According to Wentworth, quoted by Stiles, Bennett and Green, 1937)

		Values of p.			
λ (nm.)		468	522	582	672
Fovea	$\alpha=0^\circ$	2·2	2·0	1·8	1·1
Parafovea	$\alpha=5^\circ$	23	28	97	3·7
	$\alpha=10^\circ$	26	58	202	4·3
	$\alpha=25^\circ$	239	3430	750	4·8

It has generally been assumed that the chromatic threshold remains constant during the scotopic phase of dark adaptation in the peripheral retina. Lie (1963) and Stabell and Stabell (1965) have shown however that the chromatic threshold starts increasing again after the first phase of dark adaptation, (fig. 20), red light behaving differently, as might be expected.

Even when a coloured light is of sufficient intensity to appear coloured, it does not follow that the colour name assigned to it by an observer will be the same as when the light has a relatively high intensity. Farnsworth (1955) put forward the hypothesis that reducing the luminance of a normal field was equivalent to reducing the field size at constant luminance and therefore normal colour vision should assume the characteristics of tritanopic vision at low intensities, as in the small field dichromatism first observed by König (1903) and investigated by Willmer and Wright (1945). Blaise (1960) using point sources and colours produced by interference filters, investigated the changes in the colour sensation in the vicinity of the threshold against backgrounds ranging from 0 to 0•01 cd.m^{-2}. He concludes that

> for red, the colour sensation lasts till vision disappears,
>
> yellow looks orange and even red at low levels,
>
> green and blue cannot be distinguished at low intensities, the observer indicating indiscriminately green or blue at these levels,
>
> violet appears diffuse and spread out but the colour sensation persists to the foveal threshold.

The last observation would appear to be in agreement with those of McCree (1960), who found that fixation could seriously reduce colour discrimination, but that discrimination between blue and violet (430 nm.) could be very good at low luminances, if fixation were avoided. It is interesting to note that very weak white lights may appear as an unsaturated red, (Broca and Polack, 1907).

From the practical standpoint, the values of the photochromatic interval and the achromatic threshold do not give sufficient information if the colour of a signal light must be discriminated from related colours, e.g. red from orange, blue from green. Bearing in mind that in practice a colour signal is often obtained by combining suitable filters with an incandescent electric lamp, MacNicholas (1936) experimented with such combinations and recommended the minimum signal intensities given in Table 5 for the recognition of colour. He found that

Table 5.

Minimum signal intensities recommended for signal colours

(MacNicholas, 1936)

	Minimum signal illumination at observer's eye (mile-candles)
Red	5·0
Orange-Yellow	15·0
White	12·0
Green	7·4
Blue	3·7
Purple	2·5

the recognition of purple depends on the appreciation of the physically complex nature of purple as a mixture of red and blue, which is rendered possible by the chromatic aberration and scattering within the eye. MacNicholas' values are largely in excess of the accepted practical limit of 0·5 mile candle or 2×10^{-7} lux for the achromatic threshold. In the U.S.S.R. the following values have been suggested for the threshold of recognition of coloured lights, but they may be applicable only to

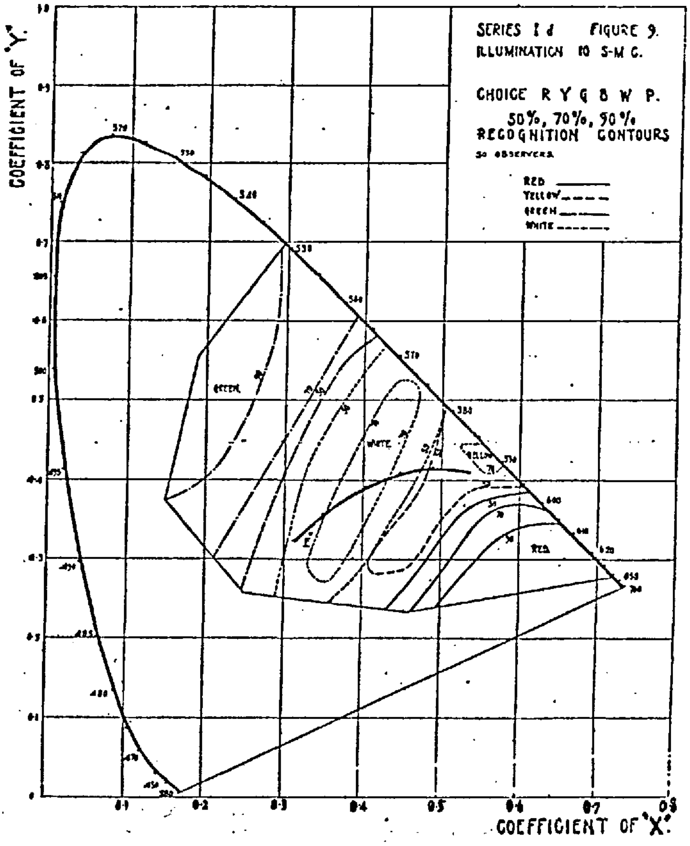


FIG. 21 Colour recognition contours at an eye illumination of 10 s.m.c. (Holmes)

spectral colours (Rautigan, 1958):

white	3×10^{-7} lux
red	5×10^{-7} lux
green	5×10^{-7} lux
yellow	10×10^{-7} lux
blue	7×10^{-7} lux

Holmes (1941) and Arndt and Voit (1960) have further studied the problem of recognition of coloured signals. In an extensive series of experiments, Holmes presented effectively punctual sources which reproduced in energy distribution and intensity coloured light signals as used in practice to observers who were asked to name the signal colour. His results can be represented as frequency of signal colour recognition contours (Fig.21) - a 50% red contour means that each point on the contour is recognised as red on 50% of occasions. The results of Arndt and Voit for a 1·5' test field (Fig.22) show that the minimum eye illumination for precise colour perception varies relatively little with the background luminance. During the daytime (B_u=316 cd.m^{-2}) this limit is only a factor of 30:1 higher than during the night (B_u= 0·0316 cd m^{-2}).

Information coding through flash patterns, moving sources and localization accuracy.

Besides colour coding, it is possible to use array coding, flash-frequency coding and flash-pattern coding to convey additional information through flashed signals. In array coding, the geometrical appearance of the array changes with the direction

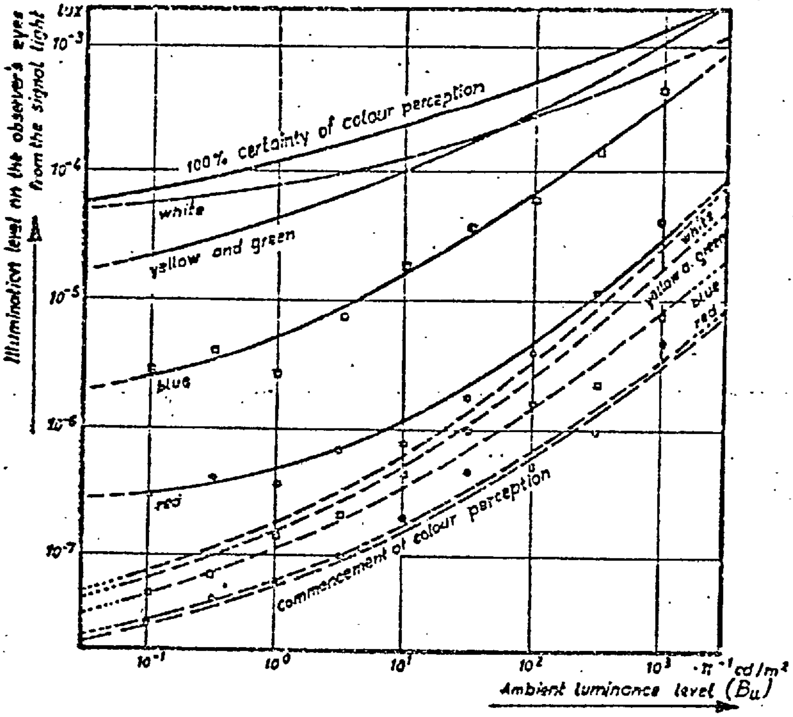


FIG. 22 Summary of test results on colour perception for a test field of angular diameter 1·5'.

---------- beginning of colour perception
———————— 100% certainty of colour perception

Chromaticity co-ordinates for signal lights:

red:	x = 0·689	y = 0·310
yellow:	x = 0·536	y = 0·459
green:	x = 0·324	y = 0·502
blue:	x = 0·191	y = 0·354

(Arndt and Voit)

of viewing and the larger number of flashing lights required may seriously reduce the conspicuity of other signals; such coding should not therefore form the basis of a navigation light system, though it may have incidental value in systems employing other types of coding.

Observers find it difficult to identify isolated flash rates (Cook and Beazley, 1962). In his experiments on the effect of frequency on the apparent intensity of flashes of constant duration near the absolute threshold, Schuil (1940) observed that the flashing character was only clearly readable up to frequencies of 5 c/s. Between 5 to 13 flashes per second the light appeared to flicker and at higher repetition rates the observer was unaware of its flashing nature and Talbot's law applied (Fig. 23). Flickering would not appear to be of much practical importance as the apparent intensity was less than that of a flashing light giving a readable flashing indication. Gebhard (1949) found that there were only six identifiable flash rates in the range from 120 to 2100 flashes per minute. Cohen and Dinnerstein (1958) using nine flash rates between 15 and 720 flashes per minute, found that only five categories could be identified without errors under ideal conditions and that in general the higher flash rates were more quickly recognised. Robinson (1959), from tests on aircraft anti-collision light systems, reported that subjects confused a light flashing at 80 flashes per minute with flash rates of 40 to 160 flashes.

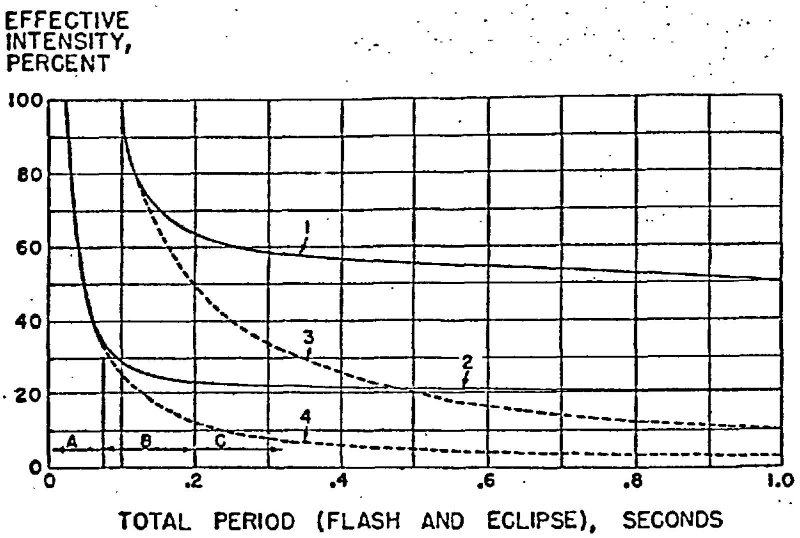


Figure 23. Effective intensity of flash relative to fixed intensity, for repeated flashes, as a function of the period of the flash cycle, with the flash duration kept constant and the eclipse time varied to obtain different repetition rates. (Schuil).

Curve 1, experimental curve for 1/10 second flash.

Curve 2, experimental curve for 1/40 second flash.

Curve 3, Talbot's law for 1/10 second flash.

Curve 4, Talbot's law for 1/40 second flash.

(*Note:* Three regions for curve 2 are distinguished: A, in which the light appears steady, B, in which the light appears to flicker, and C, in which the flashes are seen as separate and distinct.)

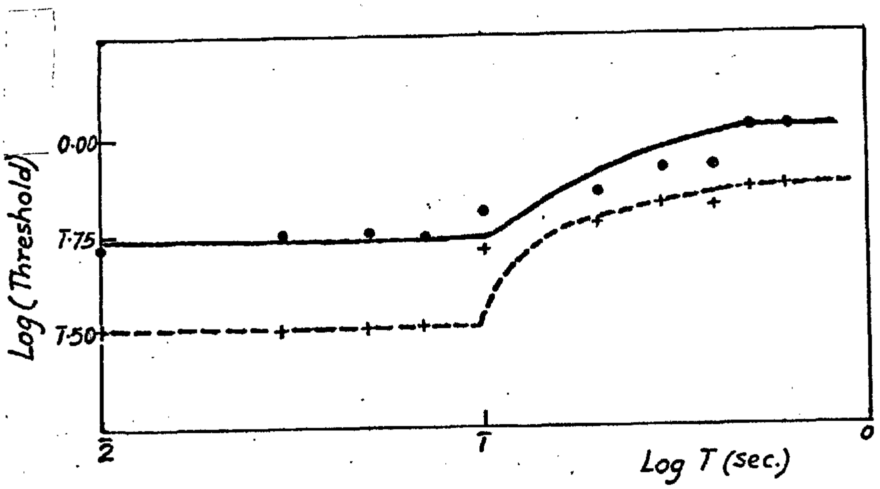


Fig. 24. Threshold for a double flash as a function of the interval T between the flashes (Davy).

per minute. It would seem therefore that not more than three, or at most four, frequencies could be used in navigation light systems, and that even this small number may result in errors of some consequence (C.I.E., E-3.3.3., 1963).

If a large amount of information is to be coded into a signalling system, pattern coding would thus seem to be unavoidable. Such coding may also be used to increase the relative conspicuity (p.21) of a signal. Experiments with dot and dot-and-dash patterns, (Applied Psychology Corporation, 1962), showed that on an average neither pattern was responded to more quickly than the other when all observers were considered, though for some observers one type of flash pattern was more readily detected than the other. It was also found that longer responding times were obtained against backgrounds containing densely packed city lights, lights of different colours or high intensities, or other flashing lights. This would be in agreement with the findings of A. Crawford (p.52). On the other hand, the difference in detectability of red, green and white lights was not influenced by the kind of signal flash pattern used or the colour of the background, nor did the interaction between the background and the flash pattern seem significant. Davy (1952) has investigated the effect on the threshold of multiple light flashes of 0.01 second duration at 15° with the visual axis for the dark adapted eye. So long as the maximum duration of the train of pulses was less than 0.1 second the flashing character could not be identified and the results agreed with Talbot's law. When two flashes were however separated by more than this critical duration the threshold energy rose and at 0.5 secs. was the same as for a single flash - under the latter circumstances both his subjects reported seeing two flashes 100% of the time (Fig. 24).

Under certain dynamic conditions, as with an aircraft, relative motion against a background may be the most reliable method of identification. Bouman and van den Brink (1953), starting from the fundamental aspect of all threshold determination that sufficient energy must be presented within a sufficiently short time in a sufficiently small area to evoke a sensation, predicted the behaviour of absolute and incremental threshold values for moving point sources, and verified their theory experimentally at the absolute threshold for red and green lights in the periphery, at 7° eccentricity. Bloch's law was found to apply within the critical duration and one paradoxical prediction that was adequately confirmed was that for all flash durations t, the necessary total energy for perception became independent of t when vt was large enough, v being the angular velocity of the source across the field of view. Brown (1955) has found in foveal observation that there is a speed for any given exposure time for which the threshold for perception of direction of motion is a minimum, and that in general the threshold luminance decreases with increase in exposure time. Complete summation occurs for durations less than 0.1 second when the discrimination of velocity depends upon a constant amount of energy (fig. 25). Leibowitz (1954) had reported earlier that motion perception was increasingly dependent on the inference of movement at longer stimulus durations: "for long exposures and slow rates successive events may be involved rather than the direct perception of velocity".

It has generally been considered that a long flash is necessary if a satisfactory visual bearing is to be taken on a flashing light. Concentration of the total light flux of a long flash into a flash of shorter duration can however considerably increase the effective intensity of the signal, and if the navigator had the choice between a long flash which were barely visible and a shorter one he could clearly see, the preference would be for the shorter one. The development of condenser discharge type lamps and of more efficient optical systems which make it possible to project narrower and more intense light beams from sources using revolving optics have revived the interest in short duration flashes. A brief flash always appears to last for about 0.15 second, the persistence being caused by a delay in disappearance which is greater than the delay in perception. This would appear to lead to the conclusion that if flashes of about 0.15 second duration prove satisfactory for taking a bearing, flashes of any shorter

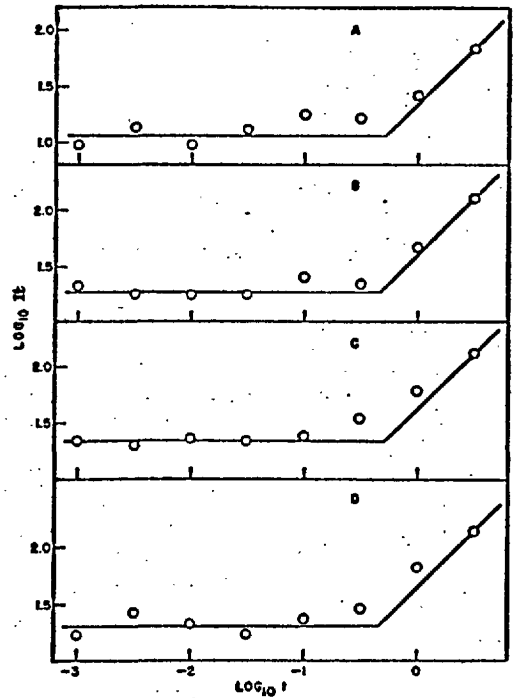


FIG. 25. The intensity-time relation based on the threshold luminance required to discriminate the direction of a velocity in a middle range of speeds for each stimulus duration. The logarithm of the product of intensity and duration (It) is plotted as a function of the logarithm of the exposure time (t). Each point is the mean of 16 measurements. The curves represent the anticipated theoretical relationships with the horizontal line $It=C$ and the inclined line with unit slope $I=K$. (Brown)

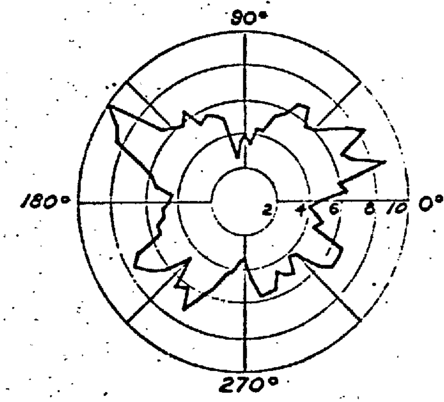


FIG. 26. Mean localization error in degrees of arc for various radial positions.
(Leibowitz, Myers and Grant)

duration should be equally usable. Blondel and Rey (1912), from experiments with flashes of duration in the range 0.001 sec to 1.0 sec, concluded that the length of the flash had no significance in the ability to take a bearing provided the eclipse period between the flashes did not exceed about 5 seconds. More recently, Leibowitz, Myers and Grant (1955) have shown that the accuracy of localization of the radial position of a single stimulus is independent of luminance and duration, but varies with the radial position. If the stimulus is seen at all, the localisation accuracy is at a maximum and further increase of the stimulus energy, whilst increasing the probability of seeing, has no effect on the accuracy of localization. Their results for five out of their six subjects indicated superior performance along the horizontal and the vertical meridian (fig. 26) It seems likely that group flashing may make it easier to take a bearing whilst retaining the advantages of the shorter flash.

Photometric units, Riccò's Law, Variation in Pupil Size.

When a source of light, such as a distant signal or a star, subtends a small angle of less than 1' or 2' of arc at the eye, the appearance of the source depends solely on the illumination (illuminance) E it produces at the plane of the observer's eye pupil, assuming a constant pupillary aperture. It has therefore become customary to express the effect of such a "point" source in terms of this illumination, the quantity being termed the "point brilliance" of the source. Point brilliance may be expressed in terms of ordinary illumination units (lux, foot-candle, phot), but as it is generally very small, especially for sources near the threshold of visibility, it has often been found convenient to employ a submultiple like the microlux (micro lumen/m^2) or a smaller unit such as the mile-candela (illumination produced by a source of one candela at a distance of one mile), the sea-mile candela (s-m.c), or the kilometre candela (microlux). The method is basically the same as that used in astronomy for comparing the apparent magnitudes of stars, though the scale of stellar magnitudes is a logarithmic scale on which increasing numbers represent decreasing values of point brilliance and is therefore unsuitable for the photometry of terrestrial sources.

When dealing with extended sources it is more common to denote the physical stimulus by the luminance (B or L). At a given point on a surface and in a given direction, this is "the quotient of the luminous intensity (luminous flux per unit solid angle) in the given direction of an infinitesimal area of the surface containing the point under consideration, by the orthogonally projected area of the surface element on a plane perpendicular to the given direction," (Wyszecki and Stiles, 1967). Now, luminous flux F is the quantity derived from the radiant flux by evaluating radiant energy according to its action on a selective receptor, the spectral sensitivity of which is defined by the relative luminous efficiency function (V_λ) relating to vision by the photometric standard observer having the characteristics laid down by the C.I.E. The relative luminous efficiency function is the ratio of the radiant flux at wavelength λ_m to that at wavelength λ, when the two fluxes produce the same luminous sensation, λ_m being so chosen that this ratio has the maximum value unity. Luminous flux is thus defined by the C.I.E. formulae.

$$F = K_m \int_\lambda P_\lambda V_\lambda \, d\lambda \text{ for photopic vision,}$$

or

$$F' = K'_m \int_\lambda P_\lambda V'_\lambda \, d\lambda \quad \text{for scotopic vision,}$$

where F = photopic luminous flux (photopic lumens),

$P_\lambda \, d\lambda$ = radiant flux emitted in the wavelength interval $d\lambda$, containing λ, (watts),

V_λ = the photopic relative luminous efficiency function for the C.I.E. standard observer,

K_m = the maximum luminous efficiency (lumens per watt) corresponding to the wavelength at which $V_\lambda = 1$,

and F', K_m', V_λ' are the corresponding quantities for scotopic vision. Starting from the Planckian formula for a black body radiator and the definition of the primary standard source of light it is possible to calculate the constants K_m, K_m', and Wyszecki and Stiles (1967) give their values as

$K_m = 680$ photopic lumens/watt

$K_m' = 1745$ scotopic lumens/watt.

In table 6 are listed some commonly used illumination and luminance units with suitable conversion factors.

TABLE 6: Illumination and luminance conversion factors.

(1) Illumination conversion factors.

	Lux $(1\,\mathrm{lm.m}^{-2})$	Phot $(1\,\mathrm{lm.cm}^{-2})$	Footcandle $(1\,\mathrm{lm.ft}^{-2})$	mile candle $(1\,\mathrm{lm.mi}^{-2})$	seamile candle $(1\,\mathrm{lm.sm}^{-2})$	microlux or kilometre candle $(1\,\mathrm{lm.km}^{-2})$
Lux	1	10^{-4}	9.290×10^{-2}	2.591×10^{6}	3.435×10^{6}	10^{6}
Phot	10^{4}	1	9.290×10^{2}	2.591×10^{10}	3.435×10^{10}	10^{10}
Footcandle	$1,076\times10$	1.076×10^{-3}	1	2.788×10^{7}	3.697×10^{7}	1.076×10^{7}
milecandle	3.859×10^{-7}	3.859×10^{-11}	3.587×10^{-8}	1	1.326	3.859
seamile candle	2.911×10^{-7}	2.911×10^{-11}	2.705×10^{-8}	7.542×10^{-1}	1	2.911
microlux or kilometre candle	10^{-6}	10^{-10}	9.290×10^{-8}	2.591	3.435	1

(2) Luminance conversion factors.

	Nit $(1\,\mathrm{cd.m}^{-2})$	Stilb $(1\,\mathrm{cd.cm}^{-2})$	Apostilb $(\frac{1}{\pi}\,\mathrm{cd.m}^{-2})$	Lambert $(\frac{1}{\pi}\mathrm{cd.cm}^{-2})$	Footlambert $(\frac{1}{\pi}\mathrm{cd.ft}^{-2})$	Candela ft^{-2} $(1\,\mathrm{cd.ft}^{-2})$
Nit	1	10^{-4}	3.142	3.142×10^{-4}	2.919×10^{-1}	9.290×10^{-2}
Stilb	10^{4}	1	3.142×10^{4}	3.142	2.919×10^{3}	9.290×10^{2}
Apostilb	3.183×10^{-1}	3.183×10^{-5}	1	10^{-4}	9.290×10^{-2}	2.957×10^{-2}
Lambert	3.183×10^{3}	3.183×10^{-1}	10^{4}	1	9.290×10^{2}	2.957×10^{2}
Footlambert	3.426	3.426×10^{-4}	1.076×10	1.076×10^{-3}	1	3.183×10^{-1}
Candela ft^{-2}	1.076×10	1.076×10^{-3}	3.382×10	3.382×10^{-3}	3.142	1

The dimensions of the test patch and the non-uniformity of the retinal structure play an important part in the determination of the visual threshold and it may be pointless to look for simple laws except within a small area in the peripheral retina. To a first approximation however, if L be the threshold luminance of a test patch subtending a solid angle ω, irrespective of the shape of the test patch, the results may be represented by a formula of the type

$$I\omega^k = C \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (24)$$

where C is a function of the exposure time t, the background luminance B, the eccentricity θ ° etc., and k is a summation index. The earliest researches were those of Riccò (1877) and Charpentier (1882), and for the dark-adapted eye, Riccò found that with circular test fields up to 42' 40" in diameter k=1, the threshold luminance being inversely proportional to the area of the test patch (Riccò's Law). The size of the test field for which complete summation was obtained would indicate that Riccò's experiments must have been extra-foveal. Piper (1903) investigated the relationship extra-foveally for larger test fields between 2° 45' and 26° and found $k = \frac{1}{2}$, the threshold being inversely proportional to the angular diameter (Piper's law). Many later investigators have found a fairly sharp transition in the value of k from about 1 to about $\frac{1}{2}$ as the field size is increased, but some like Graham, Brown and Mote (1939) and Barlow (1958) found k decreasing steadily with increase in stimulus size. It is doubtful whether Riccò's law holds exactly for sources larger than a few minutes of arc at the fovea, but there is general agreement that spatial summation increases with eccentricity; thus, Weinstein and Arnulf (1946) found that for small sources (angular diameter $\alpha < 30'$), summation is almost complete with $k = 0.9$ at eccentricity $\theta = 7^\circ$, and attaining the value unity at $\theta = 30^\circ$. According to de Groot et al (1953), Ricco's law is only a first approximation in peripheral vision, where the actual law depends on the retinal position and under certain circumstances values of k greater than unity may be obtained. Graham and Goldman (1932) could find no simple relation between threshold luminance and the number of cones stimulated at the fovea, but Haig (1948) claimed that the equation

$$\frac{L \times A}{S} = \text{constant} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (25)$$

held for all regions of the retina, including the fovea and some with large variations in cone size, A being the area of the retinal image and S the cross-sectional area of the inner cone segment.

Under any given conditions, the point brilliance of a source at threshold will be independent of the angular subtense of the source, provided this is within the Riccò limit of complete summation, and it seems therefore desirable that results be expressed in terms of point brilliance only for sources satisfying this condition. For very small fields, Riccò's law must necessarily hold because of the optical imperfections of the eye and limits set by diffraction. For the dark adapted eye and a white test field the angular diameter for which Riccò's law holds at the fovea has been estimated by various authors as between 2' and 6' (Abney and

Watson, 1916; Graham et al, 1939; Lamar et al, 1947; Baumgerdt, 1949; Willmer, 1950; Hillmann, 1958; Zegers et al, 1964; Glezer, 1965). In the parafovea field sizes of the order of 1° are quoted: 42' 40" (Ricco, 1877), 30' (Weinstein and Arnulf, 1946), 10' (Bouman and van der Velden, 1947); Glezer (1965) found that the zone of complete summation increased little in the periphery, varying from 61' at $\theta = 2° 50'$ to 77' at $\theta = 40°$. Fewer data seem available about the size of the Riccò area for incremental thresholds against high background luminances, but the results of Blackwell (1946) and Glezer (1965) would indicate that it may be well below 1' at the fovea. Brindley (1954) found that for the red and the green thresholds against green and red backgrounds of 600 m L and 60 m L respectively, at 55' from the visual axis, the critical field size was below 2' of arc; for blue thresholds against the same backgrounds, however, summation occurred for field sizes up to 13' and decreasing the background luminances in this case by a factor of 2000 had no effect on the summation area. It is possible that summation over maximum field sizes of only a few minutes of arc may be explained purely on an optical basis, but larger summation fields reflect some deeper physiological mechanism.

The illumination at any point on the retina is proportional to the product of the luminance L in the corresponding direction in the external field and the area S of the entrance pupil, natural or artificial, viewed from that direction. The product LS forms a useful measure of the internal stimulus from which the effects of pupil variation are absent and was suggested as a conventional measure of the retinal illumination by Troland (1922). The conventional unit of retinal illumination is named the "troland" after its originator and corresponds to the retinal illumination when a surface of luminance 1 cd.m^{-2} is viewed through a pupil of area 1mm.^{2} A surface of photopic luminance L_p photopic cd.m^{-2} and scotopic luminance L_s scotopic cd.m^{-2} will thus have photopic and scotopic troland values T_p and T_s defined by

$$T_p = L_p S \quad \text{photopic trolands,} \quad \ldots \quad \ldots \quad (26a)$$

$$T_s = L_s S \quad \text{scotopic trolands,} \quad \ldots \quad \ldots \quad (26b)$$

and, in general, for a surface emitting radiation of relative energy distribution $E_\lambda.d\lambda$,

$$\frac{T_s}{T_p} = \frac{K'_m \int E_\lambda V'_\lambda \, d\lambda}{K_m \int E_\lambda V_\lambda \, d_\lambda} = 2.567 \frac{\int E_\lambda V'_\lambda \, d\lambda}{\int E_\lambda V_\lambda \, d\lambda} \quad .. \quad (27)$$

The photopic troland value as defined above does not take into account the changes of response with pupil size due to the Stiles Crawford effect (Stiles and Crawford, 1933), but Le Grand (1946) has defined an effective troland by replacing S by a smaller effective pupil area S_e and this takes into account the actual effect of the radiation on the retina. Similar formulae have been developed by Moon and Spencer (1944), De Groot and Gebhard (1952).

If a source of luminance L cd.m^{-2} subtend an angle α' at the eye of an observer at a distance of d metres, the intensity of the source is

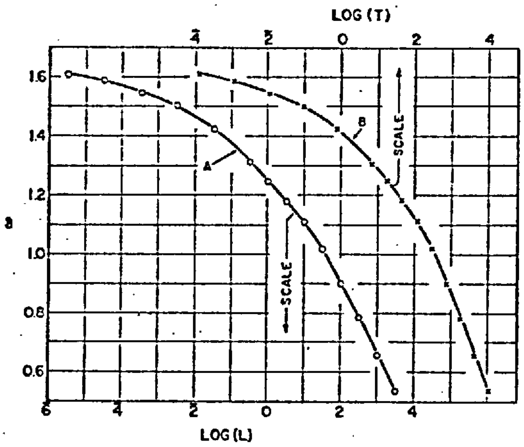


Fig. 27. Graphs for obtaining log (T, trolands) from log (L, luminance in cd/m^2) and vice versa. Curve A: $\log T = \log L + \delta$; curve B: $\log L = \log T - \delta$. Based on data of DeGroot and Gebhard (1952).

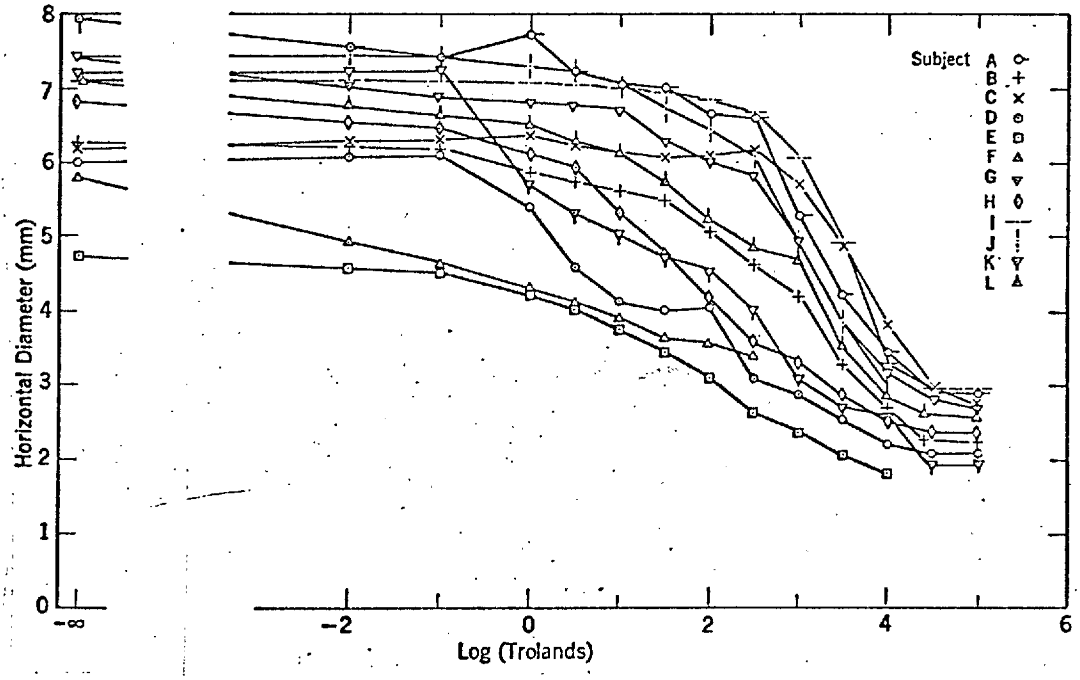


Fig.28. Pupil diameter in viewing a 52° uniform field of different troland values. Curves for 12 subjects under identical conditions (from Spring and Stiles 1948).

$$I = \frac{\pi}{4} \left(\frac{\alpha d}{3438}\right)^2 L \text{ candelas} \quad . \quad . \quad . \quad . \quad . \quad (28)$$

and its point brilliance E and troland value T are given by

$$E = \frac{\pi}{4} \cdot \frac{\alpha^2}{(3438)^2} \cdot L = 2{\cdot}115 \text{x} 10^{-8} . \, \pi \alpha^2 L \text{ lux} \quad . \quad . \quad (29)$$

and

$$T = \frac{\pi}{4} p^2 L \text{ trolands} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

where p is the diameter of the eye pupil, so that

$$E = 8{\cdot}46.10^{-8} . \frac{\alpha^2}{p^2} . \, T \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

This formula allows conversion from point brilliance in lux to retinal illumination in trolands. Similar formulae can be worked out in other cases and the appropriate conversion factors are given in table 7.

The change in the diameter of the eye pupil with field luminance has been the subject of many investigations: Reeves (1918), Couvreux (1924), Holladay (1926), Lythgoe (1932), Crawford (1936), Spring and Stiles (1948), De Groot and Gebhard (1952), and large individual differences have been observed (Fig. 28). Nevertheless, a mean curve such as that shown in fig. 29 is useful in that it allows some measure of comparison among visual observations through different sizes of artificial or natural pupils through their troland values. Fig. 27 allows rapid conversion of log (external luminance L_p) to log (photopic troland value T) and is based on the mean results of several observations as compiled by De Groot and Gebhard (1952).

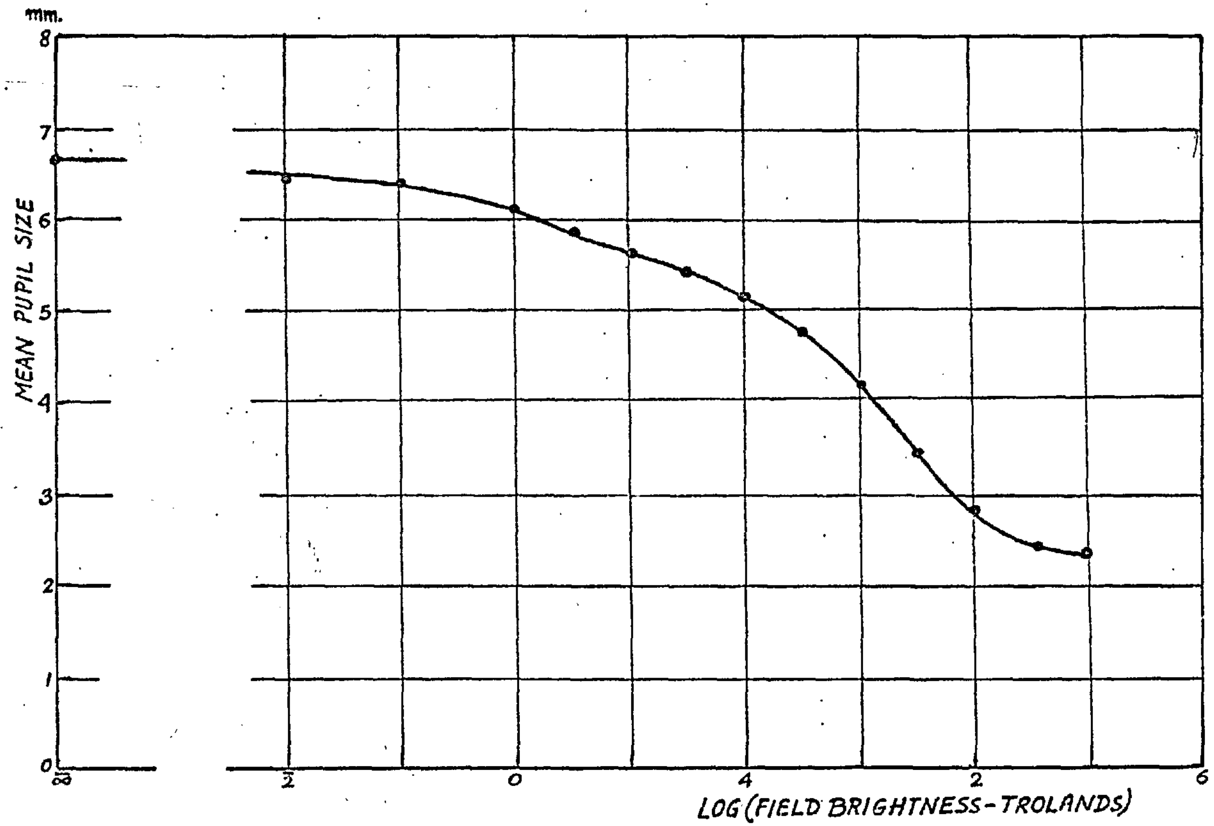


Fig. 29. Mean Pupil size/Field Brightness curve for a 52° field derived from fig. 28. (Spring and Stiles).

Table 7. Conversion factors for point brilliance and retinal illumination.

The relations between point brilliance E and conventional retinal illumination T in trolands are of the form

$$E = A \cdot \frac{\alpha^2}{p^2} T$$

and

$$T = B \cdot \frac{p^2}{\alpha^2} E$$

The values of A and B are listed below when different units are used for expressing the point brilliance.

Unit used for point brilliance	A	B
Lux	8.46×10^{-8}	1.185×10^{7}
mile candle	2.19×10^{-1}	4.57
sea-mile candle	2.91×10^{-1}	3.44
microlux	8.46×10^{-2}	11.85

Chapter III.

The experimental equipment.

A description is here given of the apparatus designed and constructed by the author for the present investigations. Earlier observations had been carried out on a pilot model embodying the same general principles, but the present arrangement includes refinements for making the operation more simple and reliable.

Functions of the apparatus:

The parameters which may conceivably influence the perception of a flashing signal are numerous: size, colour, luminance of the test field and the background, light-dark ratio, duration and frequency of the flash, retinal location, state of adaptation of the eye, presence of other lights, etc. The possible combinations are of almost infinite variety, but the number which has practical and theoretical interest is more limited, though still very large. It seemed desirable to design a piece of equipment which would allow a fairly wide range of experiments at threshold and supra-threshold levels, while retaining a basically simple optical design. The features aimed at were:

(a) a wide range of intensities for the flashing light, continuously variable from threshold to glare levels,

(b) angular subtenses for the test patch as met with in practice (1' to about ½° or 1°),

(c) a "square-wave" pulse with variable light dark ratio and a suitable range of frequencies,

(d) provision of a background field of variable size and luminance,

(e) means for establishing simple photometric comparisons between the flashing light and a steady light and for following the course of adaptation at various retinal locations.

(f) possibility of setting up simple arrays of flashing lights and flash patterns, e.g. group flashing,

(g) use of coloured test fields and backgrounds,

(h) provision for monocular or binocular viewing, and for using the binocular matching technique (haploscopic method) if necessary,

(i) simple means of checking the photometric calibration at frequent intervals.

Further, the equipment should maintain its alignment and calibration over reasonable periods of time, be fairly compact and "semi-portable" if possible, and allow for operation by a single observer.

The Optical System.

The basic optical system is illustrated in fig 30 (a,b), the high intensity requirements in the flashing and the comparison beams deciding in favour of Maxwellian fields. The light source is a 6 - volt, 108 - watt ribbon filament lamp, with the filament ab about 16 mm. in length. An image a_1b_1 (fig 30a) of this is projected by a large aperture (about f/1) condenser system C_1 (a combination of an aspheric and a double convex lens designed to work at a magnification of x3 or x4) at about x4 magnification upon

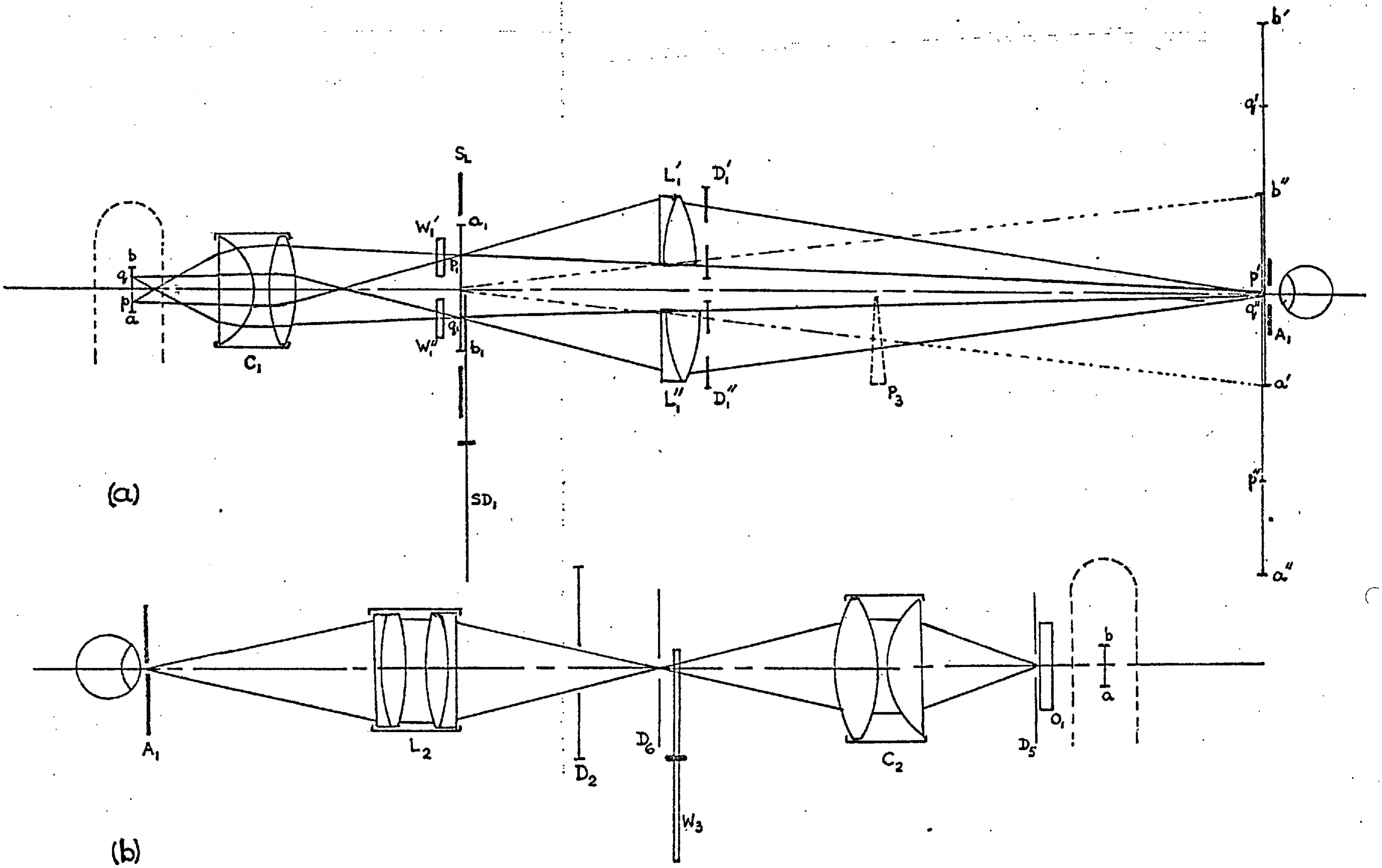


Fig. 30. Basic optical system used in (a) flashing and comparison fields, (b) background field.

a vertical slit S_L, (50 x 0.6 mm), which passes only light from the central part of the image, where this is of fairly uniform luminance. Two images a'b', a'' b'' of the slit are formed by the halves L_1', L_1'', of the split achromat at a distance of two metres from the variable apertures D_1', D_1'', the images overlapping over about half their lengths. An eye viewing the apertures D_1', D_1'', through an artificial exit pupil A_1 placed in the region of overlap, sees these apertures filled with light in Maxwellian view. From the geometry of fig 30 (a), it is clear that light entering the eye from the aperture D_1' originates from a small area at p on the filament, coming to an intermediate focus p_1 in the plane of S_L, q and q_1 being the corresponding points for the beam through the aperture D_1''. The points p,q are about 6 to 7 mm. apart and sufficiently near the centre of the filament to avoid the zones of steep temperature gradients near its ends. A sector disc SD_1 rotating across the lower half of the slit and close to it chops the lower beam, producing a fairly good "square wave" flash even at small sector openings, and the beam intensities are controlled by two straight neutral density wedges W_1', W_1'' moving perpendicular to the plane of the diagram and a few millimetres from the slit, so that the effective cross-sections of the beams in the plane of the wedges are about one square millimetre when the apertures D_1', D_1'' are fully open. A crown glass prism P_3 of about 2° refracting angle moving longitudinally in the path of one of the beams may be used to alter the angular separation between the two sources, when the slight dispersion caused by the prism does not prove troublesome;

under certain circumstances a Wollaston prism near the exit pupil in combination with suitably orientated polaroids has been found more suitable.

Light from the other side of the ribbon filament (fig. 30b) illuminates the opal disc O, and the condenser C_2 images the aperture D_5 at about x3 magnification upon the aperture D_6 which obstructs the outer parts of the image. A symmetrical lens system L_2 (two achromats about 5 cm. diameter and 17.5 cm focal length) images D_6 at the exit pupil A, at about unit magnification, providing the background field of about 12½° diameter in Maxwellian view. Luminance control is achieved through the circular neutral density wedge W_3.

The manner in which the two optical systems are brought together at the same exit pupil A, by the mirrors M_1, M_2 (about 10 cm. square), the right-angled prism P and the beam splitter B (a thin glass plate or partly silvered mirror) is illustrated in fig. 31, where the symbols (primes being omitted) have the same meaning as in Fig. 30. Fig. 31 also gives an idea of the general lay-out and other optical components. D_2 is a field stop which is imaged by the lens L_2 and the beam splitter B at two metres from the exit pupil to appear in the same plane as the test patches, and a graticule G close to it can be used for fixation. Fixation can also be achieved by looking at the image of the filament of the pea-lamp L_p (lamphouse H_3) as formed through the red filter F_r, the lens L_4 and the highly polished surfaces of the steel ball bearings S_1, S_2. For binocular viewing an image of the slit S_L (which is adjustable in width) is projected

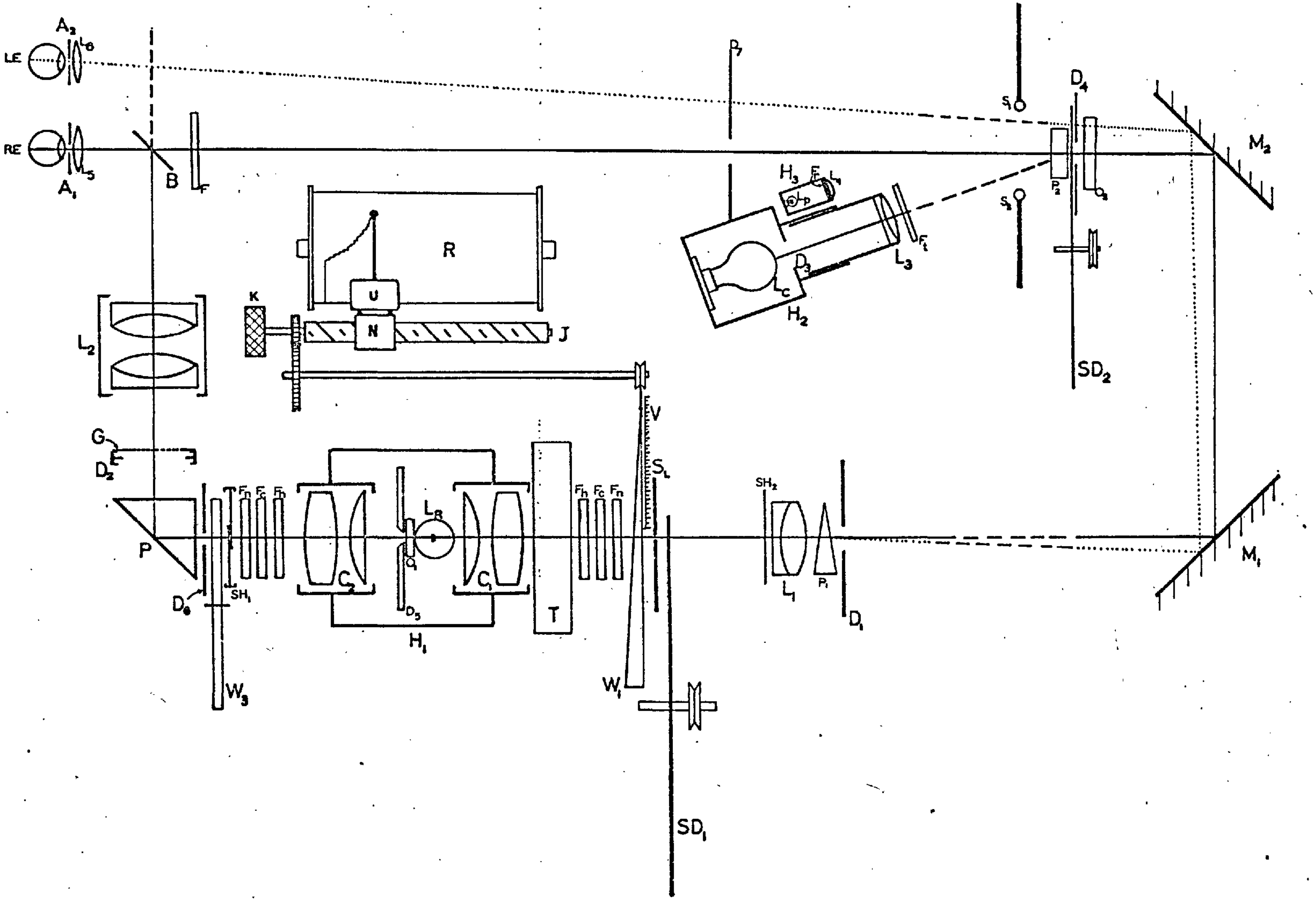


Fig 31. DIAGRAM OF APPARATUS (PLAN VIEW, NOT TO SCALE).

by L_1 on to a plate of opal glass at O_2 and with suitable apertures at D_4 (1 metre from the exit pupil) simple arrays of synchronous lights may be obtained. A prism P_1 of small refracting angle in front of the lens L_1 deviates the comparison beam as shown along the dotted path into the left eye of the observer, allowing binocular matching, the dispersion caused by the prism being offset by the chromatic aberration of the eye when the pupil is slightly decentred. F_h, F_c, F_n are heat-absorbing, colour and neutral density filters respectively, and L_5 and L_6 lenses from a spectacle trial-case for correcting the observer's vision if required.

The lamp L_c (lamphouse H2) is a 240 volt, 150 watt opal lamp run at 230 volts from a constant voltage transformer. An image of the aperture D_3 is projected by the lamp L_3 at an obliquity of about 15° on a matt white surface at D_4 and a hole through D_4 allows the observer to sight the aperture D_1, permitting a photometric match. A flicker method of comparison can also be used by sighting the white sector disc SD_2 through the aperture D_7; the slight ripple (about 5%) in the light output from the lamp L_c does not appear to have any appreciable effect on the flicker match as the same result has always been obtained by both methods. This provides a comparison source for a rapid approximate check on the calibration of the main beams, the filter F_t being used to improve the colour temperature match between the sources.

Construction.

Plate 1 shows a general view of the apparatus with the shields for cutting out stray light removed. All the components, except for the power supply units, are mounted on a wooden baseboard 120 x 75 cm. and one inch thick. The ribbon-filament lamp and the condenser lenses are contained within the main lamphouse H, (fig. 31). The 6-volt, 108-watt lamp is run at 5.6 volts off three Chloride lead-acid batteries of 150 amp.-hr. capacity maintained on float charge by a Davenset rectifier to which power is supplied via an Advance constant voltage transformer of 500 watts rating. As the life of an electric lamp varies inversely as $V^{13.3}$, where V is the voltage across its terminals (Stevens, 1951), under-running the lamp ensures very long life and stability, and one such lamp had been in use for over 2000 hours before there was any noticeable drop in the light output. Suitable rheostats (coarse and fine) are included to adjust the voltage across the lamp terminals and this is measured by a voltmeter with a large scale on which changes of 3 to 4 millivolts can be detected. The light output has been checked by a PIN diode connected to an oscilloscope and any residual ripple must be less than 0.01%. Further, it has been measured with a selenium photo-voltaic cell connected to a low impedance galvanometer over a period of several days and was found constant to within 1%. About 20 to 30 minutes is the time required for the lamp to attain temperature equilibrium within the lamphouse. The large aperture condenser lenses cause considerable heating at the focal point S_L and suitable cooling devices are required to protect the photometric wedges. A glass tank T containing distilled water followed by a heat absorbing filter F_h proved suitable. It was in fact to avoid a

Plate 1 General view of apparatus

similar arrangement in the reverse beam, where lower intensities were judged adequate, that the opal disc O_1 was inserted. This incidentally makes it easier to position the lamp which is mounted so as to allow for some degree of rotation and translation along three perpendicular axes.

The neutral density wedges are mounted in thin brass frames which slide in slots machined in a thick perspex plate and move against a scale V fixed to the plate. To the ends of the frame is attached a length of terylene twine which passes over the pulleys P_1, P_2, P_3, (Fig 32a) and is wrapped twice round the grooved drum K', being kept under tension by the helical spring S. Movement is achieved by applying a torque to K'. For single observer operation and measurement of the course of adaptation, a recording unit was necessary, and the manner in which this is coupled to the photometric wedges is best understood from fig. 31 and plate 2, which shows the recording unit and the observing end of the equipment. The drum R (6" long and 8" in circumference) is fitted on a steel shaft which rests in semi-circular grooves on stout pillars, allowing for rapid change of the recording chart, and is driven by a small clockwork motor at the rate of one revolution every four minutes. J is a multiple ten-start screw of german silver of half-inch pitch, providing reasonably fast and smooth movement and eliminating the effects of machining errors, and it drives the brass nut N which is prevented from rotating by a channelled guide parallel to the screw shaft. The brass nut carries the pen unit which is of the type used in Honeywell recorders

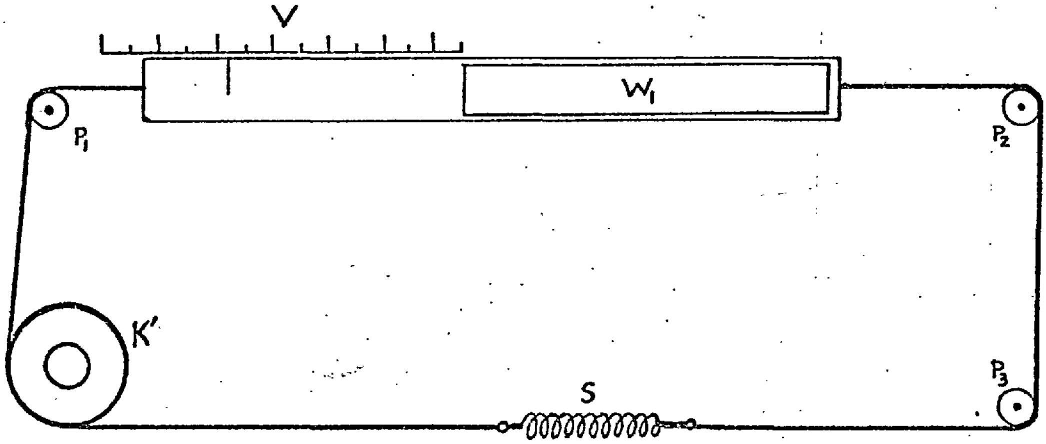


Fig. 32. Movement for photometric wedge.

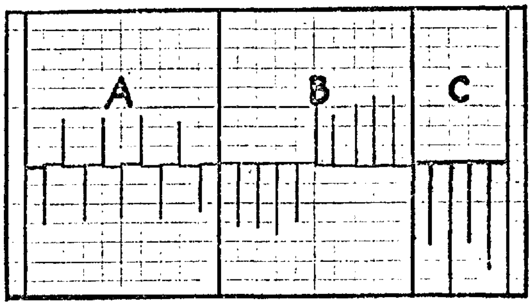


Fig. 33. Record made for checking backlash on recording equipment (18th June 1968).

and kinematically mounted. A pinion on the screw shaft is geared via an idler to a cog wheel on the shaft carrying the drum K' which moves the wedge assembly. By suitably engaging the gears the position of either the upper or the lower wedge may be recorded. The provision of some degree of adjustment on the position of the shafts driving the photometric wedges makes it possible to offset the backlash between the gears against the backlash between the nut and the screw, the stretch in the terylene twine being negligible under the tensions involved, and by careful machining of the drum K' one inch movement on the chart has been made to correspond to a change of half a log unit in optical density along the wedges. If a continuous record is not wanted, a short trace may be obtained by switching on the chart drive for about two or three seconds. The unit has required no adjustment since it was originally set up and fig. 33 recorded at the time of writing gives an idea of the accuracy attainable. In the traces A, a given setting of the wedge against the main scale V has been approached alternately from above and from below, and the error due to backlash is less than 0.005 of a log unit. The first five traces in set B are obtained by approaching from below and the next five from above. For the traces C, the recording drum and the pen unit were removed and reset after each trace.

The sector disc SD,, is of the adjustable Napoli-Abney type and is illustrated in fig. 34. The disc A, fixed to the main shaft has two 90° sectors removed and a second identical disc is rigidly attached to a sleeve sliding on the shaft. Another sleeve carrying a wheel W has a pin engaging in a grooved helix of large pitch on the

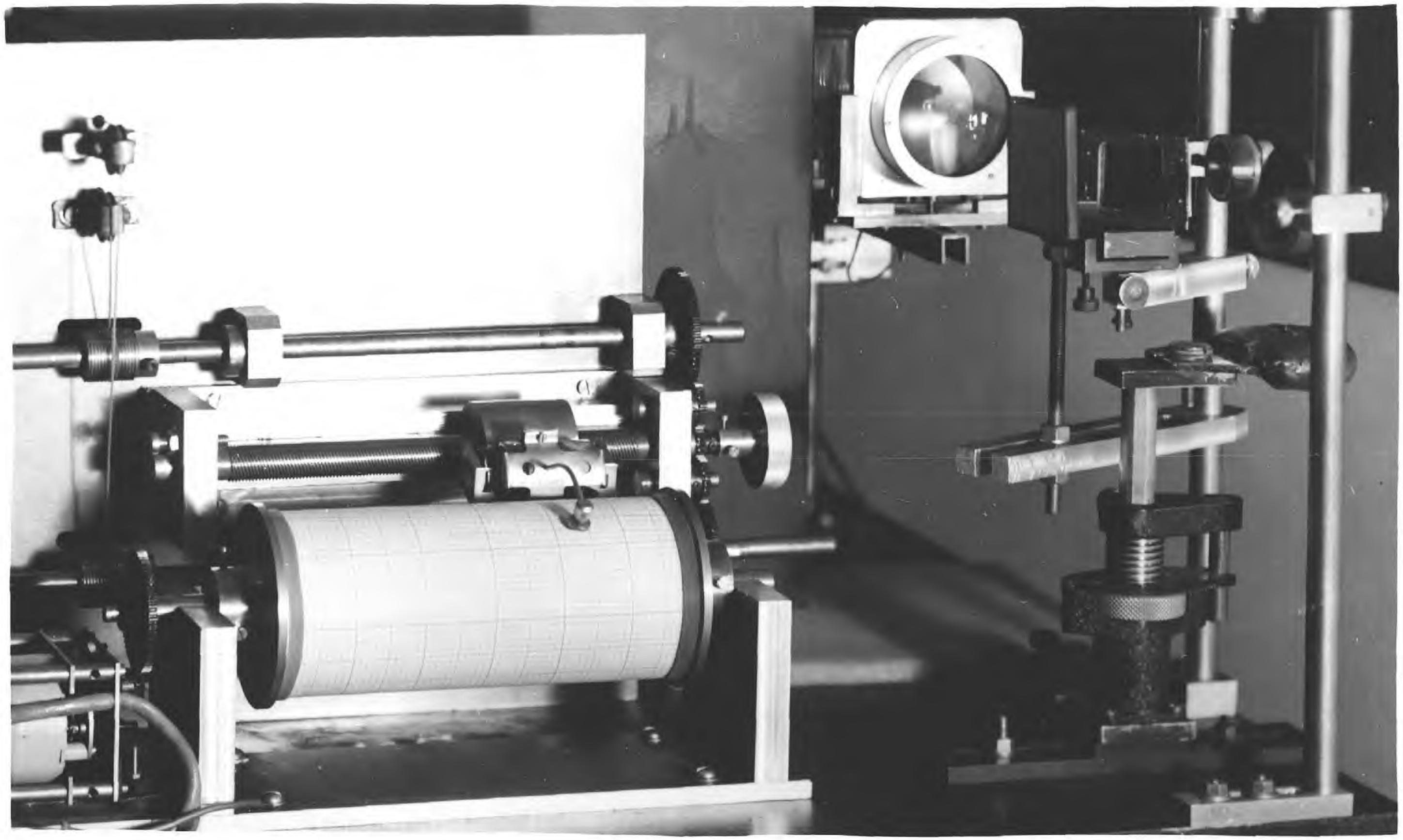


Plate 2 The Recording Unit

first sleeve and another pin engaging in a longitudinal groove on the main shaft. The width of the sector opening may thus be altered without stopping the rotation of the shaft by the action of the lever L moving on a divided scale, another scale being engraved on the sector discs themselves. Unfortunately it is very difficult to avoid some backlash in the mechanism, and as the need for altering the sector opening during rotation was not felt, it has been the practice to tape the two discs together at any desired setting. The use of sector discs as illustrated in fig. 35 makes it possible to study multiple flashes within a rather limited range of light-dark ratios. It may be of interest to place on record that the sector disc used here is one of the original sector discs made by Sir William Abney for his researches on colour vision, and is still in good operating condition.

The sector shaft is driven via a belt and pulley drive by a synchronous motor rotating at 1500 r.p.m. and geared down by a worm and gear in the ratio 12•5:1. Combinations from three pulleys on the sector shaft and eight on the motor unit (plate 1) allow 21 flash frequencies to be obtained in the range $\frac{1}{3}$ to 16 c/s with continuously variable light-dark ratios from 1:99 to 1:1. Covering up one of the sector openings extends the frequency range down to $\frac{1}{6}$ c/s, with 9 additional frequencies, the light-dark ratios being in the range 1:199 to 1:3.

The sectors SD_2 for the photometric flicker matches are cut out of thin aluminium plate and can be rotated at speeds giving flash frequencies continuously variable from about 3 c/s up to about 100 c/s. This is achieved through a fractional H.P. motor to which power is

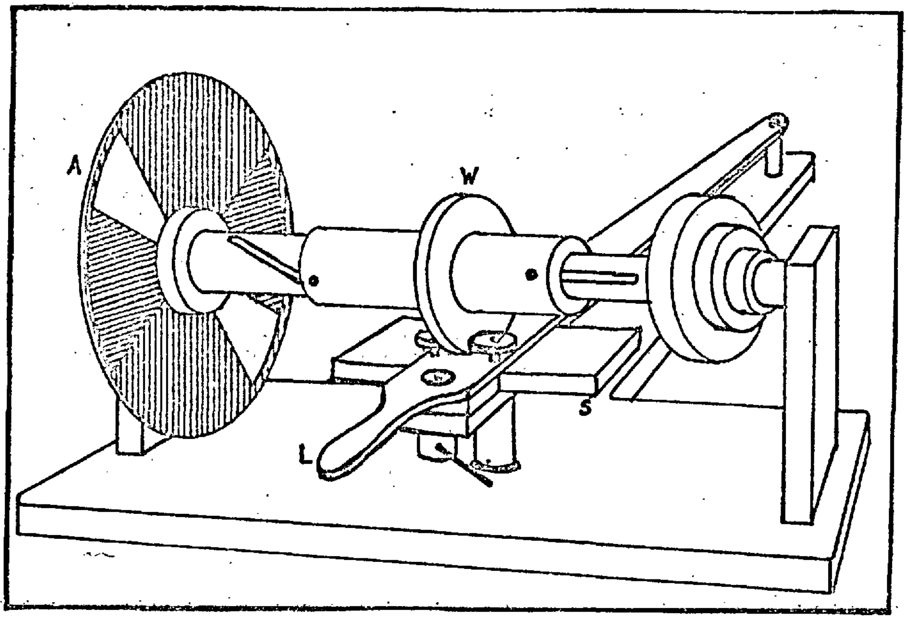


Fig. 34. The Napoli-Abney Sector Disc.

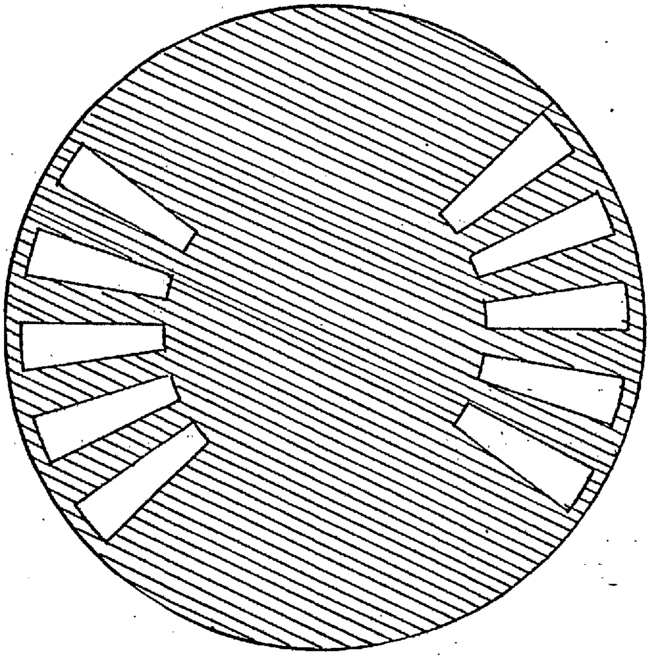


Fig. 35. Sector Disc as used for experiments on group flashing.

supplied by a variac transformer through a rheostat. The surfaces of these sectors as well as other matt white surfaces used were produced by spraying with a matt white commercial paint (U-spray) which seems to retain its reflecting characteristics fairly constantly after an initial ageing period of about a month, if not exposed to the atmosphere when not in use.

The photometric wedges W and neutral density filters Fn used are of Ilford manufacture (colloidal carbon in gelatine in combination with suitable dyes) and the spectral transmission curves for these as obtained from a Beckmann DK 2 ratio recording spectrophotometer are given in Fig 36. The colour filters Fc were interference filters. Two of these (G and R_2) were Balzers B-40 filters, and two others (B and R1) were 15-layer dielectric interference filters made in a vacuum-evaporation unit set up by Dr. C. Butler, (see fig. 36 for transmission characteristics).

The artificial exit pupils are of 2 mm. diameter, though, for certain experiments, exit pupils of 5 mm. and 6.4 mm. diameter have been used. A mouthpiece mounting is fixed to the observing end of the instrument to which a small plate carrying a dental impression made by the observer can be bolted. The observer, biting on this impression, has his head rigidly fixed in position relative to the instrument as a whole (plate 2). Observations can be made up to angles of about 12° or 15° with the visual axis, the apparatus combining the properties of a perimeter and a simple photometer within this angular field.

Calibration.

If radiation of energy distribution $E_\lambda \, d\lambda$ be incident upon a filter which transmits a fraction t_λ of this energy at wavelength λ, and K_λ characterises the response of a detector, then the transmission T of the filter as measured by the detector will be given by

$$T = \frac{\int_\lambda K_\lambda \, t_\lambda \, E_\lambda \, d\lambda}{\int_\lambda K_\lambda \, E_\lambda \, d\lambda} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (32)$$

and the filter density by

$$D = \log_{10} \left(\frac{1}{T}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (33)$$

Thus, the density of a filter as measured by any particular detector will be a function of the energy distribution in the incident flux and the response characteristics of the detector. Further, the density will vary with the angle of convergence of the beam through the filter as this may change the effective path length through the absorbing medium and the amount of light scattered in the direction of the detector if the filter contains fine particles in suspension. It seems desirable therefore that the calibration of filters be carried out in situ, under conditions approximating as closely as possible to those prevailing in actual use. Physical detectors permit a much higher degree of accuracy in measurement than the human eye, but no physical detector will reproduce exactly the response characteristics of the eye. Hence a visual method has been preferred for the calibration of the photometric wedges and neutral density filters used with the equipment.

Neutral density wedges may show some variation in their spectral

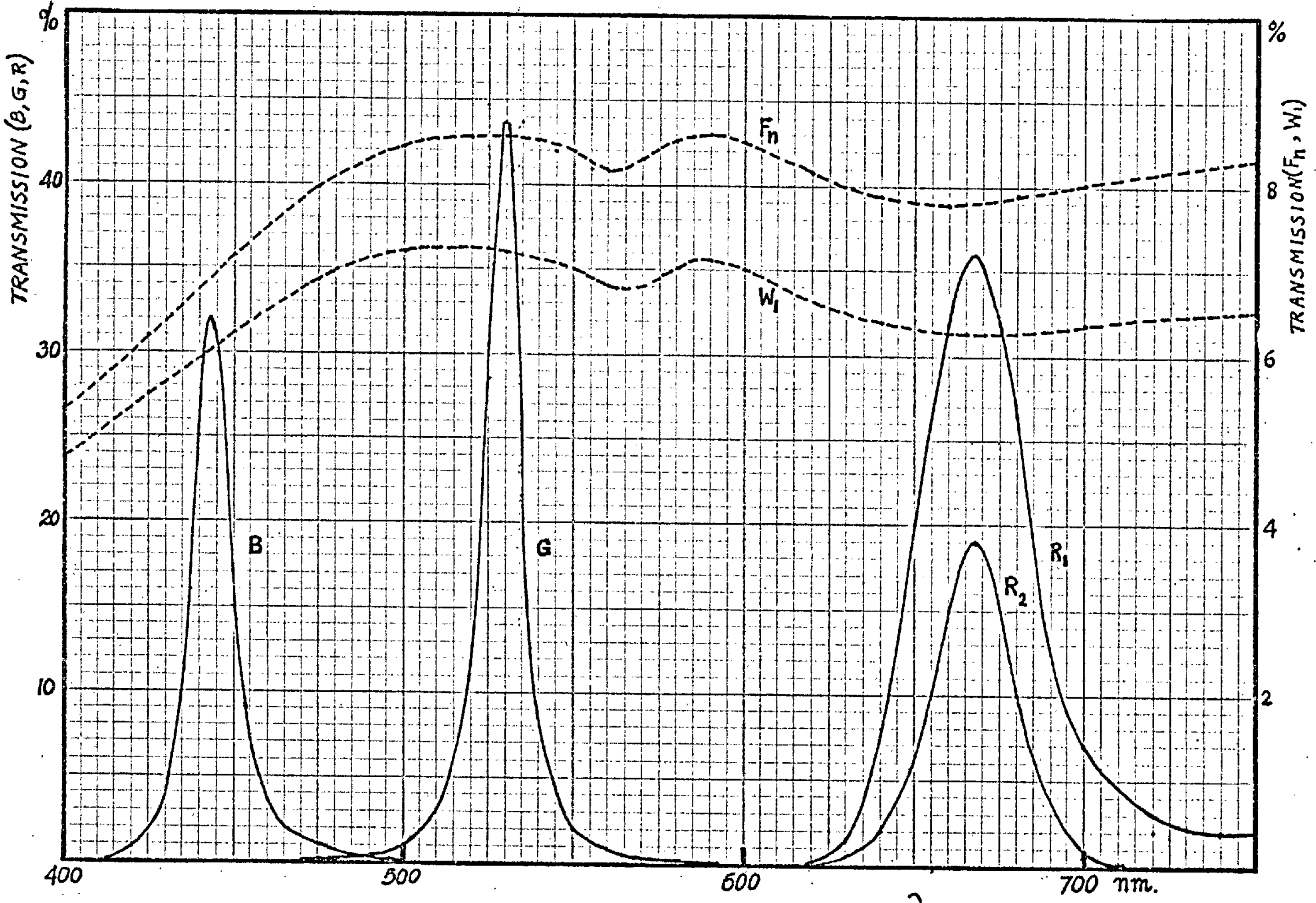
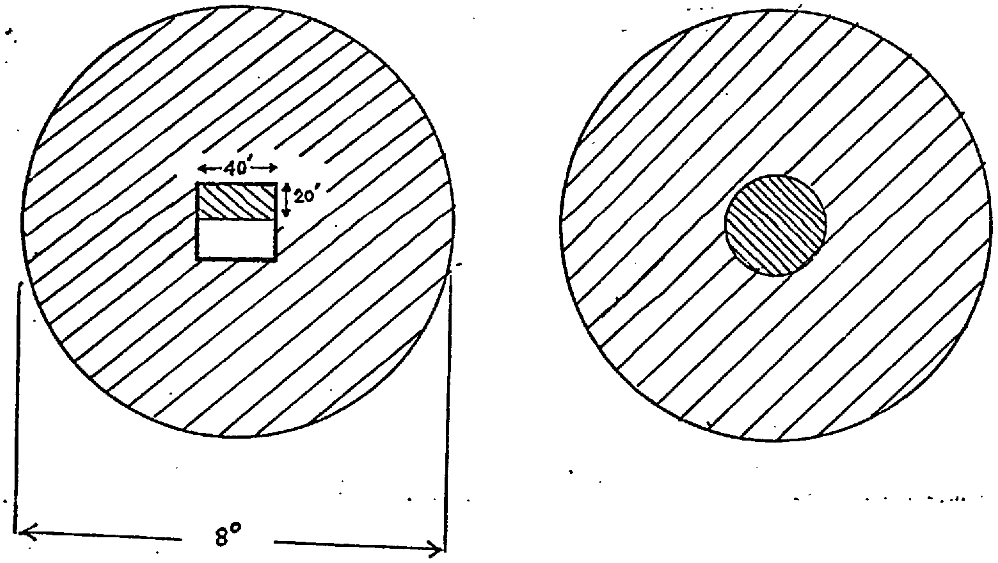


Fig. 36. Transmission curves for photometric wedge (W_1) neutral density filter (F_n) and colour filters (B,G, R_1, R_2).

transmissions and local irregularities in the gradient of optical density. The photometric wedges (length 12.5 cm, density gradient about 0.2 log unit per cm.) were selected to have closely similar transmission characteristics, and checked for local irregularities by measuring the transmission at 2 mm. intervals with a Megatron barrier-layer type selenium cell connected to a low resistance galvanometer - this gives an almost linear response for this photovoltaic cell. Two selected wedges W_1', W_2' (fig. 30) were then mounted in the apparatus which had been adjusted to produce a photometric field as in fig. 37 within a surround of about the same luminance. A photometric match was first established with the wedges at some settings A', A'' (fig. 38) near the high transmission end, neutral density filters being introduced to cut down the luminance to a troland value of about 1000. With the sector set at an opening of 12.5% and rotating at a speed well above the critical fusion frequency, the upper wedge was moved to restore the match at some setting B'. The sector was then stopped at its open position and the lower wedge moved to another setting B'' matching the two fields. Assuming Talbot's law, A'B' and A''B'' represented intervals corresponding to an increase of 0.903 in the optical density along the wedge. Starting from B', B'' two other points C',C'' were similarly found further along the wedges. The positions of A',B' ...... were the means of 100 individual settings in each case with a standard deviation of about 0.2 mm.

With the wedge W_1' set at P_1', a neutral density filter Fo of optical density about 0.2 was introduced in the path of the beam and the reading of the galvanometer connected to the photovoltaic cell noted. F_0 was then removed and the wedge moved to a position P_2' giving the same reading. P_1' P_2' gave an interval on the wedge corresponding to an increase in optical density equal to that of Fo. Provided the wedge and the filter Fo have similar transmission characteristics, which is very nearly true in this case, the response of the detector should not influence the setting P_2', and as the selenium cell approximates in response to the eye the error in this "substitution" method is negligible- this has been confirmed by visual matching. Starting from P_2', other points P_3', P_4' ...... were found along the wedge defining a number of steps of equal increment in the optical density. A large scale plot was made of the number of such steps against wedge position, and a curve drawn through the points taking into account the irregularities in the gradient as previously determined by the photovoltaic cell. From this graph and the known change in optical density over the intervals A'B', B'C' it was possible to deduce the optical density of the filter Fo and derive a table giving the optical density at millimetre intervals along the wedge, the zero point being arbitrary. The values of the optical density of Fo as derived from the intervals A'B' and B'C' differed somewhat owing to the modification of the spectral composition of the beam by the wedge which was not strictly neutral, and the mean of determinations with the two wedges was $0.171_2 \pm 0.002_4$ log unit. The wedges could now be used for calibrating the other neutral density filters and the filter Fo for calibrating the wedge W_3 in the adapting beam by a similar method. The part of the calibration involving



(a) (b)

Fig. 37. Photometric fields as used in calibrating the apparatus.

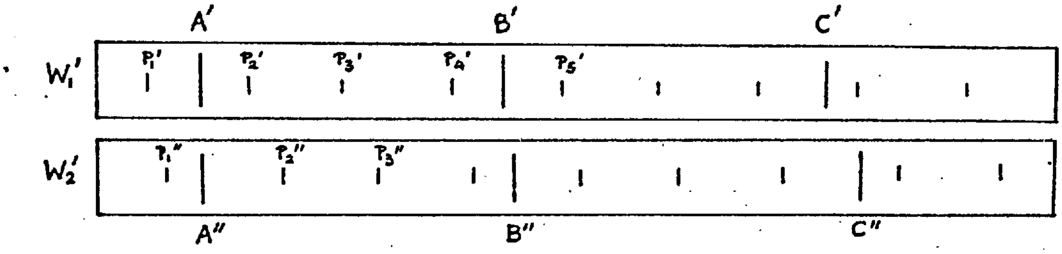


Fig. 38. Equal density intervals along the photometric wedges illustrating the method of calibration.

the sector disc was repeated with the colour filters in position to obtain suitable conversion factors for calculating the optical densities in these cases.

The luminances of the test fields and the background were determined for one wedge setting using a Holophane lumeter (fig. 39). This is a portable instrument in which the comparison lamp is within a whitened enclosure with a diffusing window which illuminates the comparison surface. The exposed area of this window can be varied by a sectored disc, a scale attached to the knob turning the disc being calibrated in terms of the illumination on the test plate. This test plate (depolished pot opal glass) is sighted through the instrument at 30° with the normal as for this angle of viewing the luminance of the plate varies little with the angle of incidence of the light upon it (Walsh, 1951). The reflection characteristics of the test plate were first obtained by comparison with a magnesium oxide surface in a Beckmann DK-2 ratio-recording spectrophotometer, after which the lumeter calibration was checked against a standard lamp on a photometric bench. The lumeter was next mounted at the position of the exit pupil of the apparatus and used to measure the luminance of the white surface of the sector disc SD_2 or the similar white surface of a plate at D_4 (fig. 31), illuminated by the comparison lamp. The luminances of the test and comparison fields were then adjusted to match this either by a flicker match or using a photometric field as in fig. 37 (b), provided by an aperture in a similar plate at D_4. The luminance of the background was then calibrated by comparison with one of the fields of known luminance.

The above calibration, carried out with a 2-mm. exit pupil at a troland-value of about 100, is based on a very indirect method, and an independent check seemed therefore indicated. A photovoltaic cell with a suitable aperture was therefore set up at the exit pupil and the wedge adjusted to give the same deflection as when the cell was under a known illumination from another standard lamp. The measurements were a luminance level corresponding to about 10^6 trolands with the 2-mm. exit pupil and gave a result which was about 0.11 log. unit (22%) lower than the value deduced from the visual calibration. The discrepancy appears rather large at first sight, but may not be too surprising in view of the difference in response between the photocell and the eye and one field being 10^4 times brighter than the other. The troland value of the field at the higher luminance as given by the visual method depends on the values assumed for the optical densities of the neutral density filters, and these are about 3.4% lower when obtained by direct measurement with the photovoltaic cell (table 8) - this in itself could account for the differences observed. Visual calibrations at about 4- to 6- month intervals differed only by a few percent (about 0.02 log unit) among themselves. It seems likely that the visual calibration is accurate to within 10% (0.04 log unit) in the middle of the range of luminances with a possible increase in the error up to about 30% or 40% (0.15 log unit) near the extreme ends of the range available on the instrument. The visual calibration has been used throughout and all results expressed in photopic troland values, no correction being applied for the Stiles-Crawford effect.

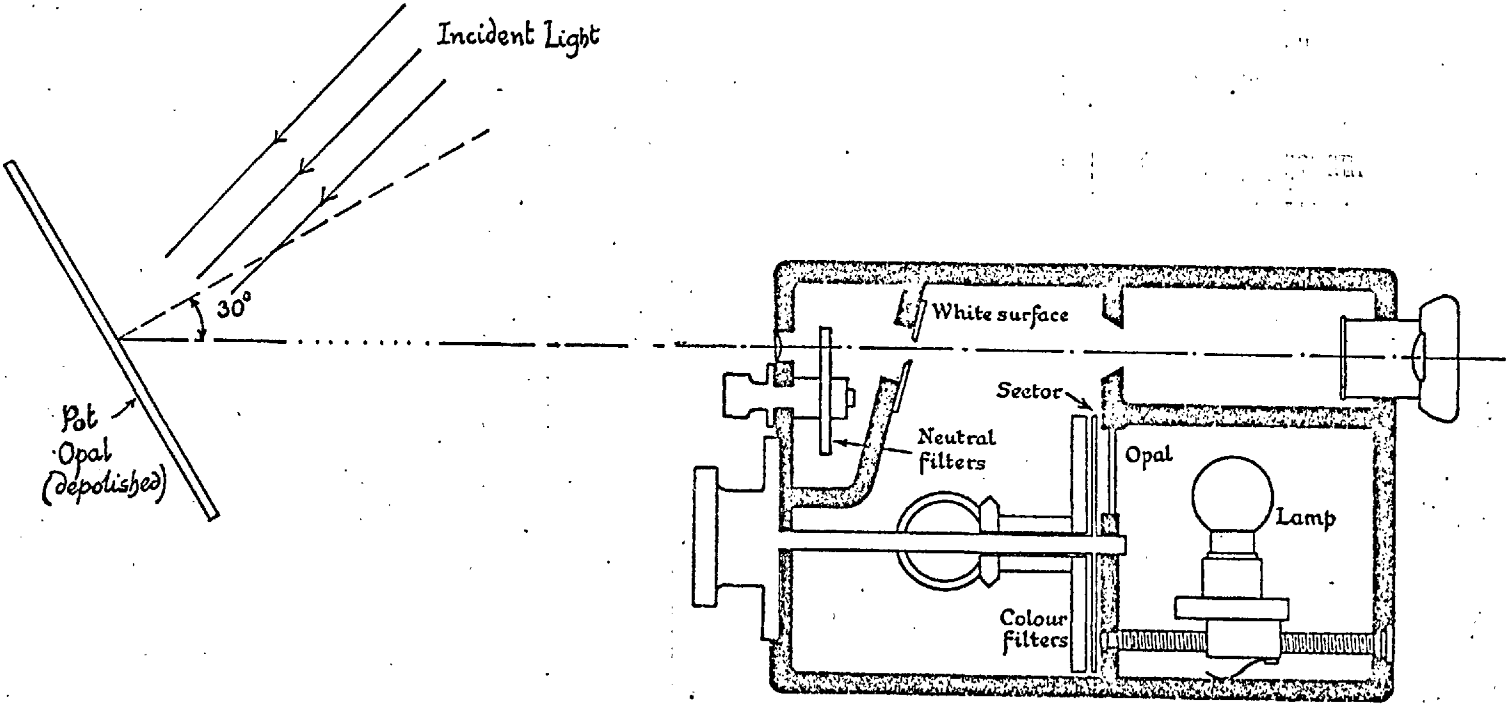


Fig. 39. The Holophane Lumeter

TABLE 8.

Optical densities of neutral density filters as measured (a) visually (D_1), and (b) with a photovoltaic cell (D_2).

Filter No.	D_1	D_2	D_1/D_2
1	1.254	1.216	1.030
2	1.207	1.167	1.034
3	2.104	2.020	1.041
4	2.284	2.196	1.040
5	1.169	1.120	1.044
6	2.186	2.118	1.032
7	2.071	1.987	1.042
10	1.515	1.482	1.022
11	0.498	0.486	1.025
S	0.1712	0.1666	1.026

When using coloured lights, observer differences can be appreciable, especially at the blue end of the spectrum; each observer therefore did a flicker match between the colour field and the comparison white, and the results are expressed in terms of the troland values relevant to the particular observer. The maximum troland values attainable with a 2-mm. exit pupil were about 2×10^6 tr. for the test field and 10^4 tr. for the background; with the green filter, 10^5 tr. and with the blue and the red filters, 2×10^3 tr. could be obtained in the test fields.

Owing to imperfections in the geometry of the sector discs, and the finite thickness of the blades, the effective flash durations from the two sector apertures differ slightly from each other, and appreciably from the nominal value at small sector openings. Only one aperture was therefore used with short flashes and the effective duration determined with a photomultiplier coupled to an oscilloscope for which the linearity of sweep had been checked with a square wave from a signal generator. Such an oscilloscope trace is shown in plate 3 for the smallest sector opening used, which at a rate of rotation of $\frac{1}{2}$c/s should give a nominal flash of 10 ms. The actual flash duration measured at half the pulse height is only about 6.8 ms., though the wave shape is reasonably square with a rise time of about 0.34 ms.

The colour temperature of the source has been measured at the exit pupil at about 10^6 trolands by comparing the deflections obtained with a photovoltaic cell when broad band pass orange and blue-green filters were placed in the beam. The device had been previously calibrated against sources of known colour temperatures. The value of 3030° K obtained was about 200°K higher than that of the source and is no doubt due to selective absorption and reflection by the various components, and in particular by the walls of the water tank.

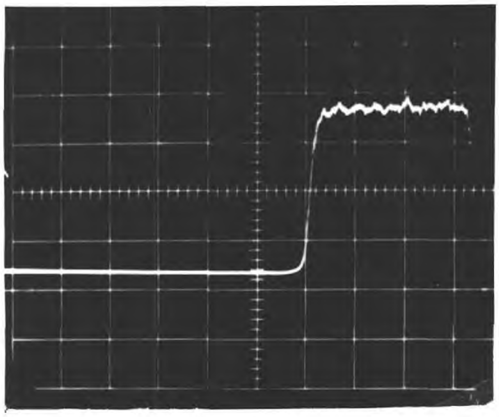


Plate 3 Oscilloscope trace for 7 ms pulse

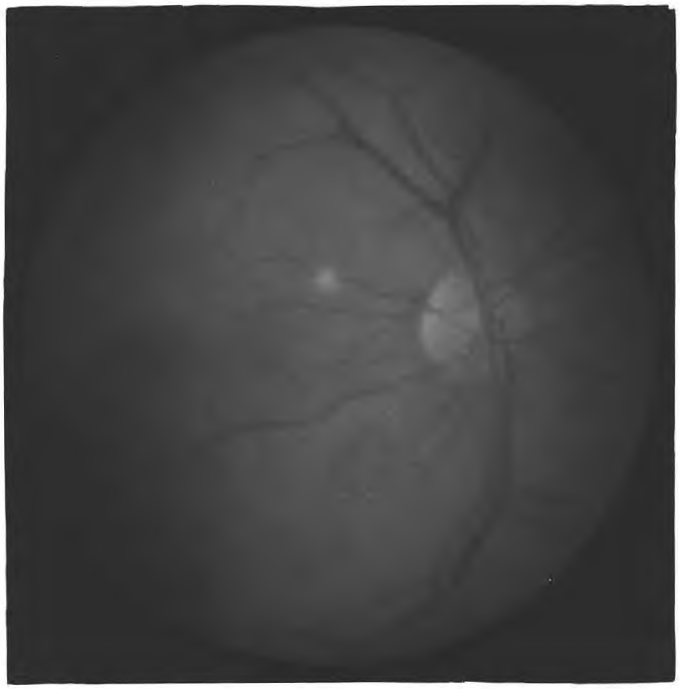


Plate 4 Fundus photograph for observer RJW (right eye)

CHAPTER IV

Conditions of observation.

The experiments to be described in the following chapters have been spread over a period of eighteen months and are not necessarily given in the order in which they were performed. Most observations have been carried out with the present apparatus though a few results obtained with the earlier equipment have been included where the validity of the conclusions seemed justified.

The Determination of the threshold.

A large number of the experiments consist of the determination of the visual threshold, and some of the conditions which may influence this have been studied by Blackwell (1952, 1953). As the magnitude of a stimulus is increased, the probability of its detection against the background increases in general according to some sigmoid curve (fig. 40). Various assumptions (Poisson, normal, log-normal distributions) have been made from time to time about the exact form of this curve, but these differ so little from each other that so far it has not seemed possible to decide by experiment which is the correct one and caution must be exercised in basing visual theory upon the form of the curve. With a given observer, the slope of the curve may change with the conditions of observation; under similar conditions of observation, some observers obtain much flatter curves than others (Crawford and Pirenne, 1954). The threshold may be defined conventionally as being the stimulus magnitude corresponding to a given probability of perception, often taken as 50%.

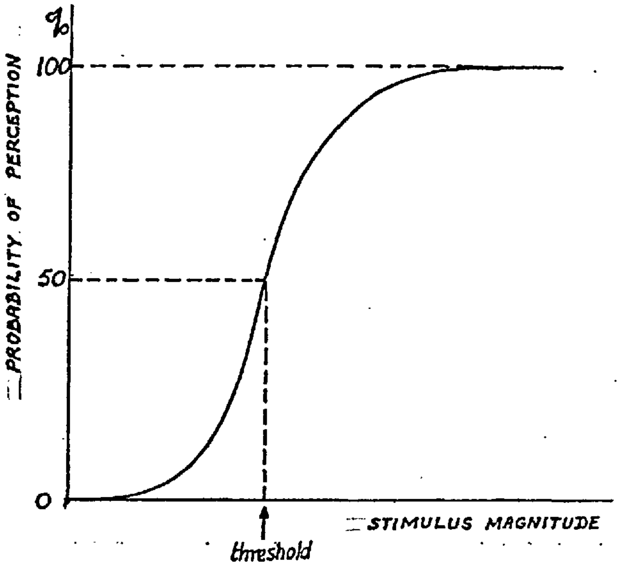


Fig. 40. Frequency of seeing curve.

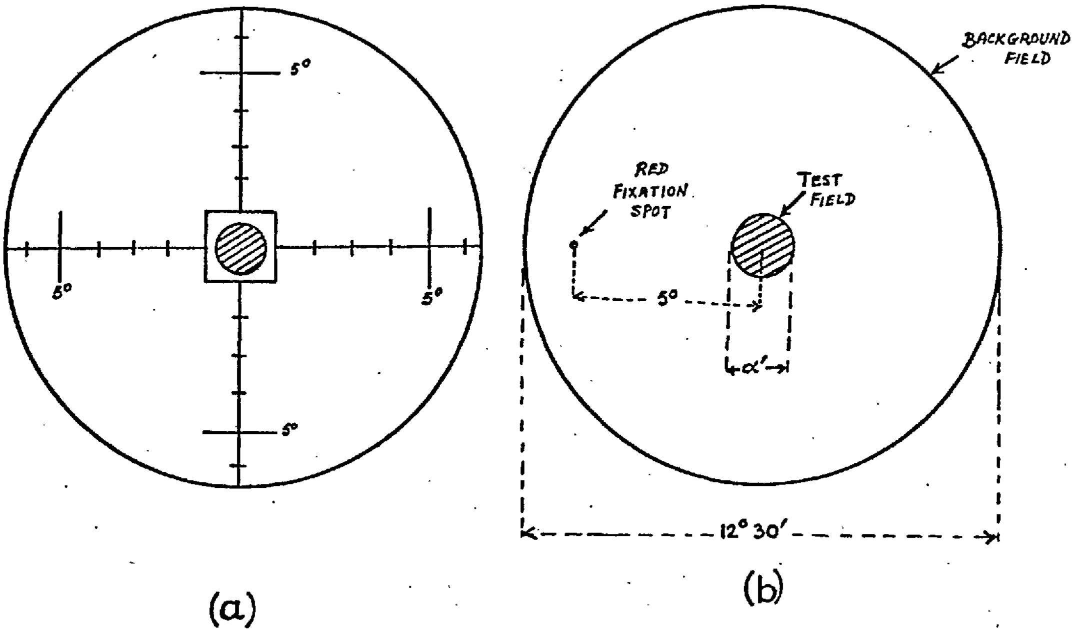


Fig. 41. Fields used for threshold determinations.

Three main psychophysical methods seem available for threshold determinations:

(i) the observer adjusts the magnitude of the stimulus until he can just detect it against the background,

(ii) the experimenter adjusts the stimulus magnitude in ascending or deccending order until the observer reports a just noticeable difference,

(iii) each of a number of stimulus magnitudes over a suitable range of the sigmoid curve is presented randomly to the observer who reports whether he sees the stimulus or not, the threshold being then computed on the basis of the convention adopted about the probability of perception.

Thresholds obtained by the three methods are not identical and seemingly trivial differences in the experimental conditions may lead to large variations in the threshold values. In the first two methods, the observer is generally aware of the adjustments being made and this may conceivably affect his decision. The third method is not open to this objection and it may possibly be improved upon by asking the observer to report on the orientation or the spatial or temporal location of the stimulus; this method may however be rather time-consuming and not easily adaptable for experiments by an unaided observer.

Important aspects of threshold determination are precision, reliability and validity. Precision is reflected by the spread of the individual readings; conditions favouring a steep frequency of seeing curve will increase the precision, which is at least in part a characteristic of the observer. Reliability implies reproducibility of the results from session to session and validity is determined by how far the threshold may have been influenced by factors irrelevant to the visual function of interest. In the present experiments, the first method of threshold determination has been used throughout, and an initial period of training was generally found to yield more consistent results, the observer setting up for himself a more reproducible criterion as he gained in experience.

Some early attempts at determining the threshold for small red stimuli in the parafovea and against a background of low luminance (1 troland) in the mesopic range gave a large spread in the readings; a series of experiments was therefore performed to find out how the threshold changed during the course of prolonged adaptation to the background and whether the observations were in any manner influenced by the method of fixation used. The observer initially dark-adapted for 30 minutes after which he maintained fixation as carefully as possible on a point 5° from the test spot (fig. 41a,b), and took threshold measurements by increasing the luminance of the test field until this was just visible. The threshold was recorded at 20-second intervals for a period of about 20 minutes, blinking being restricted to the instants at which the record was being made and done as rapidly as possible so as to avoid disturbing the adaptation. Some of the results as obtained by two observers against background luminances B of 1 troland and 2000 trolands are given in fig. 42-46; α is the angular

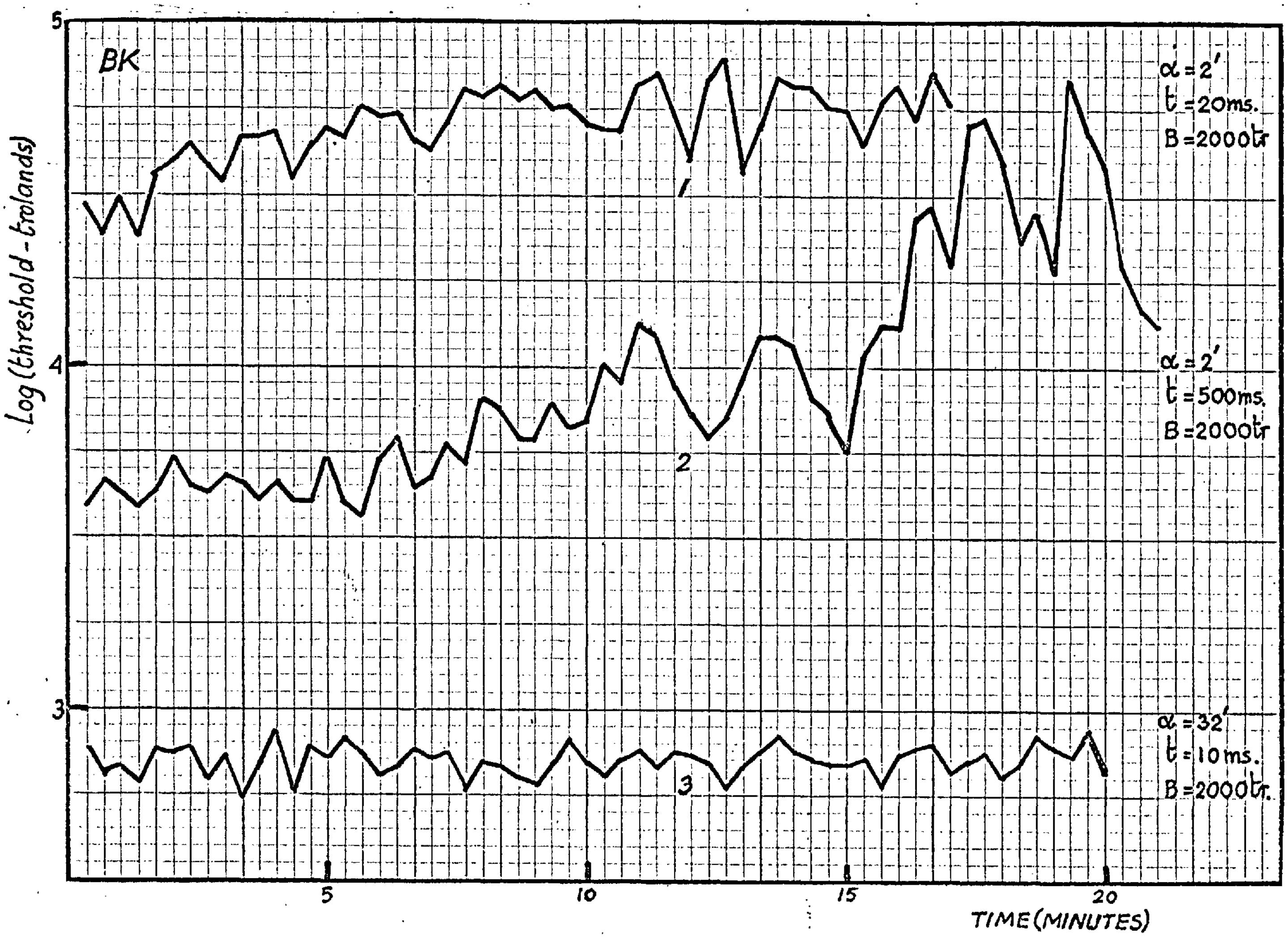


Fig. 42. Threshold changes with prolonged upward adaptation.

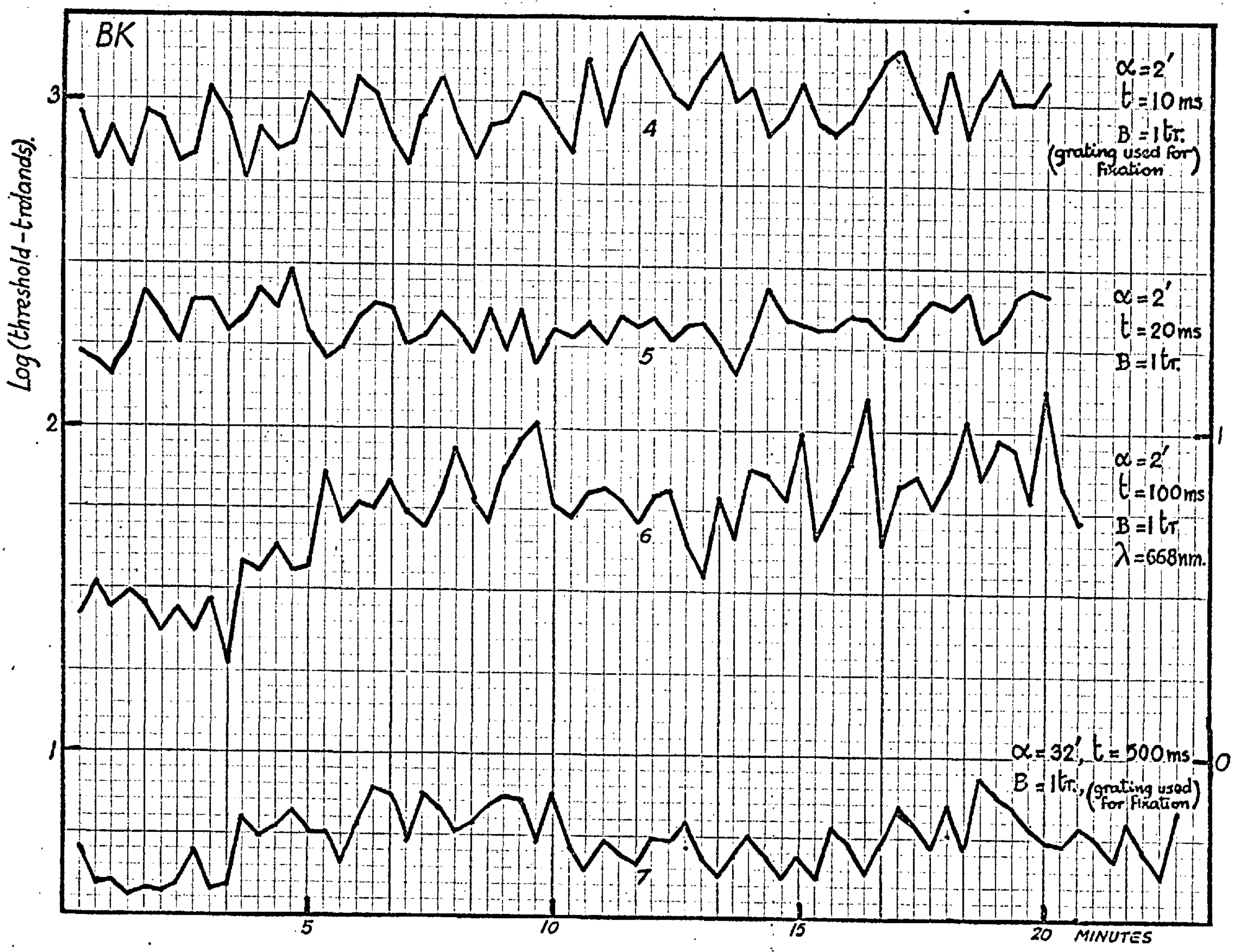


Fig. 43. Threshold changes during prolonged upward adaptation.

Fig. 44. Threshold changes during prolonged upward adaptation.

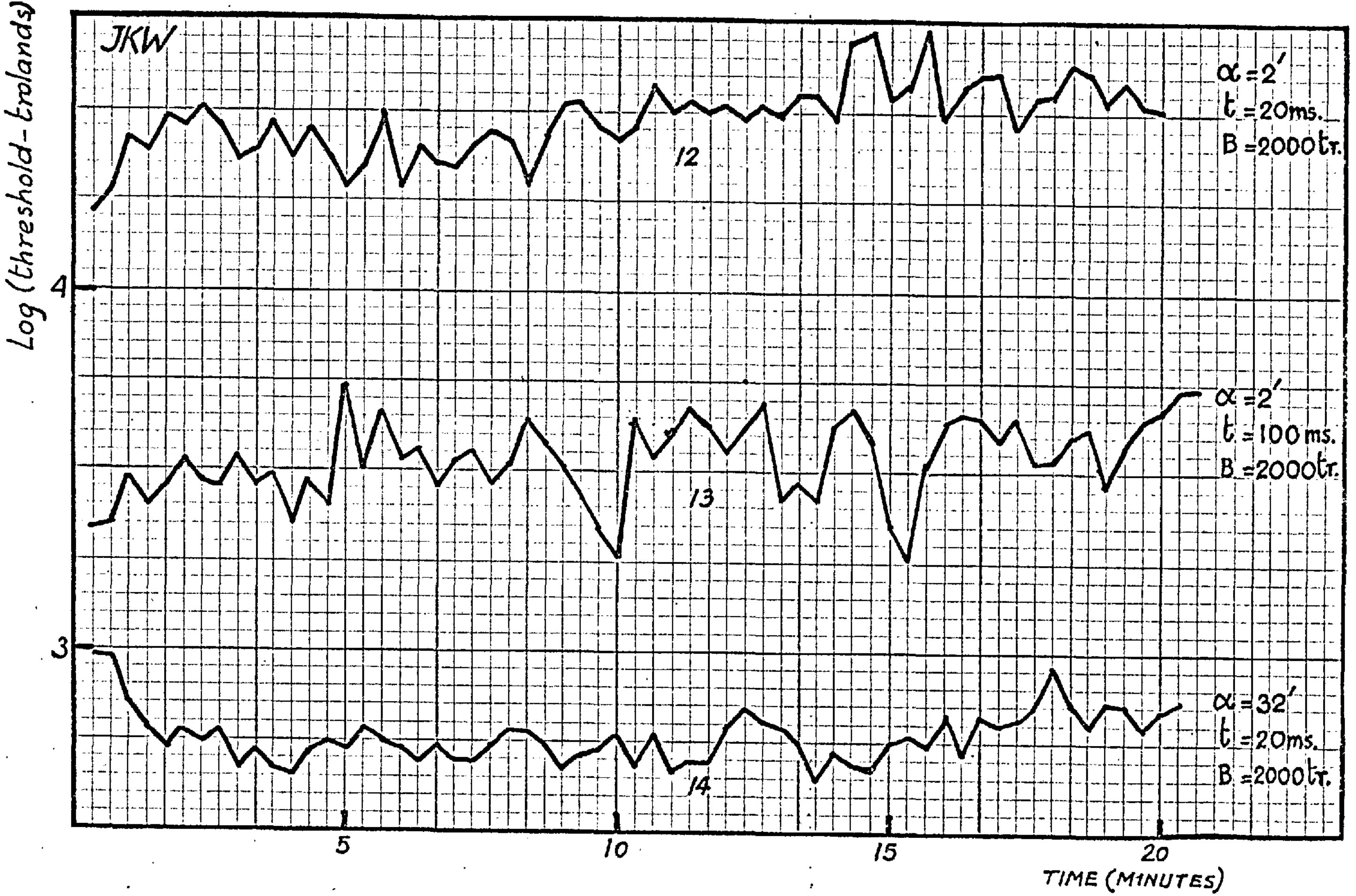


Fig. 45. Threshold changes during prolonged upward adaptation.

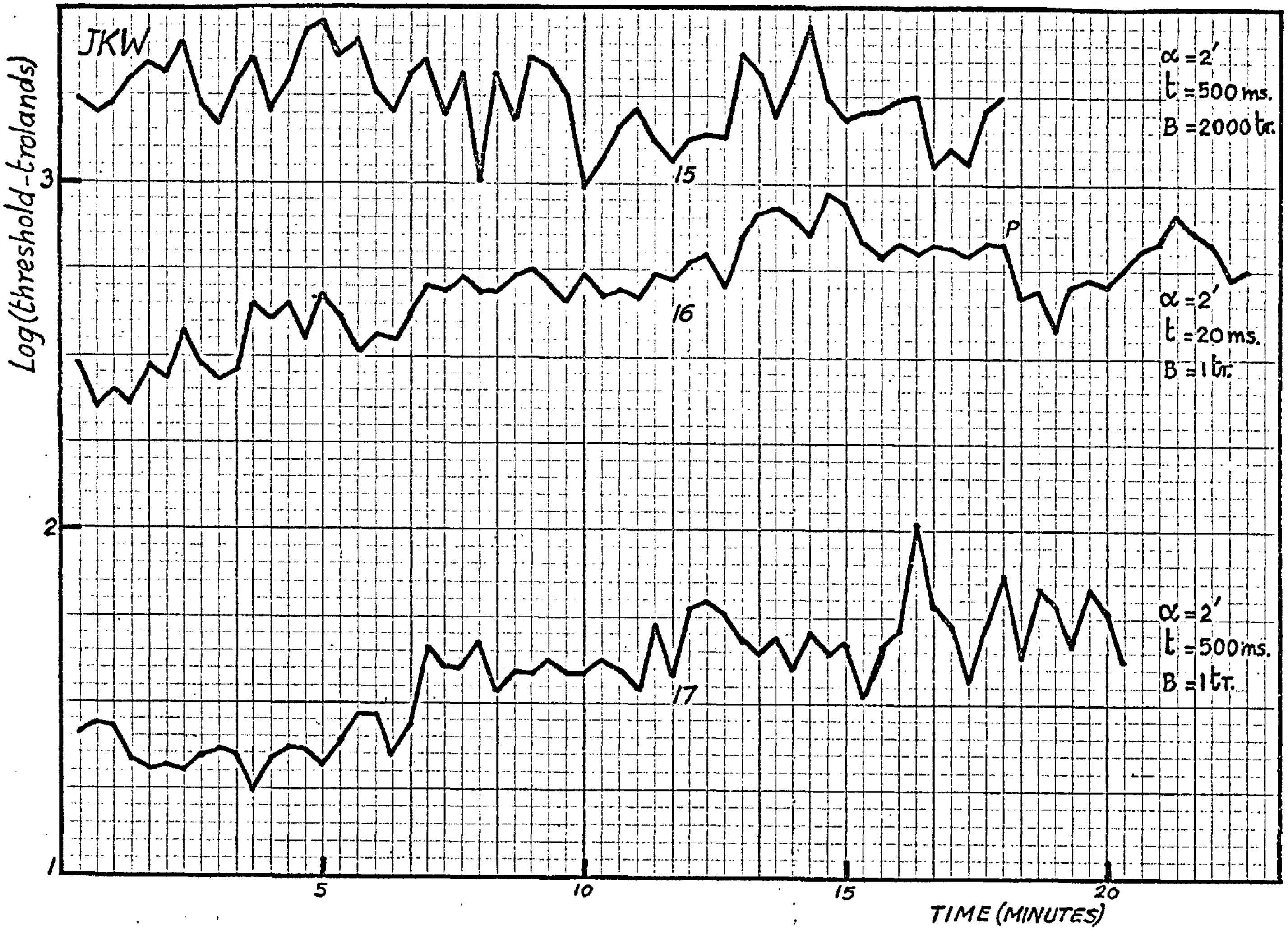


Fig. 46. Threshold changes during prolonged upward adaptation.

subtense of the test patch in minutes of arc and t the duration of the flash of frequency 1 c.p.s. The test field is white unless otherwise indicated. Comparison of these and other similar data have led to the conclusions which follow.

There is an initial period of adaptation of about 1 or 2 minutes over which the threshold may show an upward or a downward trend (graphs 11, 12, 14), after which it remains fairly constant for two or three minutes. Four or five minutes after the start, the observer starts feeling the first symptoms of fatigue and there may set in a slow rise in the average value of the threshold, occasionally preceded by a fairly rapid increase of about 0.2 or 0.3 log unit (graph 8). This is generally accompanied by a marked increase in the spread of the readings, more pronounced with small test fields viewed against backgrounds of high luminance. Considerable strain may develop within the next few minutes (graphs 2,6,8,13), especially with bright backgrounds. Lengthening the flash duration or reducing the size of the test spot leads to a marked increase in the spread of the readings.

Changes in the value of the threshold over the first one or two minutes would be associated with the depression of sensitivity occurring with upward adaptation to the background, which is almost complete within about 100 seconds (Wright, 1946; fig. 47). One might expect an increase in the threshold value, and the initial decrease occasionally observed (graph 14) may in part be due to the glaring effect of the background, which diminishes with adaptation, though the possibility of the observer readjusting his criterion

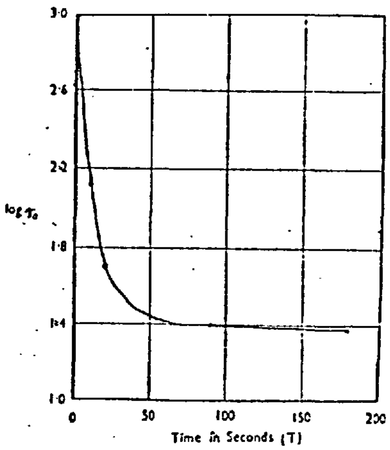


Fig. 47. Depression of sensitivity with increasing time T of adaptation to white light of colour temperature 2800° K. r_0 is the amount of red light (650 nm.) required in a colour match for a yellow (580 nm.) test colour immediately after the adapting field is cut off (Wright).

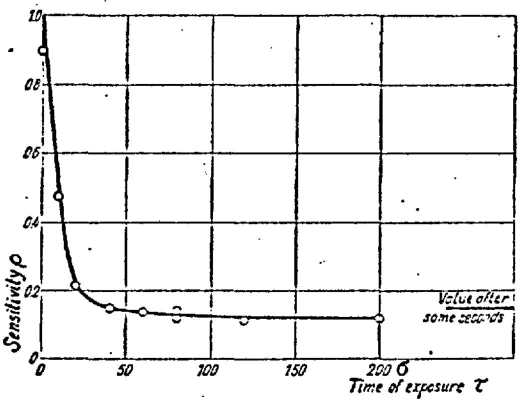


FIG. 48. Curve showing dependence of the sensitivity upon the time as measured with the slit-wheel, during the first 0.2 sec. of exposure. Glare angle $\varphi = 6°$. Illumination at the eye 180 lux. Each point gives the mean of four readings. (Schouten and Ornstein)

between successive observations cannot be ruled out. With small test patches, the local illumination on the retina may be fairly high even at threshold, and this may appreciably reduce the sensitivity of the area illuminated. Small eye movements which image the spot upon a fresh portion of the retina may thus lead to large variations in the value of the threshold. The effect may be more marked with longer flash durations in view of the rapid α-adaptation process (possibly of electrical origin) demonstrated by Schouten and Ornstein (1939), fig. 48, which may lead to a large drop in sensitivity within about 50 ms. as opposed to the slower β-adaptation (more likely of a photo-chemical nature) investigated by Wright. The fact that the lowest recorded values of the threshold may remain fairly constant whereas the higher values exhibit larger differences (graphs 1,8), would tend to support this view. The very large differences observed on prolonged adaptation would in part be ascribable to the fading of the stabilised retinal image (Ditchburn, 1954; Ditchburn and Fender, 1955; Clarke 1957, 1960) which is more pronounced with increasing eccentricity from the visual axis in vision with the unaided eyes. After five or six minutes fixation it was not unusual for the observer to observe fading of large areas of the background, the detection of the test field being very difficult if it occurred within such an area. Dark adaptation for even two or three seconds may then produce a temporary reduction in the threshold as at P in graph 16. Some effects associated with eye movements and the fading of the stabilised image will be considered again in later chapters.

In some of the earlier experiments, a graticule ruled on a glass plate had been successfully used for incremental threshold determinations against bright backgrounds. In the mesopic range however, the lower background luminance necessitated a coarser ruling and the graticule markings introduced a non-uniformity in the background which most observers considered objectionable. The use of the grating gives a greater spread in the results (graph 4,7) though it may not sensibly affect the threshold, and in this respect a non-uniform background may be comparable in effect to the presence of noise lights in the field of view (p.54). Against dark backgrounds a photographically produced graticule with clear markings transilluminated with red light has been used occasionally, but has in general proved unsatisfactory, the reason for this may be different and will be discussed later.

In view of the above, certain conditions were generally adhered to in all threshold determinations; departures from these and additional measures are indicated in the text as occasion arises. The aim has been to reproduce the conditions of observation as nearly as possible from session to session to improve the reliability. Fixation has usually been with small red spots and the graticule only used against bright backgrounds if it was found more convenient. Even when determining the incremental threshold against backgrounds of high luminance, it has been customary to allow the observer about five minutes of preliminary dark adaptation, after which he adapts for about $1\frac{1}{2}$ minutes to the background field before any readings are taken. The time taken over one observation not only depends on the nature of this observation but may vary with the psychology of the observer. A few readings are taken within the next three minutes or so after which the observer dark-adapts for about 30 seconds and the procedure is repeated until sufficient observations have been obtained for any one particular threshold. The observer then rests for two or three minutes with the observing eye dark adapted before proceeding to the next determination. To avoid fading due to stabilisation of the retinal image, small eye movements are encouraged during actual observation, fixation being carefully maintained only at the moment of making the final adjustment. For observations in the mesopic range and against dark backgrounds the same procedure has been adopted except that the preliminary dark adaptation is of the order of 20-25 minutes and one hour respectively.

It has generally been arranged that observers should have two or three practice sessions before starting on any series of observations. The sessions have been limited to a maximum of about two hours and more than two sessions per day has not seemed practicable, unless these were relatively short. In the longer sessions, or when adjustments to the apparatus between successive determinations were rather involved, a second experimenter has usually assisted the observer even if the latter were quite experienced in handling the equipment.

Approaching the threshold from above has been found to give more consistent results than approaching it from below. As the luminance of the test field is reduced a point is reached at which the observer is conscious of missing certain flashes and the flash character becomes indistinct. The transition is fairly sharp and the criterion more easily reproducible, and determinations by 3 observers gave 76%, 76.5% and 78.5% as the probability of seeing. This method has been adopted in all the later experiments and it would seem fairly reasonable to assume that the thresholds obtained correspond to a 75-80% probability of perception. Though it has not been found generally practicable to do so, the standard deviation has been indicated on some of the diagrams to convey an idea of the accuracy obtainable. This is rather better than would be indicated by fig. 42-46, and fig. 49 shows part of a fairly typical record for an experiment in which the variation of the threshold with flash duration t was being investigated; the reference marks A,B,C give an idea of the linearity of the intensity scale. It was often noticed that there was a slow creep in the value of the threshold during the course of an experiment; the practice was therefore adopted of repeating the first reading at the end of the session. If differences of more than 0.1 log unit were observed, the observations were repeated in reverse order at a subsequent session and the mean of the two sets of readings taken.

Recording the dark adaptation curve.

In the earlier experiments the observer continuously adjusted the luminance of the test patch so that it appeared at threshold and

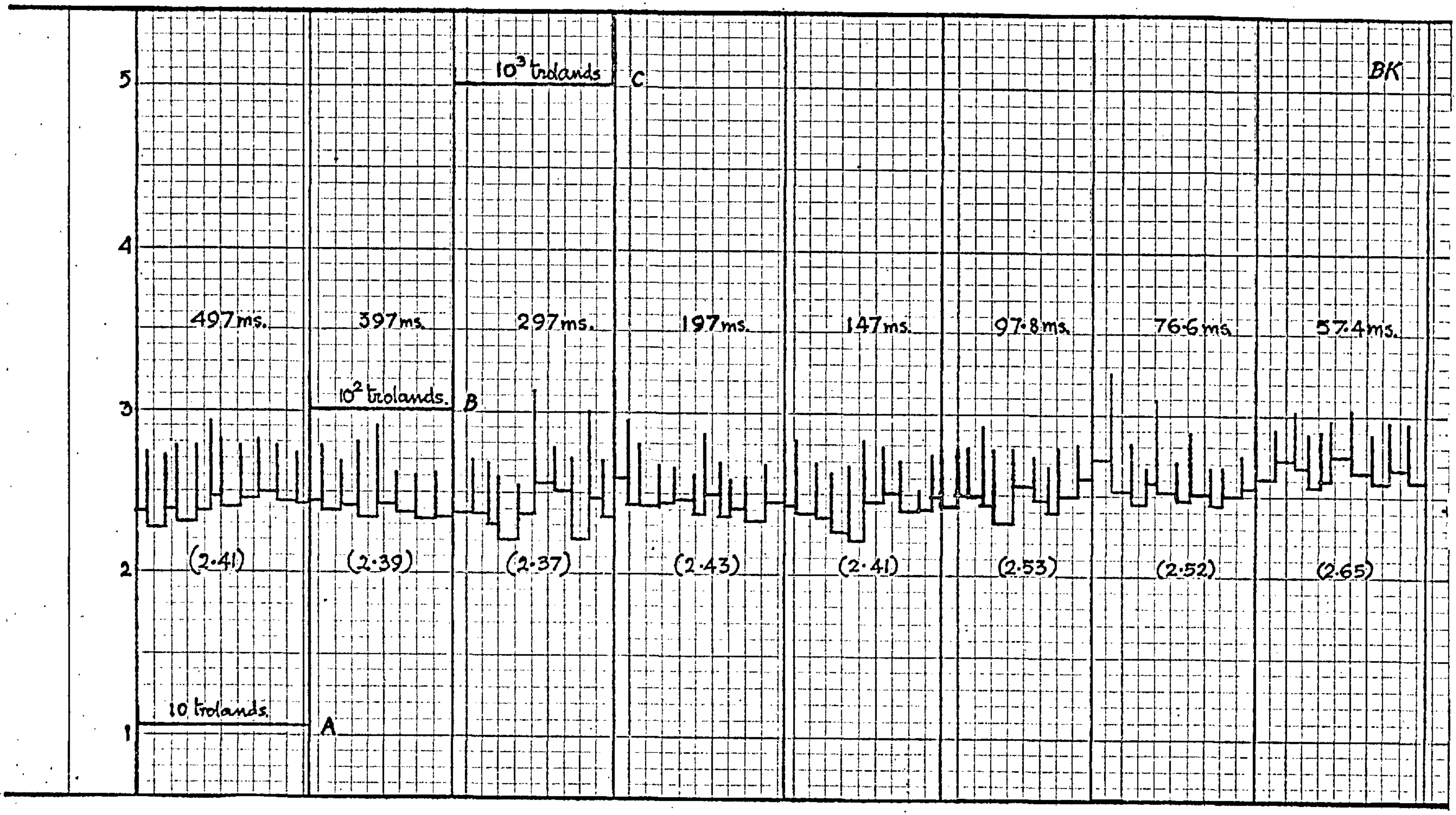


Fig. 49. Record of threshold values (α = 32', Θ = 5° nasal, B = 1000 tr., flash frequency = $\frac{1}{2}$ c/s).

fig. 50 illustrates such a set of traces and the method by which the final curve is arrived at. A different method has been used in the later experiments as it was found more reliable and more satisfactory to all the observers. Fig. 51 shows a trial by observer JKW. At a suitable auditory signal at A the observer switches on the recording device and at another signal cuts off the adapting field at B by operating the camera shutter SH_1 (fig. 31) and starts observations. The observer waits until he just sees the flash, then lowers the intensity by moving the neutral density wedge and waits till he sees the flash again; eye movements are encouraged during the waiting periods. The threshold curve is taken as that passing through the points P_1, P_2, P_3, P_4 ..... of the recorded trace. The initial intensity is previously adjusted by trial and error so that the observer misses the first flash but sees the second. The time scale is correct to about $\pm\frac{1}{2}$ second.

Observers.

Altogether, five observers have generally participated in the experiments, though the larger part of the observations have been carried out by the author (observer BK). Except for BK (40 yr.) all the observers were in the age group 22-28 years and with normal eyesight and colour vision as tested with Ishihara plates and the Farnsworth-Munsell 100-hue test. Observer BK had normal hue discrimination but slightly reduced sensitivity at the blue end of the spectrum, partly because of age but mainly becuase of greater absorption by the macular pigment (Ruddock, 1963,1965); his V_λ-curve as

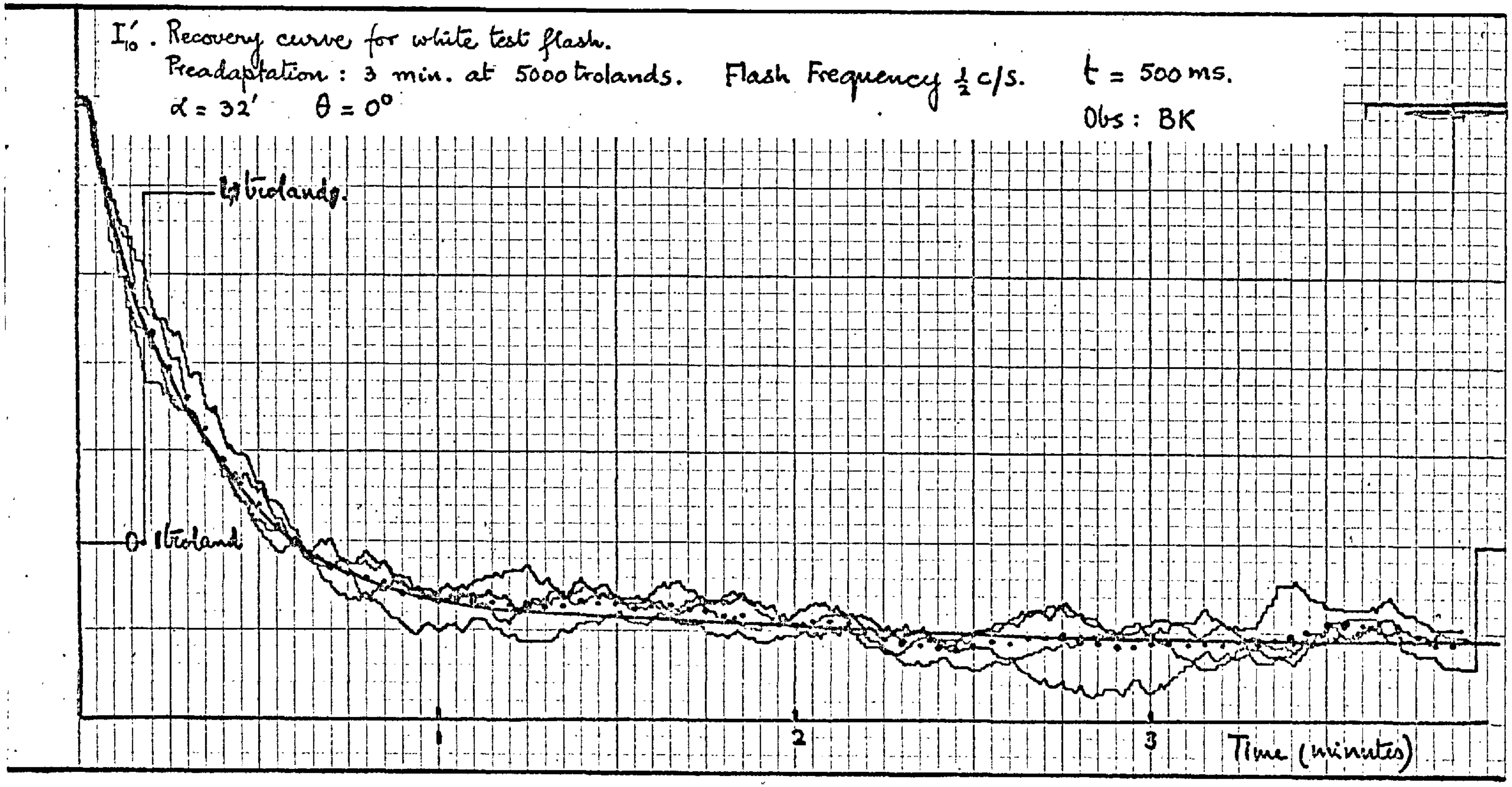


Fig. 50. Dark adaptation traces from recording unit.

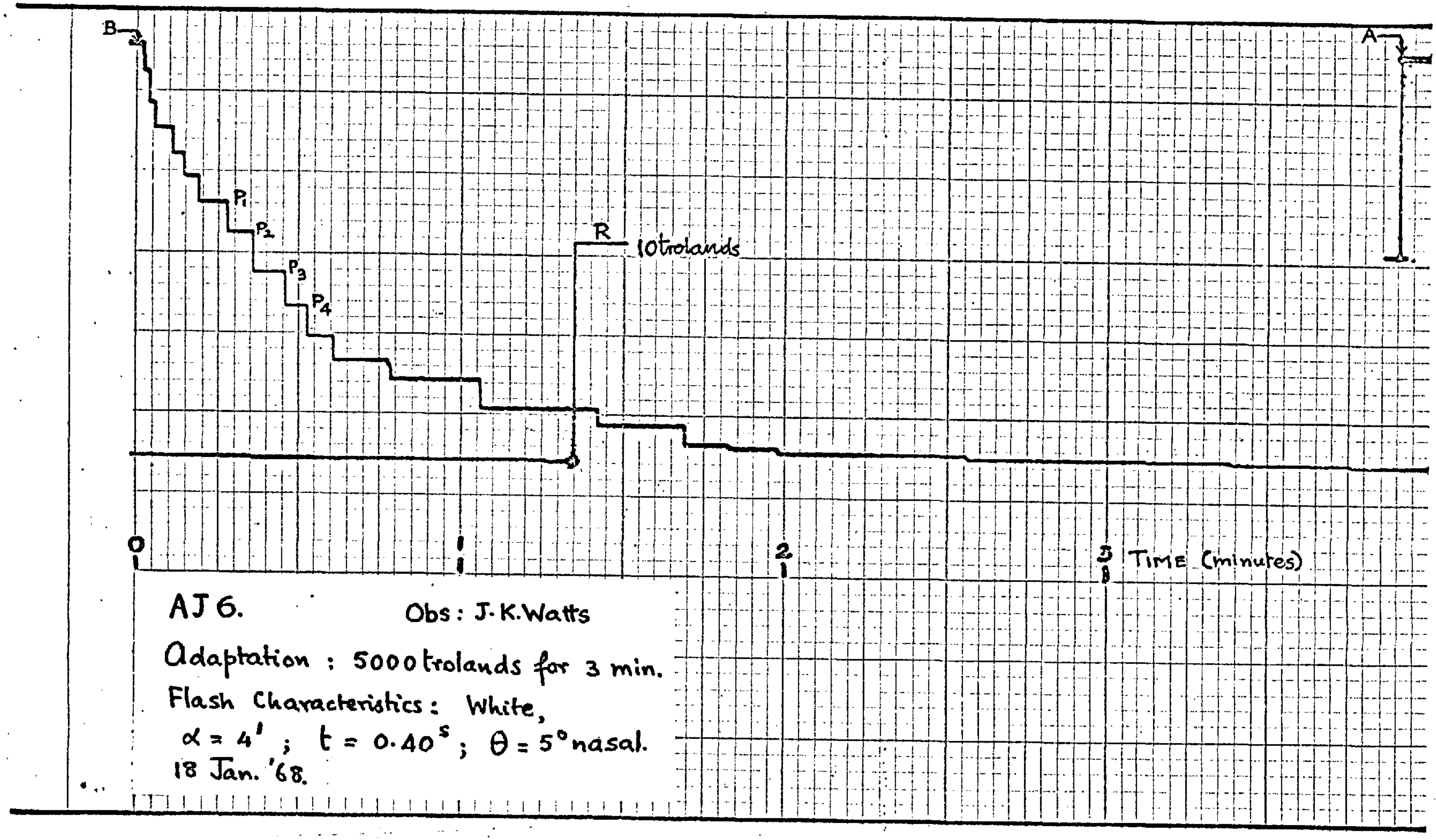


Fig. 51. Dark adaptation trace from recording unit.

determined on the Wright colorimeter is given in fig 52. Two sets of results have been included in the text for observer OT who was a deuteranope.

Of the five observers, RJW, JKW and BK had plenty of practice and understood the operation of the equipment, MG and PD have had no other experience of this type of work.

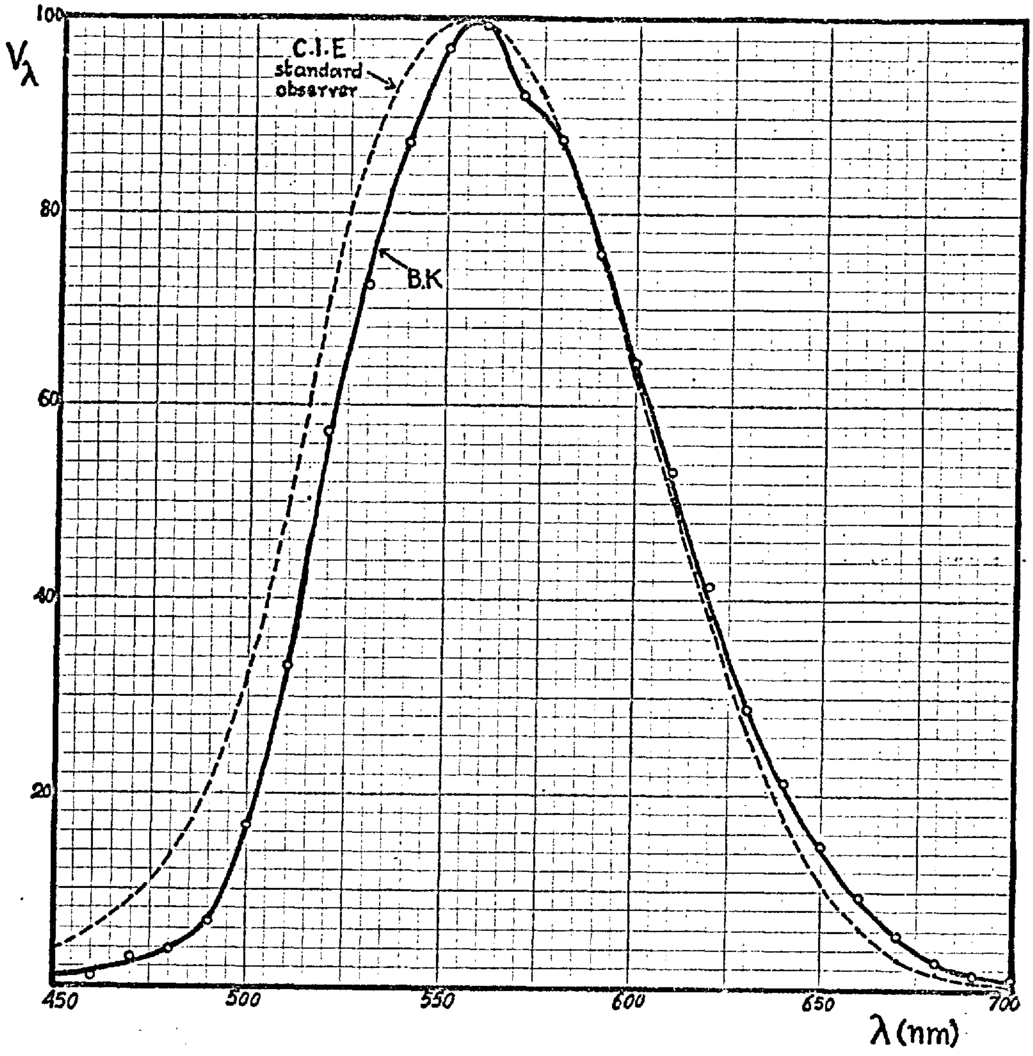


Fig. 52. V_λ curves for observer BK and C.I.E. standard observer.

CHAPTER V.

The variation of the threshold across the central retina.

Two methods have been employed for studying the gradient of the visual threshold across the retina. In kinetic perimetry, as used by most earlier workers (Ferree and Rand, 1919; Wentworth, 1930), the field of vision is explored by moving a test object of given luminance radially across it until a threshold position is arrived at. Although this method is not time-consuming, the rate at which the test patch is moved and the promptness with which the observer reports its perception lead to unavoidable variations in the results. It is increasingly becoming the practice now in clinical perimetry to determine the threshold by changing the magnitude of a stationary stimulus (static perimetry), local adaptation fatigue being avoided by intermittent exposure of the test field. With the introduction of projection perimeters, notably that of Goldmann around 1945, the method has been used to study the changes in the incremental threshold and the spatial summation across the retina (Goldmann, 1945; Dubois-Poulsen and Magis, 1957; Sloan, 1961; Verriest and Israel, 1965; Meur, 1965) and the colour field (Kelsey and Schwartz, 1959; Connors and Kelsey, 1961).

Stiles and Crawford (1937) must have been among the first to use static perimetry in their investigation of the variation of the absolute threshold for white light with retinal location (fig. 53). Varriest and Israel (1965) have determined the achromatic incremental threshold gradient across the retina for

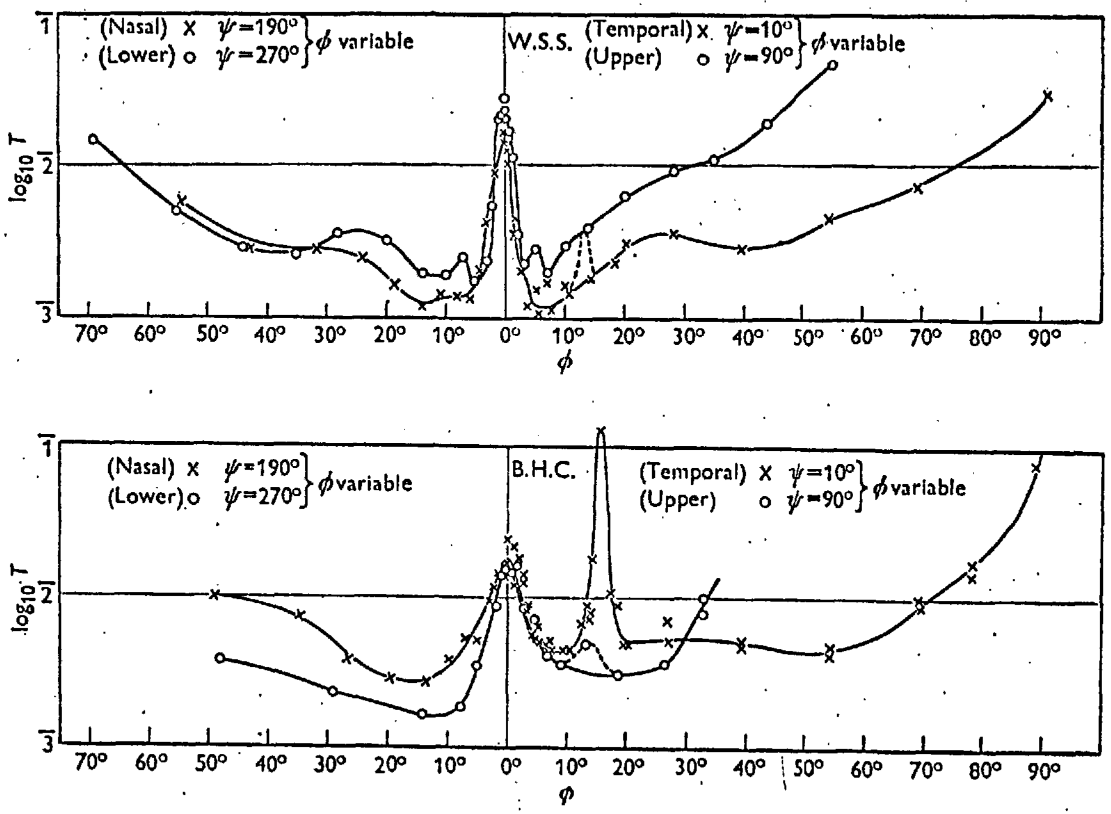


FIG. 53. Variation with retinal position of the absolute threshold T in white light, measured in cd./ft.^{2} for a test field 0.072° (4.3′ of arc) in diameter exposed in 0.05 second flashes to the fully dark-adapted eye. Two subjects (W.S.S. and B.H.C.) were used. The eccentricity ϕ is the angle between the fixation direction and the line joining the eye to the test field; ψ is the azimuthal angle measured from a reference plane which, with the eye upright and looking horizontally, is taken as the horizontal plane on the temporal side. The measurements were made in a vertical plane through the fixation point ($\psi = 90°$; $\psi = 270°$) and in a plane inclined 10° above the horizontal on the temporal side ($\psi = 10°$; $\psi = 190°$). An inclined plane rather than the horizontal was chosen to avoid the blind spot which is centred about the point $\phi = 17°$ approximately, $\psi = 350°$ approximately. Various differences can be observed between the results for the two different planes and between the two subjects' curves. On the temporal side of the curve in the 10° plane. B.H.C. exhibits a very sharp maximum at an angle ϕ having a value of approximately 16°. This is believed to be due to a blood vessel radiating from the blind spot. (From Stiles and Crawford, 1937)

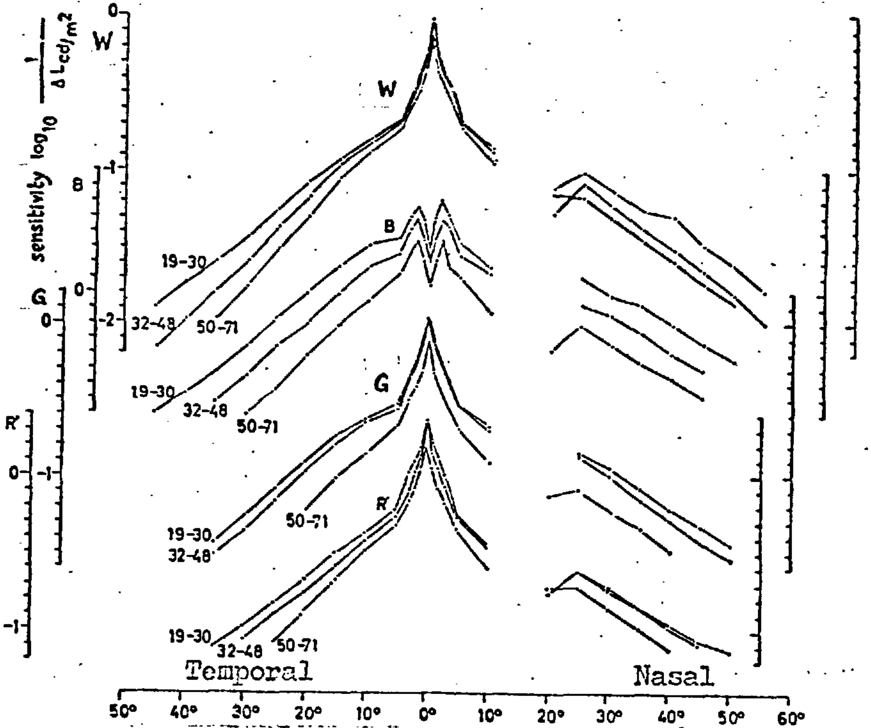


Fig. 54: Variation of sensitivity with eccentricity and with age (W: white test field, 0.275 mm^2; B: blue, 4.4 mm^2; G: green, 0.275 mm^2; R: red, 1.1 mm^2; viewed at a distance of 30 cm. against a white background of 10 cd.m^{-2}. (Verriest and Israel).

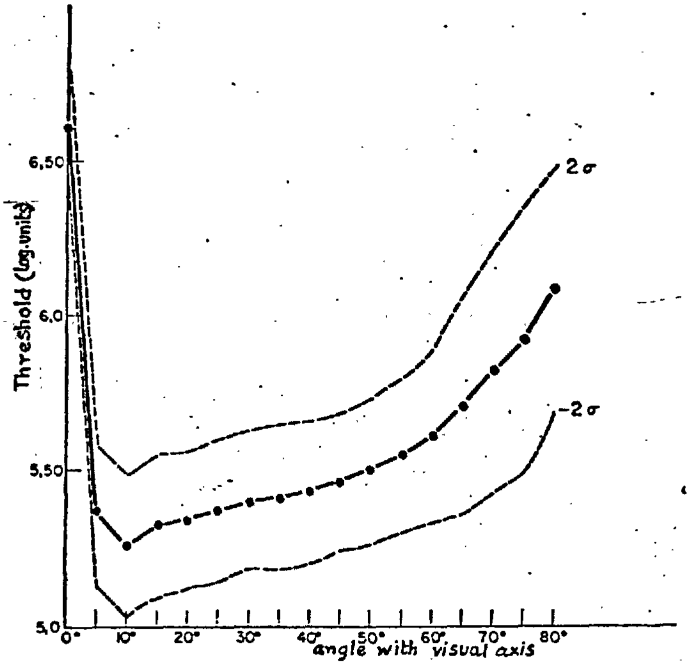


Fig. 55: Mean values of absolute threshold for 50 observers in the age group 20-21 years on the 315° meridian. (Meur).

small white and coloured patches viewed against a background of about 100 trolands and their results (fig. 54) are based on a study of 68 normal eyes with the Goldmann static perimeter. Meur (1965) studied the inter- and intra- individual variations of the absolute threshold (fig. 55) and by a comparison of the absolute and the incremental threshold at the same retinal location showed that the scatter in the threshold values increases with the level of light adaptation (cf. p 126).

In the experiments to be described in the present chapter, the threshold has been measured across the central 20° of the visual field for white and coloured stimuli, the aim of the investigation being to find out how it varies with the luminance of the background, the angular subtense and the duration of the test flash. According to the regional subdivision of the retina by Polyak (1941), this part of the visual field corresponds to the central or axial region of the retina, and this central region may be subdivided into

I - the central or inner fovea,
II - the parafovea,
III - the perifovea.

A brief summary is here given of some of the morphological and structural differences between these regions; for further details reference must be made to Polyak.

Region I - The central fovea or fovea centralis is a small pit-shaped depression, about 5° in diameter if we consider the entire depression from edge to edge, and is characterised by a decrease

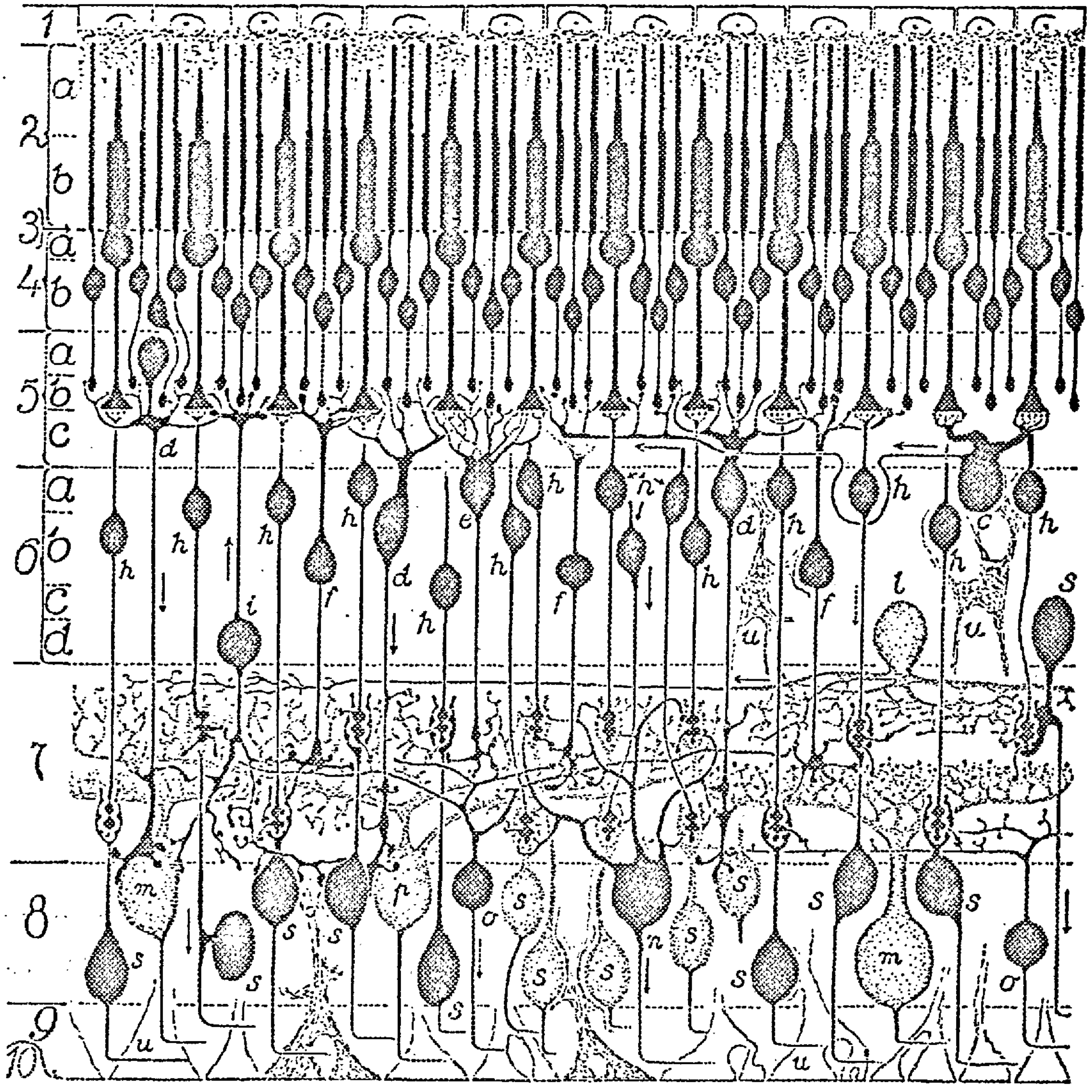


FIG. 56.—Scheme of the primate retina, showing the types of the neurons and their synaptical relationships, so far revealed by means of the method of Golgi.

The designation of the layers and the zones: (*1*) pigment layer; (*2-a*) outer zone; (*2-b*) inner zone of the rod and cone layer; (*3*) outer limiting membrane; (*4-a*) outer zone; (*4-b*) inner zone of the outer nuclear layer; (*5-a*) outer zone; (*5-b*) middle zone; (*5-c*) inner zone of the outer plexiform layer; (*6*) inner nuclear layer with its four zones; (*7*) inner plexiform layer; (*8*) layer of the ganglion cells; (*9*) layer of the optic nerve fibers; (*10*) inner limiting membrane.

The designation of the nerve cells: (*a*) rods; (*b*) cones; (*c*) horizontal cells; (*d*, *e*, *f*, *h*) bipolar cells; (*i*, *l*) so-called "amacrine cells"; (*m*, *n*, *o*, *p*, *s*) ganglion cells; (*u*) "radial fibers" of Müller.

In this scheme the nervous elements are reduced to their essentials, with, however, the characteristic features of each variety preserved—the location of the bodies, the size, the shape, and the spreading of the dendrites and of the axis cylinders—and with the synaptical contacts presented accurately.

The probable direction of the propagation of the nervous impulses is indicated by arrows.

(POLYAK)

in and partly complete absence of the inner layers 5-9 of the retinal structure (fig. 56). The photoreceptor layers, in particular 2 and 4, however, are greatly thickened. This region is characterised by a yellow pigment which permeates diffusely all structures inwards from layer 4, though this pigment cannot be seen ophthalmoscopically except under special conditions of illumination. Outside the foveal pit the pigmentation is much less intense and at a certain distance is lost, though in a broader sense the yellow spot is almost coextensive with the whole of the central area.

The diameter of the foveal floor is about 1° 20' and may vary with individuals; the floor is not quite level but shows a dip or foveola (little fovea) about 70' across in man. This region would appear to be only slightly pigmented in comparison with the foveal slopes, as the pigment appears to be confined to the inner layers which are much reduced in thickness at the foveal floor, whereas the thickened photoreceptive layers do not contain the yellow substance. In the foveola, the cones are about twice as long as on the foveal slopes and about 25,000 in number; a small central area of diameter only 20' or so contains the longest and most delicate cones in the whole retina and would yield a higher degree of acuity as the number of cones here is about 2500 - this has been termed the "bouquet of central cones" by Rochon-Duvigneaud (1907). Schwalbe (1887) found a minute depression in the very centre of the fovea, called the "foveola fundi" by Kuhnt (1890) not more than 5 or 6 cone diameters across; here the retina is almost reduced to the photoreceptive layer only. The foveola is distriguished by the exquisite regularity and uniformity of the arrangement of the cones and is instrumental in epicritic vision, as the access of the rays is free to the receptors. The use of the term foveal vision as synonymous with direct vision may occasionally be misleading as the inner fovea may be 3 to 4 times larger than the foveola.

The central rod-free area is about 2° in diameter, rods being doubtless present at more than 70' from the foveal centre, a few stragglers being found even at 50' from it. The synonymous use of the terms rod-free area and fovea should also be avoided. The number of cones in the rod-free area is about 34000, the entire foveal area containing between 100,000 to 115,000 cones.

Region II - The parafoveal region is the intermediate belt of the central area and has the greatest accumulation of nerve cells in the entire retina, especially of inner nuclei and ganglion cells. Its outer boundary is about 250' distant from the very centre and from this point onwards to the periphery of the central area the ganglion layer rapidly thins off. The space between adjacent cones is filled up by one rod on the average in this area.

Region III - The perifovea encircles the parafovea and extends to about 550' from the foveal centre. The space between adjoining cones is here filled up by about two rods in man.

The threshold for white light.

This has been determined at 1° or 2° intervals in the vertical and the horizontal meridian up to 10° with the visual axis, under conditions of dark adaptation (scotopic vision) and against backgrounds of 1 troland (mesopic vision) and 1000 trolands (photopic vision). All measurements were made with a 2 mm. artificial pupil and at a flash frequency of 1 c.p.s. The following combinations of flash duration (t) and angular subtense (α minutes of arc) of the test field were used;

(i) $\alpha = 2'$, $t = 10$ ms.;
(ii) $\alpha = 2'$, $t = 500$ ms.;
(iii) $\alpha = 32'$, $t = 10$ ms.

With an artificial pupil of 2 mm, the angular diameter of the Airy disc is about 2.2' for $\lambda = 500$ nm. and a 2' test field approximates to a point source even in the absence of eye aberrations. With such a small source it seems fairly reasonable to assume that at a given retinal location, other conditions being the same, the degree of spatial summation will not be affected by the flash duration, so that differences between (i) and (ii) can be solely ascribed to temporal summation. The flash duration of 500 ms. is also likely to be longer than the maximum summation time for the eye, so that at all retinal locations and against all backgrounds the temporal summation would be at its maximum. The shorter duration 10 ms. on the other hand would be below the visual summation time under all the experimental conditions so that any differences between (i) and (iii) should arise from spatial summation. Fig. 57-62 show a complete set of such curves for observer BK; results obtained by some of the other observers are far less complete, but show essentially the same features.

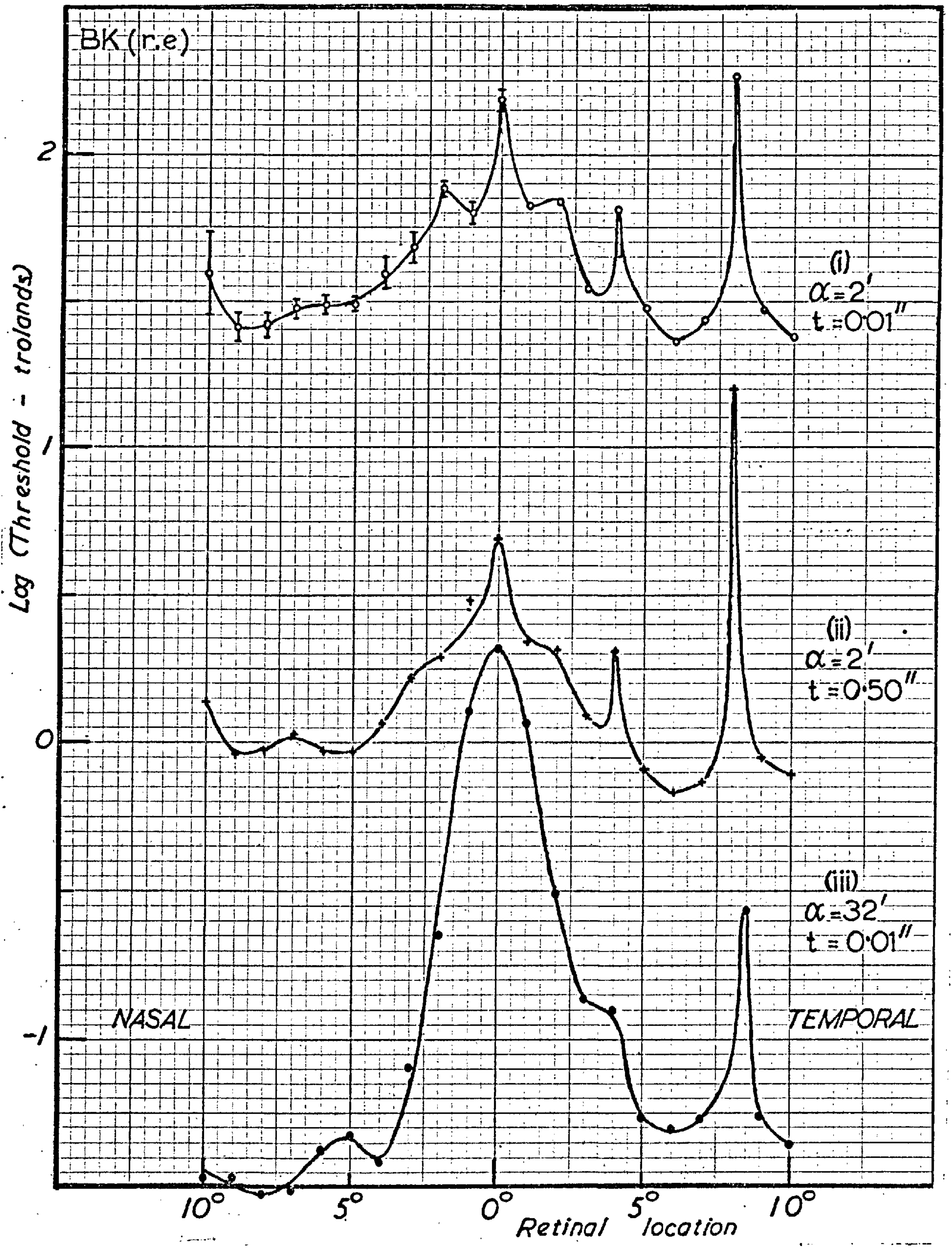


Fig. 57. Threshold variation for a white test flash against a dark background (n = 1 c.p.s.)- horizontal meridian.

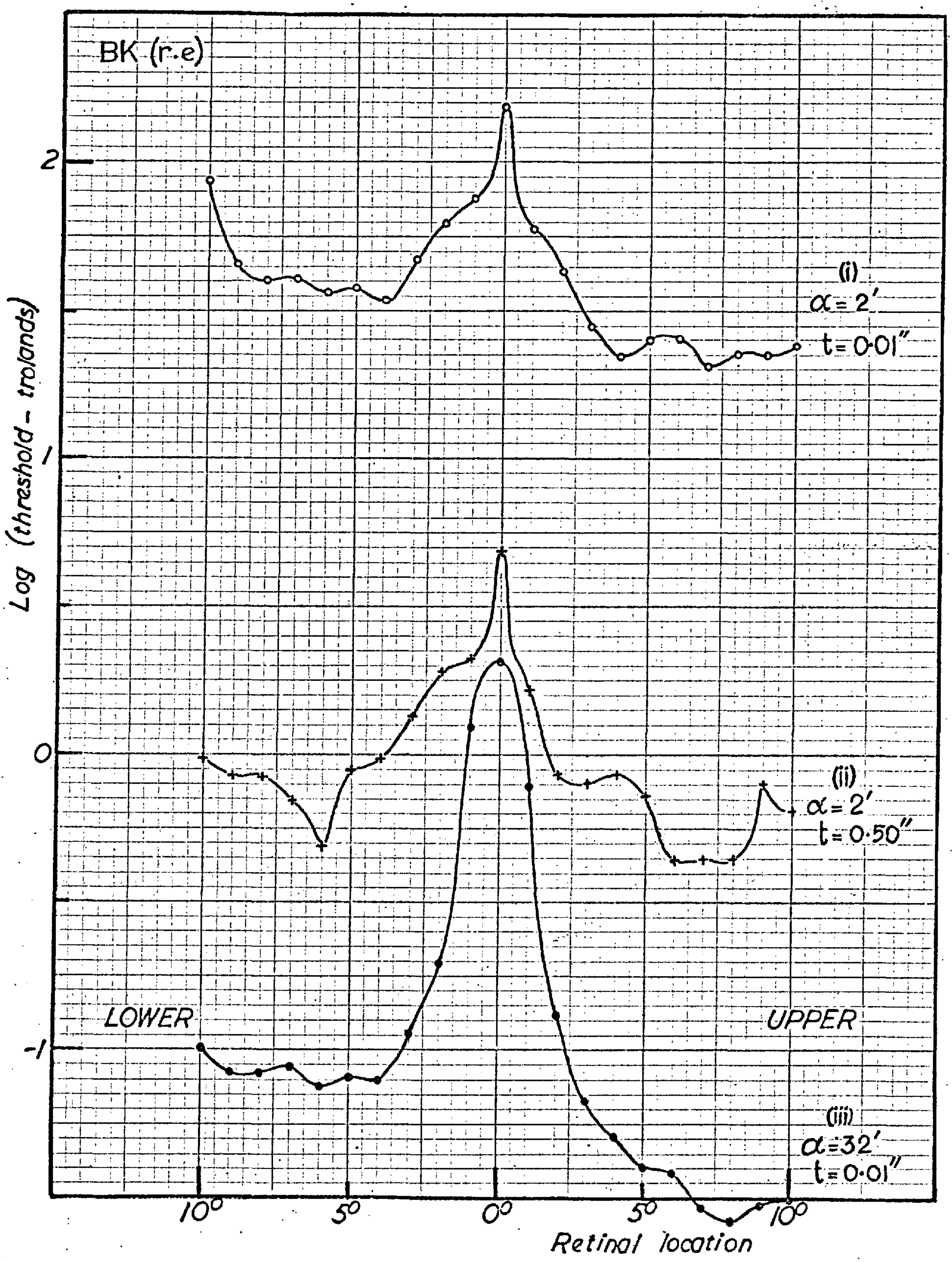


Fig. 58. Threshold variation for a white test flash against a dark background (n = 1 c.p.s.) - vertical meridian.

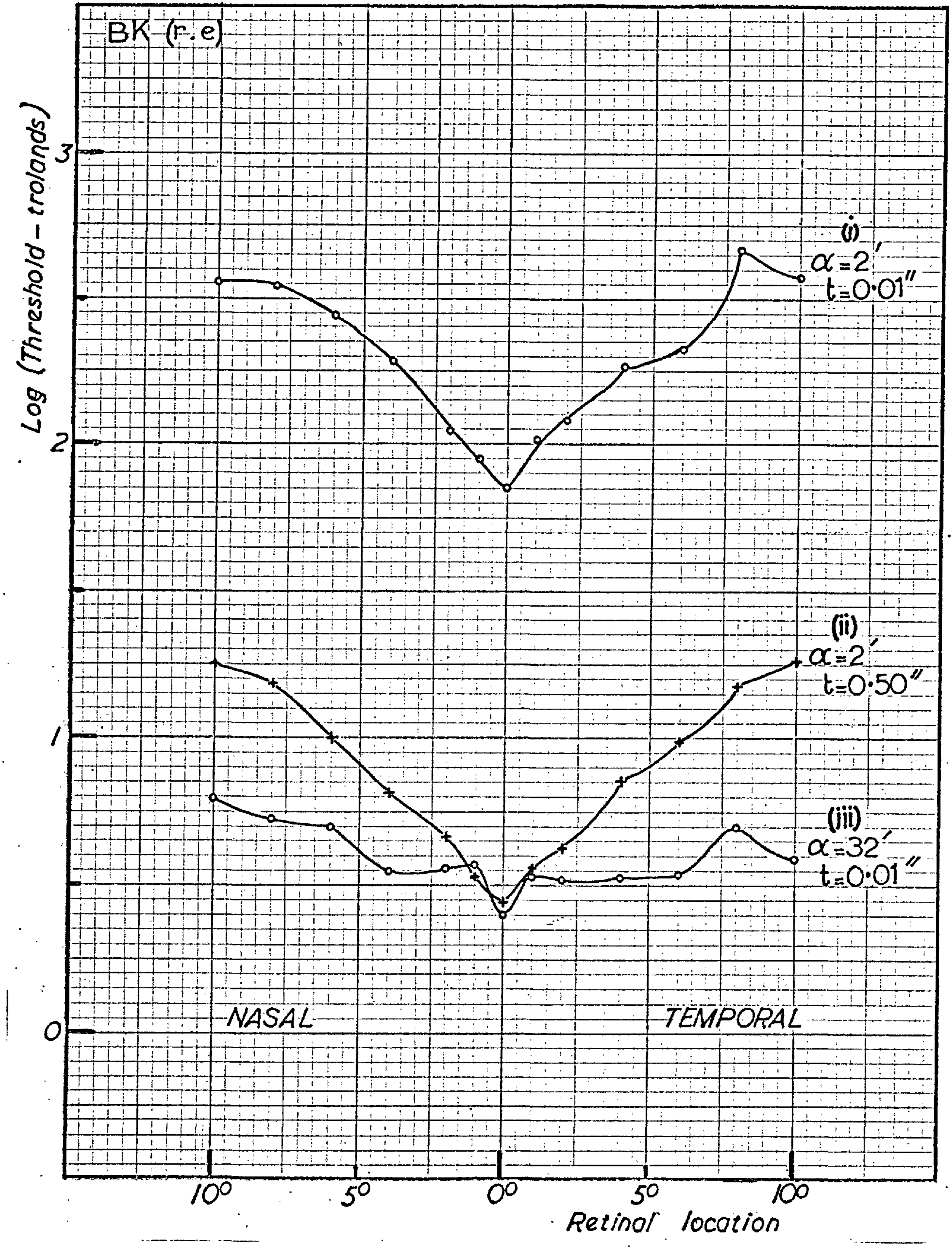


Fig. 59. Threshold variation for a white test flash against a white background of 1 troland (n = 1.c.p.s.) - horizontal meridian.

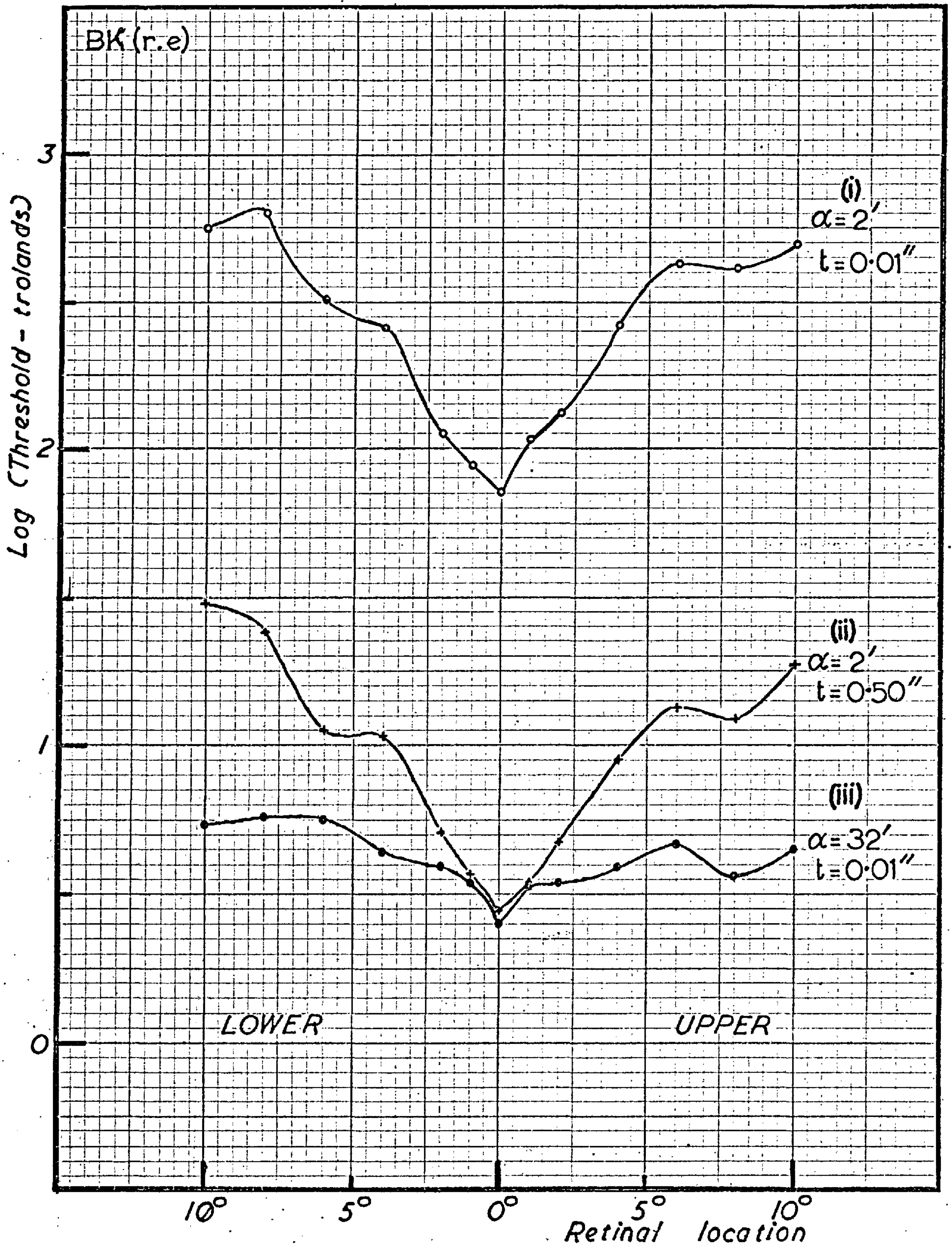


Fig. 60. Threshold variation for a white test flash against a white background of 1 troland (n = 1 c.p.s.) - vertical meridian.

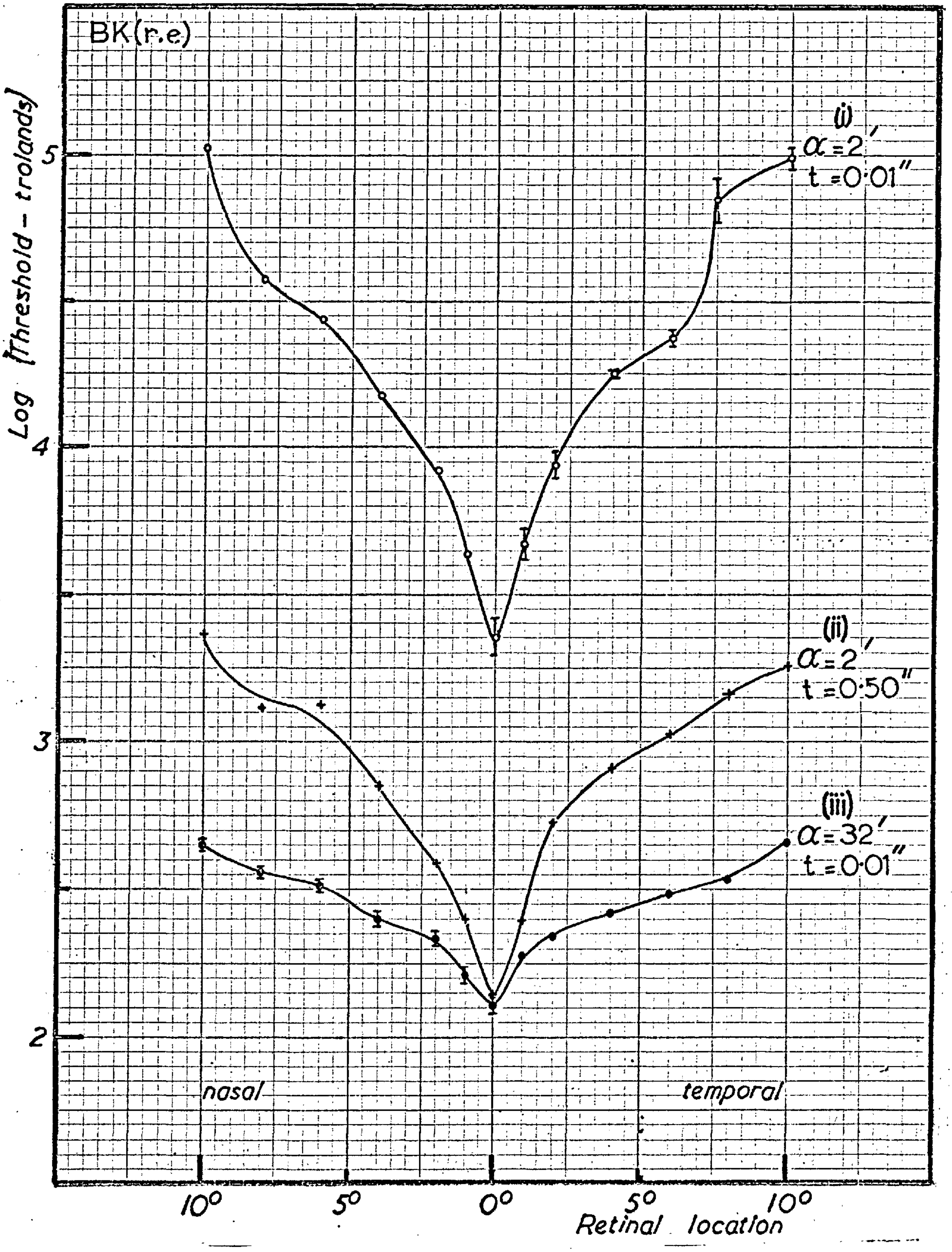


Fig. 61 - Threshold variation for a white test flash against a white background of 1000 trolands (n = 1 c.p.s.) - Horizontal meridian.

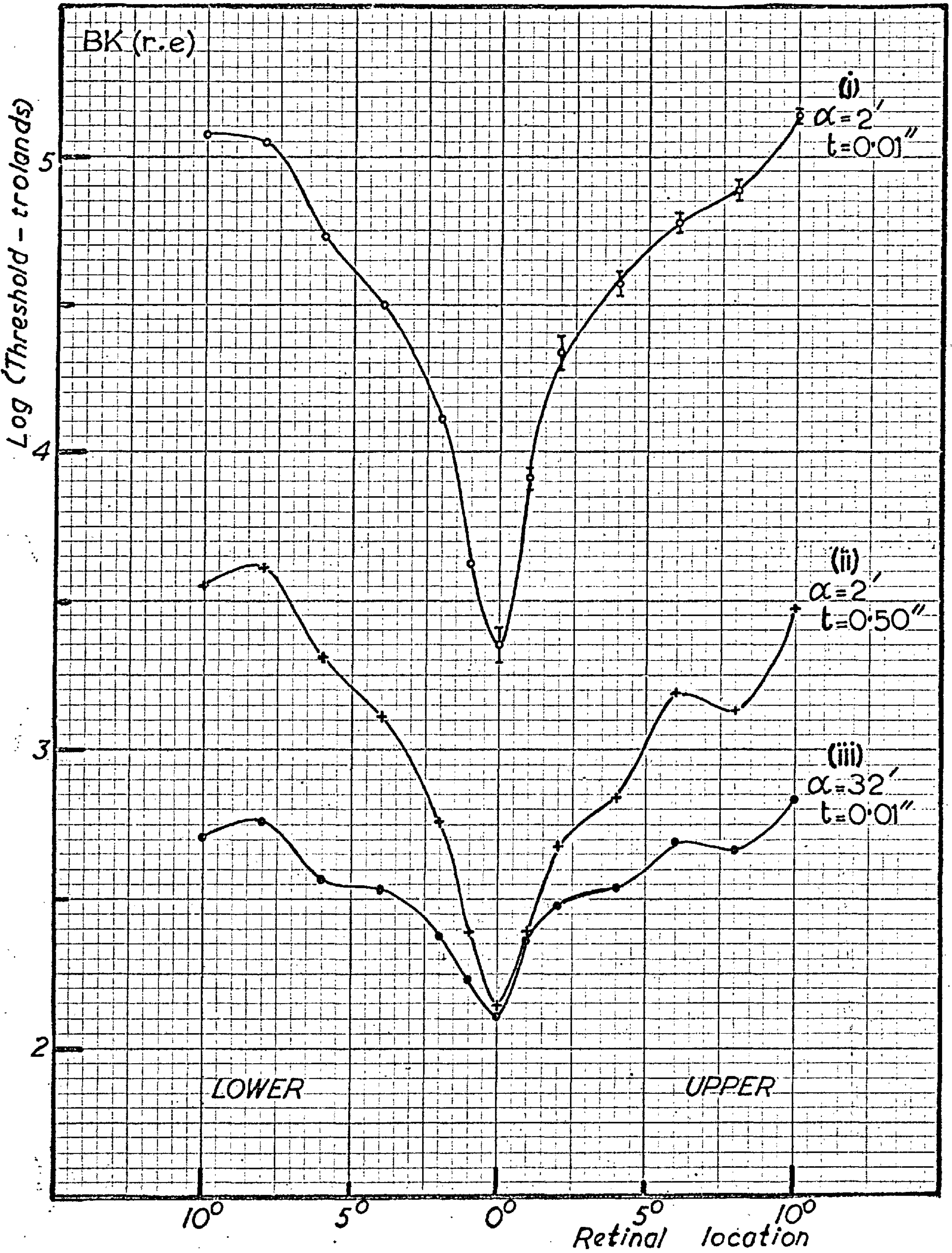


Fig. 62 - Threshold variation for a white test flash against a white background of 1000 trolands (n = 1 c.p.s.) - vertical meridian.

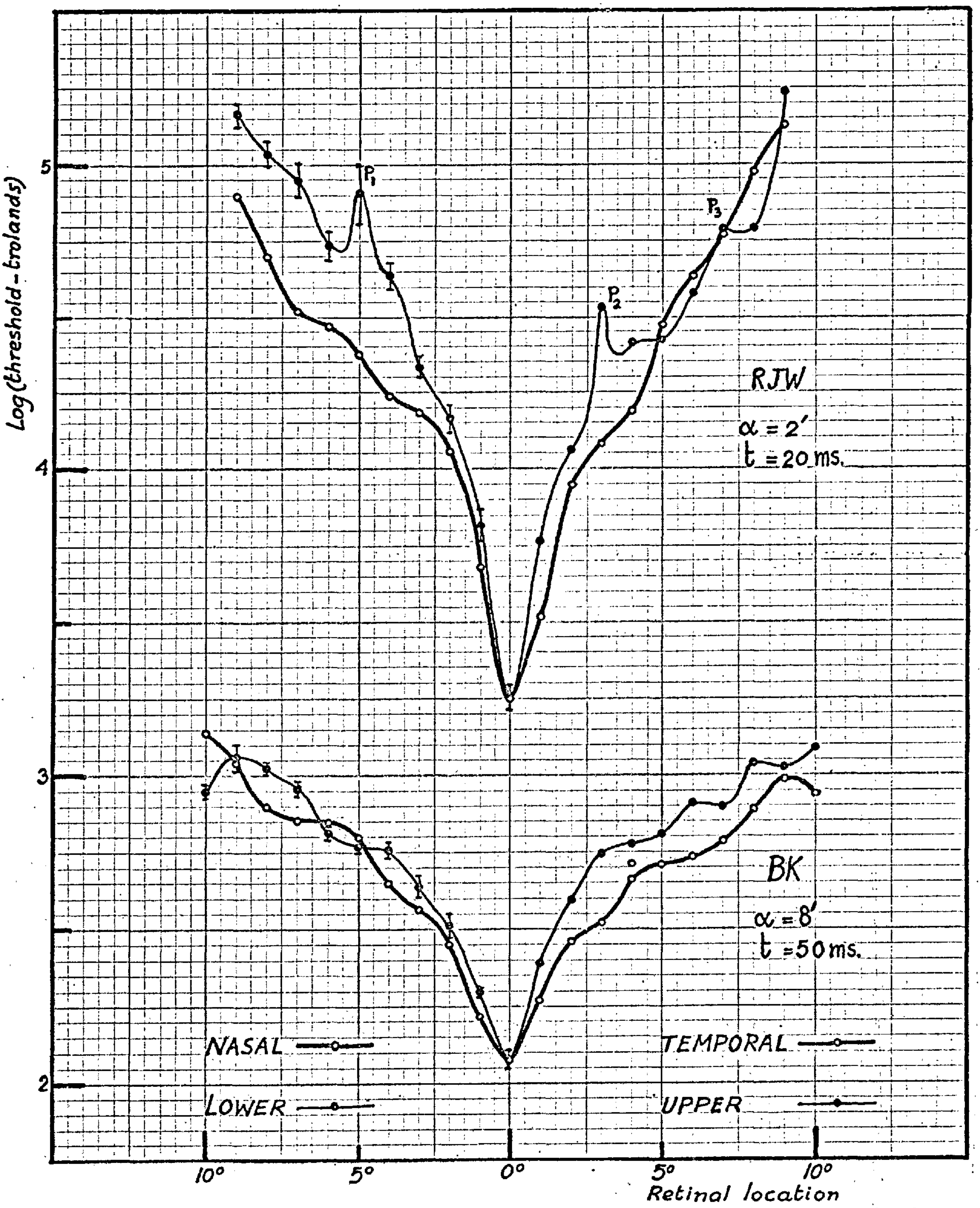


Fig. 63. Threshold variations for a white test flash against a white background of 1000 trolands - horizontal and vertical meridians. (n = 1 c.p.s.).

The curves have generally been drawn to pass through all the experimental points as there seems to be no way of deciding to which extent the irregularities are due to experimental errors or to structural variations within the eye. The sharp peaks at 4° and 8° on the temporal side and 10° on the nasal side in fig. 57 are certainly due to blood vessels,(cf. fig. 53) and high values of the threshold are generally found at these locations (fig. 59, 61), though not as well defined. At such positions the appearance of a small test patch is usually very diffuse as it is perceived by scattered light, and a small change in the direction of fixation gives a much sharper image and a lower value of the threshold, so that abnormally large variations are obtained in the readings. That the peaks are due to blood vessels and not to other scotomata has been confirmed by photographing the fundi of the observers; thus the fundus photograph of RJW (Plate 4, p. 116) shows the blood vessels responsible for the high thresholds at P_1, P_2, P_3 in the vertical meridian (fig. 63). In many experiments it is desirable to avoid such regions of the retina and the method outlined in the next paragraph has been found satisfactory.

If the interior of the eye be illuminated by light from a small source close to the edge of the pupil, a tree-like figure of fine branching dark lines can be seen, the details agreeing with the pattern of blood vessels seen ophthalmoscopically, so that there can be little doubt that it is due to the shadow of the retinal blood vessels on the receptors. If the source of light is held stationary, rapid fading occurs in the highly stabilised shadow image; movement of the source leads to some degree of lateral displacement of the pattern, and this had been used to estimate the distance of the receptors behind the blood vessels, (Müller, 1854; König and Zumft, 1894). With an observer's head fixed at the observing end of the apparatus, it is not difficult to arrange that the field is seen against the vascular structure viewed entoptically, when the fixation spot may be adjusted to image the test patch at a suitable position on the retina away from any blood vessels.

Allowing for experimental errors, curves (i) and (ii) are very similar, showing that to a first approximation temporal summation is uniform over the central retina. Changes in the duration of a flash would thus equally affect the threshold at all points in the field of view. This would be in agreement with the results of van den Brink (1966) who concludes that "for the dark-adapted eye, there is a maximum addition of subliminal effects up to 60 m sec., and no addition for intervals exceeding 110 m sec.; the addition functions are equal for rod and cone vision and are independent of the place on the retina, including the fovea." The only discrepancies observed are at large eccentricities and against high background luminances (fig. 61, 62) where a slightly greater degree of summation than at the fovea seems indicated - other experiments (Chapter VI) would show that this may very well be the case. Comparison of curves (i) and (iii) on the other hand shows a marked increase in spatial summation with eccentricity from the visual axis at all levels of background luminance. The relative displacements of curves (ii) and (iii) with respect to (i) also show that spatial and temporal summation are both lowered by an increase in the background luminance as has been found by many investigators (Stiles and Crawford, 1934; Graham and Kemp, 1938; Blackwell, 1946; Willmer, 1954; van den Brink and Bouman, 1954; Barlow, 1958).

The curves are as a rule not symmetrical about the fovea, the nasal and upper retina showing superior performance as compared to the temporal and lower retina at all levels of background luminance, (cf. fig. 54). Such an asymmetry occurs in other types of visual measurements (cf. p. 46-47) and may be related to the differences in the receptor population at these positions as found by Osterberg (1935). There is in general a steeper threshold gradient within 3° to 5° of the centre than at greater eccentricities and this is clearly seen in the results of Verriest and Israel (fig. 54). In dark adaptation, the steep fall in the threshold is certainly due to the occurrence of the rods, and the rapid decrease in the cone population with eccentricity in the central area may explain the threshold variation in photopic vision across this region. The rise in the absolute threshold at large eccentricities (fig. 53,55) must be largely due to the decrease in the relative pupil area of the eye with eccentricity (Spring and Stiles, 1948b; fig. 64). Hall (private communication) has calculated the angle of incidence of the principal ray on the retina at different eccentricities (fig. 65 a,b) from data on the Gullstrand model eye, in which the lens has a core of higher refractive index, and his results would indicate

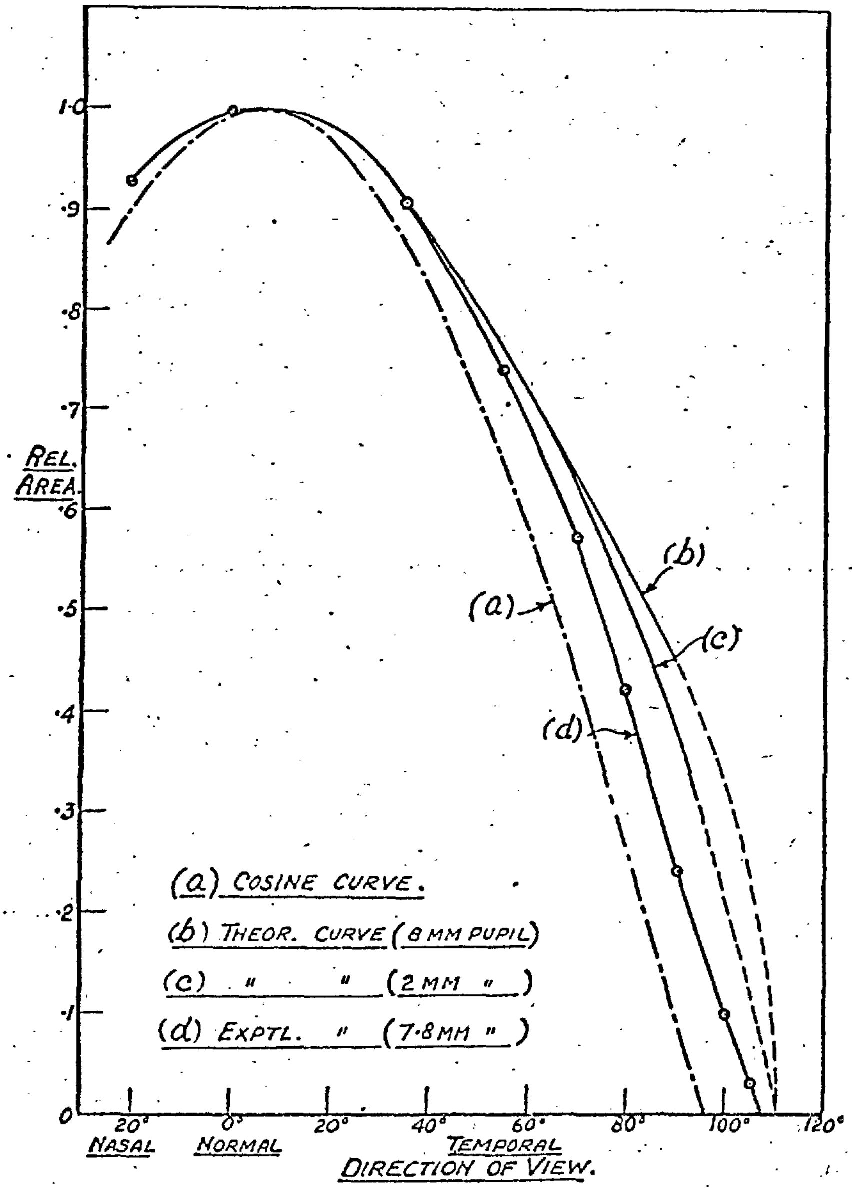


Fig.64. VARIATION OF RELATIVE PUPIL AREA WITH OBLIQUITY.

(Spring and Stiles).

that the Stiles-Crawford effect may appreciably modify the photopic threshold at large angles with the visual axis under certain conditions. These effects, however, may not satisfactorily account for the increase in the incremental threshold against high background luminances in the periphery, as they would presumably act equally on the background. Since the cone population is virtually constant from about 10° nearly up to the ora serrata (Osterberg), a fairly constant threshold might have been expected, on the assumption of a constant Weber-Fechner fraction. Though the physiological equipment for the perception of movement in the peripheral retina is not as good as in the central retina (Graham 1965; Tansley, 1965), movement perception plays a dominating role in peripheral vision, and it is possible that this is achieved to the detriment of other forms of visual discrimination.

Baumgardt (1949) concluded from extrapolation of a curve in which the ratio of the extra foveal to foveal thresholds are plotted as a function of the size of the test field (6' to 45') that this ratio must be unity for small fields. Arden and Weale (1954) found that the foveal and extra-foveal absolute thresholds as measured with a 2.7' field were nearly the same. The results obtained here with a 2' field would indicate a higher foveal threshold and would be more in agreement with the conclusions of Pirenne (1962): "It must be concluded from these results that for an effectively point source the threshold values, expressed at the cornea in terms of quanta of the most effective wavelength in each case, are higher for cone than for rod vision, the difference between cone and rod

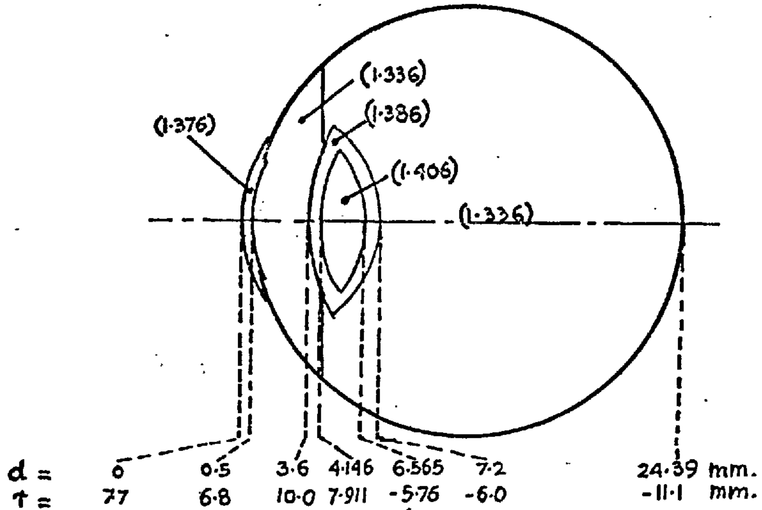


Fig. 65a. Gullstrand Schematic eye. (d = distance from corneal vertex, r = radius of curvature, bracketed figures give the refractive index.)

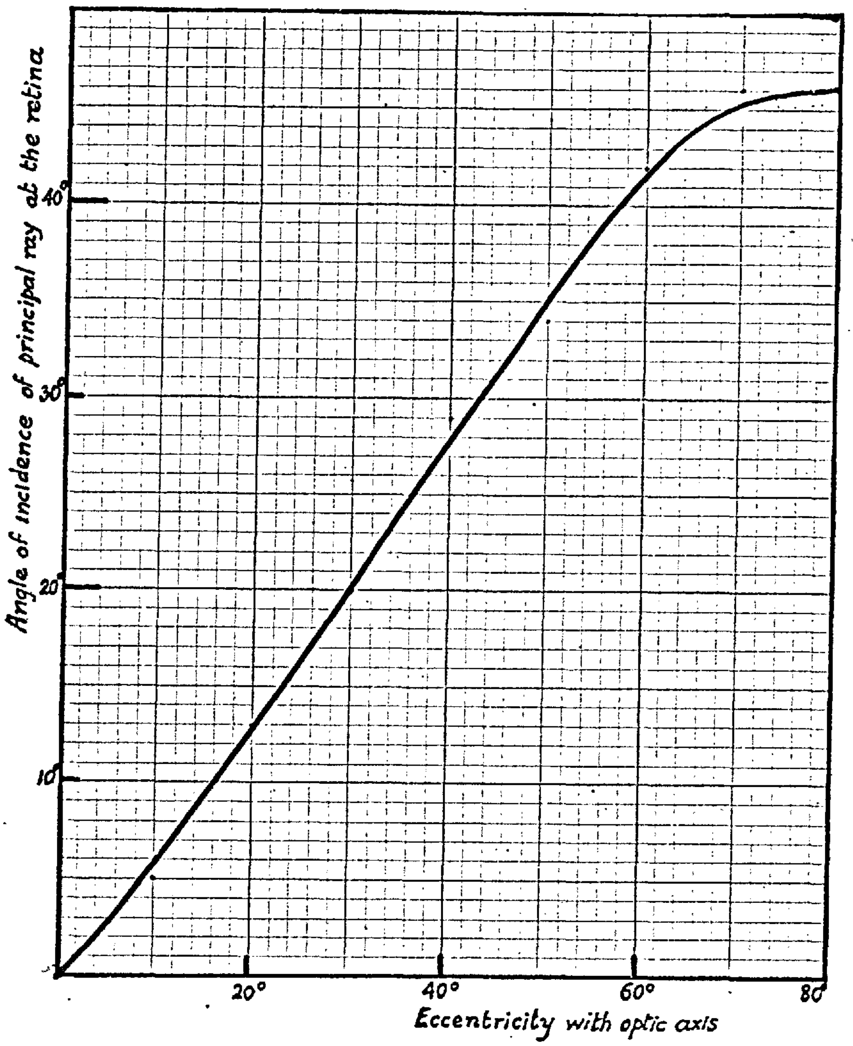


Fig. 65b. Variation of the angle of incidence of the principal ray at the retina with eccentricity from the optic axis (Hall).

vision being larger for a steady source than for a brief flash on account of the greater range of temporal summation of the rods".

Some of the results obtained during the course of these experiments would indicate that foveal thresholds for white light may show a good deal of constancy among different observers, provided the angular subtense of the stimulus is not too small. Thus the foveal threshold for a flash of 1 c/s, $\alpha = 8'$, t = 50 ms against a background of 1000 trolands as measured by 5 observers were:

B.H.C.	1.96 log units.
S.R.	2.06 " "
B.K.	2.07 " "
V.C.	2.10 " "
R.J.W.	2.09 " "

As one moves away from the axis, individual differences tend to increase, especially with small fields which show up readily local scotomata and differences in retinal structure. This would be in agreement with the observations of Meur (1965) who measured the absolute threshold for 50 soldiers between 20 to 21 years old, using an 11.6' white test field, and quotes the following values for the standard deviation of the threshold at various eccentricities with the visual axis on the 315° meridian:

Eccentricity.	Standard deviation (log units)
0°	0.091
10°	0.116
30°	0.110
60°	0.140
75°	0.217

The equivalence of corresponding points on the retina.

The asymmetry of the threshold curves about the visual axis made it desirable to find out whether points giving the same thresholds under a given set of conditions would give similar thresholds under different conditions of observation. To test this, the threshold was measured in the horizontal and the vertical meridian by two observers (fig. 63) using a small test field and a high background luminance, when the curves obtained are fairly steep and single valued. From these curves points were selected giving the same threshold, but at different angles from the visual axis, and at retinal locations which appeared to be fairly free from local scotomata and blood vessels. The thresholds at these points were again measured under conditions differing as widely as possible from the original conditions as far as background luminance, size, duration and colour of the test flash were concerned. The results are given in table 9.

Although the measured thresholds vary from about $10^{-2.5}$ to $10^{4.5}$ trolands, the agreement under any one set of conditions is often better than 0.1 of a log unit. This would imply that if one could map out the visual field with a suitable type of test flash and obtain contours of equal threshold (iso - liminal curves or isopters), such curves could be used to predict with reasonable accuracy the threshold for another test-flash at any part of the visual field, provided the threshold variations for the new flash

TABLE 9.

Threshold measurements at "corresponding points" for two observers. The figures give the logarithm of the threshold as measured in trolands, and each row gives the threshold at the four selected points for one set of observing conditions.

Obs: BK.	Colour of Stimulus	Retinal location.			
		5° Nasal	7° Temporal	5° Lower	4° Upper
	White	4.36	4.50	4.60	4.57
	"	2.97	3.10	3.20	2.85
	"	2.45	2.51	2.51	2.54
	"	2.78	2.79	2.76	2.77
	"	2.36	2.42	2.45	2.42
	"	0.91	1.05	1.03	0.95
	"	0.60	0.60	0.70	0.60
	"	$\bar{1}.50$	$\bar{1}.43$	$\bar{1}.57$	$\bar{1}.38$
	"	$\bar{1}.97$	$\bar{1}.87$	$\bar{1}.95$	$\bar{1}.94$
	"	$\bar{2}.67$	$\bar{2}.72$	$\bar{2}.90$	$\bar{2}.70$
	Blue	$\bar{3}.75$	$\bar{3}.71$	$\bar{3}.65$	$\bar{3}.70$
	Red	$\bar{2}.52$	$\bar{2}.46$	$\bar{2}.51$	$\bar{2}.47$

Obs. RJW.		7° Nasal	$5\frac{1}{2}$° Temporal	$3\frac{1}{2}$° Lower	$5\frac{1}{2}$° Upper
	White	1.84	1.76	1.78	1.82
	"	4.52	4.48	4.47	4.47
	Blue	0.10	0.06	0.01	0.03
	"	$\bar{3}.43$	$\bar{3}.39$	$\bar{3}.41$	$\bar{3}.39$
	Red	0.60	0.58	0.64	0.72
	"	1.64	1.65	1.78	1.75

TABLE 10.

Mean thresholds at two retinal locations for different types of observers according to Verriest and Israel (1965). The results are given in arbitrary log units.

Type of Observer.	Number of Observers.	Colour of stimulus.	Retinal location.	
			35° Nasal	50° Temporal.
Normal	68	White	2.28	2.26
"	25	Blue	2.58	2.50
"	25	Green	2.74	2.75
"	20	Green	2.83	2.85
"	20	Red	2.83	2.85
Protanomalous	4	White	2.40	2.30
"	4	Blue	2.65	2.63
Protanope	5	White	2.20	2.14
"	5	Blue	2.70	2.46
"	5	Green	2.78	2.70
Deuteranomalous	5	White	2.33	2.38
"	4	Blue	2.88	2.80
Deuteranope	4	White	2.10	2.10
"	5	Blue	2.56	2.50
"	4	Green	2.78	2.73
"	4	Red	2.78	2.70
Monochromat	4	White	2.60	2.65
"	4	Blue	2.35	2.50

were known along any one meridian. Some of the results of Verriest and Israel (1965), which are reproduced in table 10, would indicate that this may hold at large eccentricities with the visual axis, and even with colour defective observers in photopic vision. Isopters and being successfully used in clinical perimetry though within a more limited range of luminances.

At low intensity levels, one can envisage difficulties in predicting the threshold from curves derived under photopic conditions, as along any meridian, the retinal location becomes a double-valued function of the threshold intensity. It seems more likely that one set of curves would apply under photopic conditions and another under scotopic conditions as we pass from cone to rod vision, though the results of the experiments described here would indicate that the curves of the two sets would follow fairly close contours in the region within 8° from the visual axis.

Achromatic thresholds for coloured stimuli in the central retina.

Relatively little information seems available on the threshold variation across the retina for colour stimuli. Stiles (1949) has measured the absolute threshold across the central retina at four wavelengths (fig. 66) and Cabello and Stiles (1950) the variation of the threshold for $\lambda = 490$ nm. (fig. 67). The results of Verriest and Israel (1965) for incremental thresholds against a white background of about 100 trolands have already been given (fig. 55).

The experiments performed with coloured lights were similar

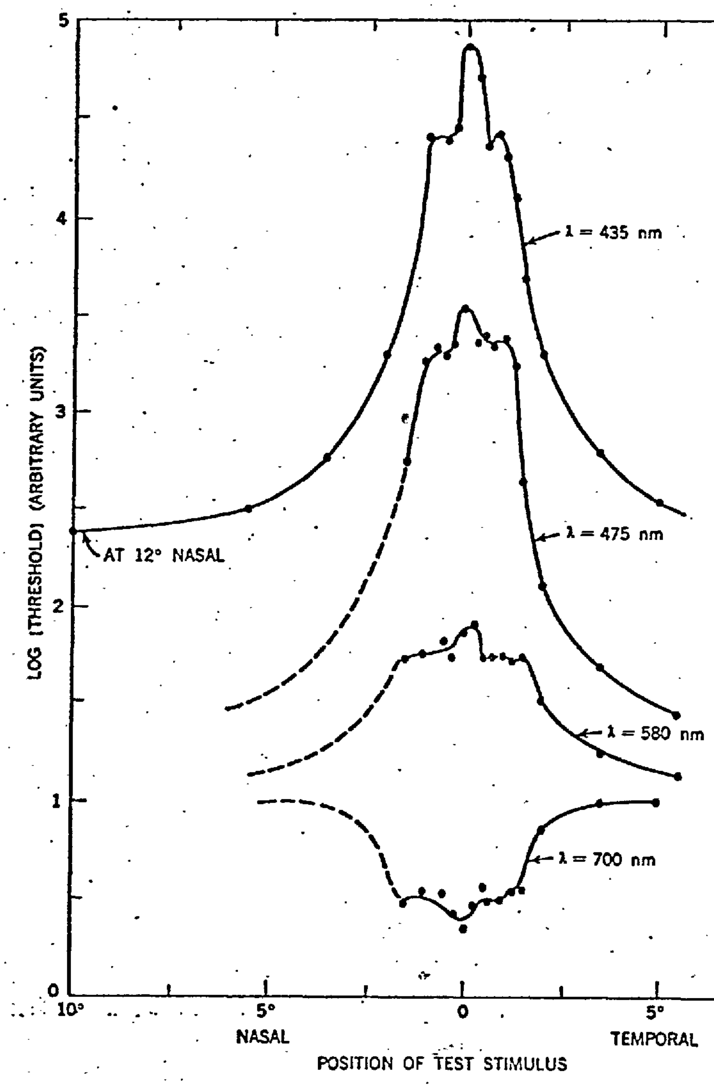


Fig. 66. Variation of increment threshold in traverses through the dark-adapted foveal and parafoveal areas with spectral test stimuli of different wavelengths. For all wavelengths except 700 nm there are sharply descending wings representing rod response. The threshold is not constant in the foveal area, and for λ = 435 nm particularly a narrow maximum is shown which is probably related to the foveal tritanopia present in normal eyes (Stiles 1949).

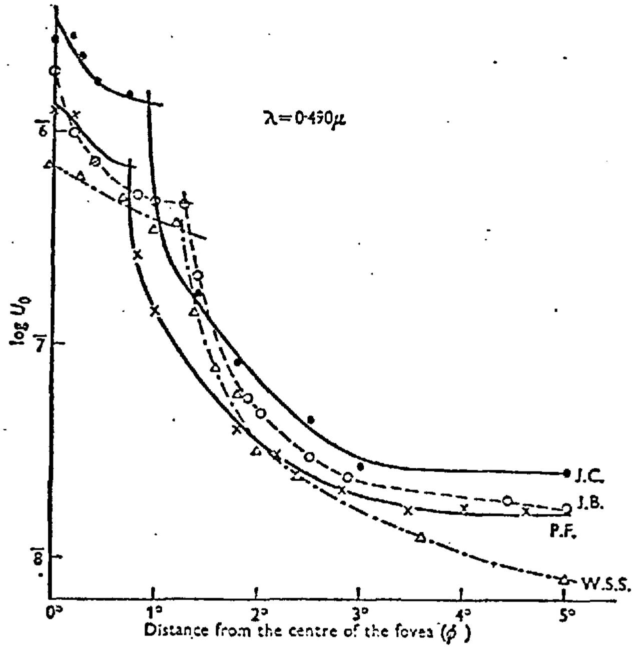


FIG. 67. Variation in and near the fovea of the absolute threshold for light of $\lambda = 490$ mμ in four subjects.

The test field was 13′ of arc in diameter and exposed in 0.2 second flashes. The measurements were made in a horizontal plane on the nasal side in the external field. All curves show a cone-rod break at an eccentricity in the neighbourhood 1°, but there are marked differences between the results for the various subjects.

The quantity U_0 represents the threshold energy in ergs per square degree per 0.2 second; U_0 must therefore be multiplied by the area of the test field, 0.038 sq. deg., to obtain the energy content of one flash at threshold.

(From Cabello and Stiles, 1950; figure reproduced in Pirenne, 1956) to those described earlier with white lights, except that the measurements have been restricted to the nasal side of the retina in the horizontal meridian. Owing to the lower luminances attainable in the test field, the maximum value of the white background luminance used with the red and blue stimuli was reduced to 100 trolands, and the variables were assigned the following values:

(i) $\alpha = 2'$, $t = 20$ ms.;
(ii) $\alpha = 2'$, $t = 500$ ms.;
(iii) $\alpha = 32'$, $t = 20$ ms.;
$B = 0, 1, 100 \ (1000)$ trolands.

All thresholds measured were achromatic. Large variations were obtained in the absolute threshold readings for a red stimulus when using a 2-mm. exit pupil; this was traced to the Stiles Crawford effect, as the mouthgrip on its own did not seem fully effective in preventing small movements of the eye relative to the artificial pupils - the use of larger artificial pupils in such determinations gave much more consistent readings. The results of the experiments are shown in fig. 68-77, and not all features of the curves admit of an easy explanation.

Thresholds for green stimuli ($\lambda = 530$ nm.) show the same type of variation as for white stimuli and the same general considerations are presumably applicable in both cases. The only difference is the higher threshold at the very centre of the field against a background of 1 troland, indicating possibly an earlier transition to the conditions of dark adaptation as the background luminance is reduced.

The curves for the red stimulus (λ = 668 nm.) against 1- and 100-troland backgrounds (fig. 72-73) agree with the curve for the green stimulus against a background of 1000 trolands within the limits of experimental error. Assuming similar distribution and summation properties for the receptor units, this may be expected on the basis that in all three cases one is determining essentially a cone threshold. It is interesting to note that observer OT, who is a deuteranope, shows good agreement with the other two observers. Against a dark background, the outer parts of the red curve show a rather reduced gradient, which may be due to some degree of rod activity. In the results of Stiles and Crawford (1933, fig. 78), the rod sensitivity at wavelengths greater than about 610 nm. may well be given by the dotted curve (added by the author), and this, though less than the cone sensitivity, is by no means negligible. The unexpected features in fig. 71 are the peaks at the very centre of the field; this has been confirmed by six observers. The visual axis is generally taken as being the most sensitive part of the retina at such wavelengths for the dark-adapted eye and the results of Stiles (fig. 66) at λ = 700 nm. would tend to support this view. The rather shorter wavelength (668 nm.) used here seems hardly likely to account for the difference, though it must not be ruled out as a possible explanation - a short discussion is given later.

The results of Verriest and Israel (fig. 55) would indicate that blue thresholds show the same type of variation with retinal

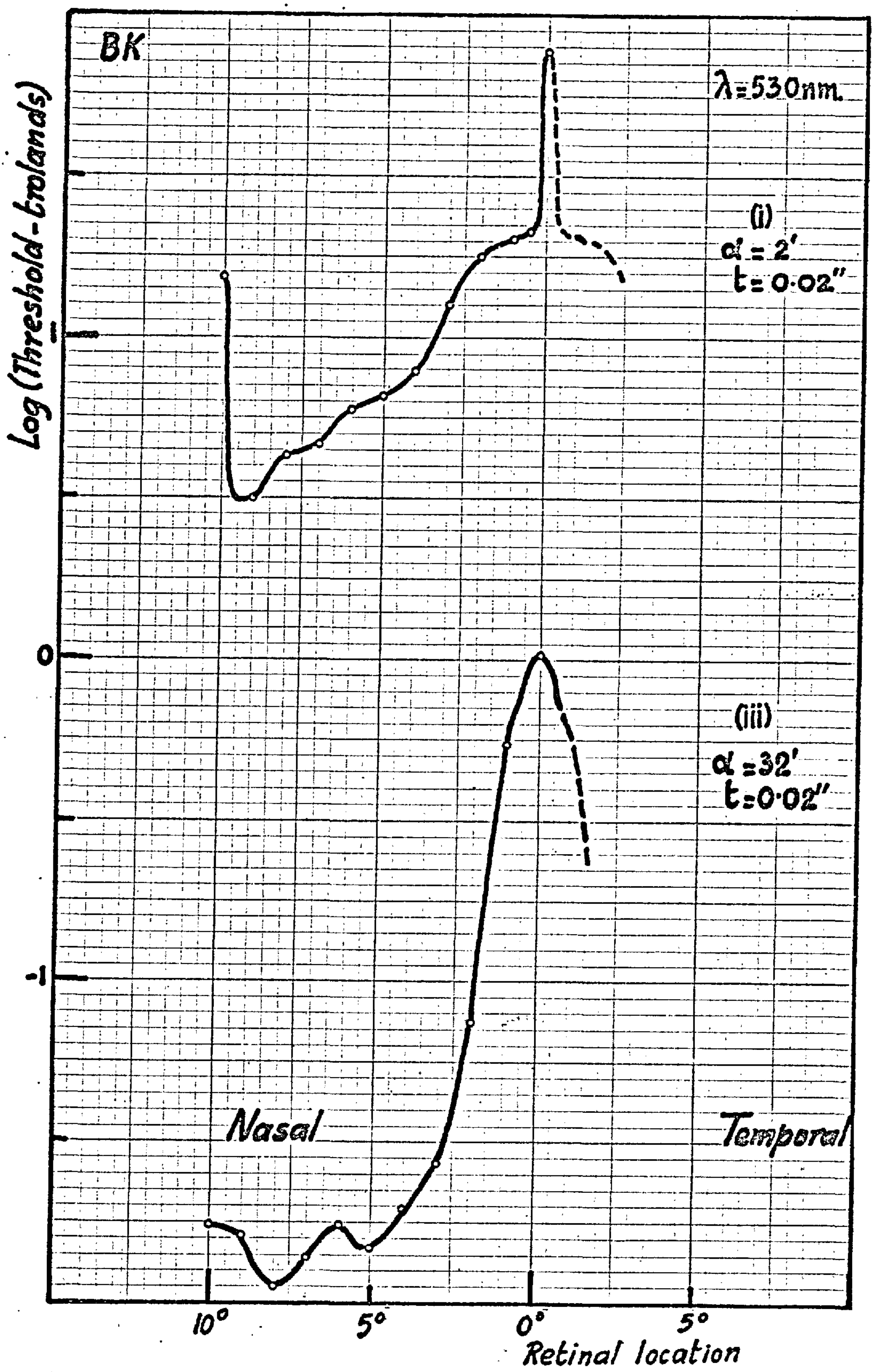


Fig. 68. Threshold variation for a green test flash against a dark background (n = 1 c.p.s.)

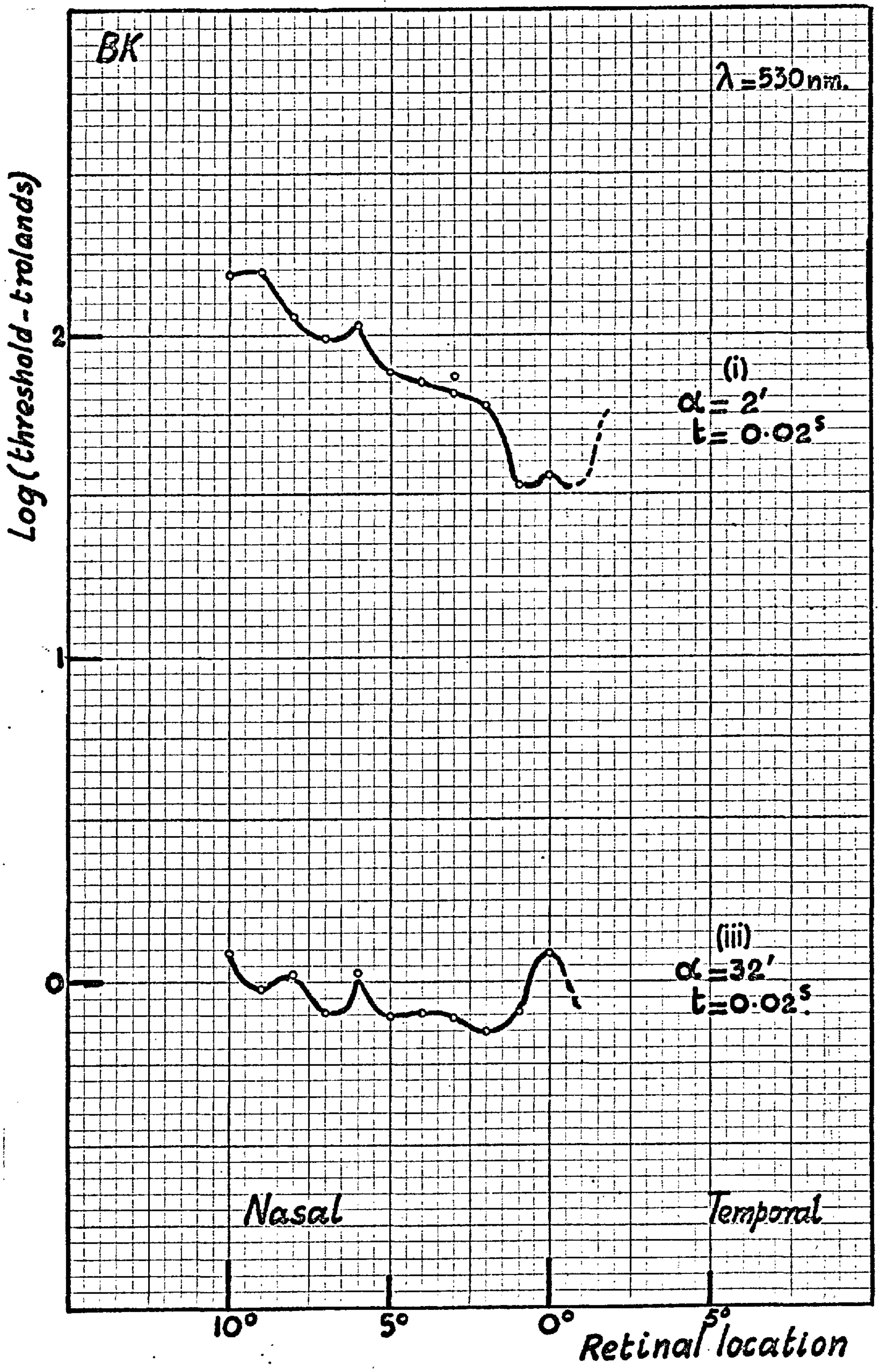


Fig. 69. Threshold variation for a green test flash against a white background of 1 troland (n = 1 c.p.s.)

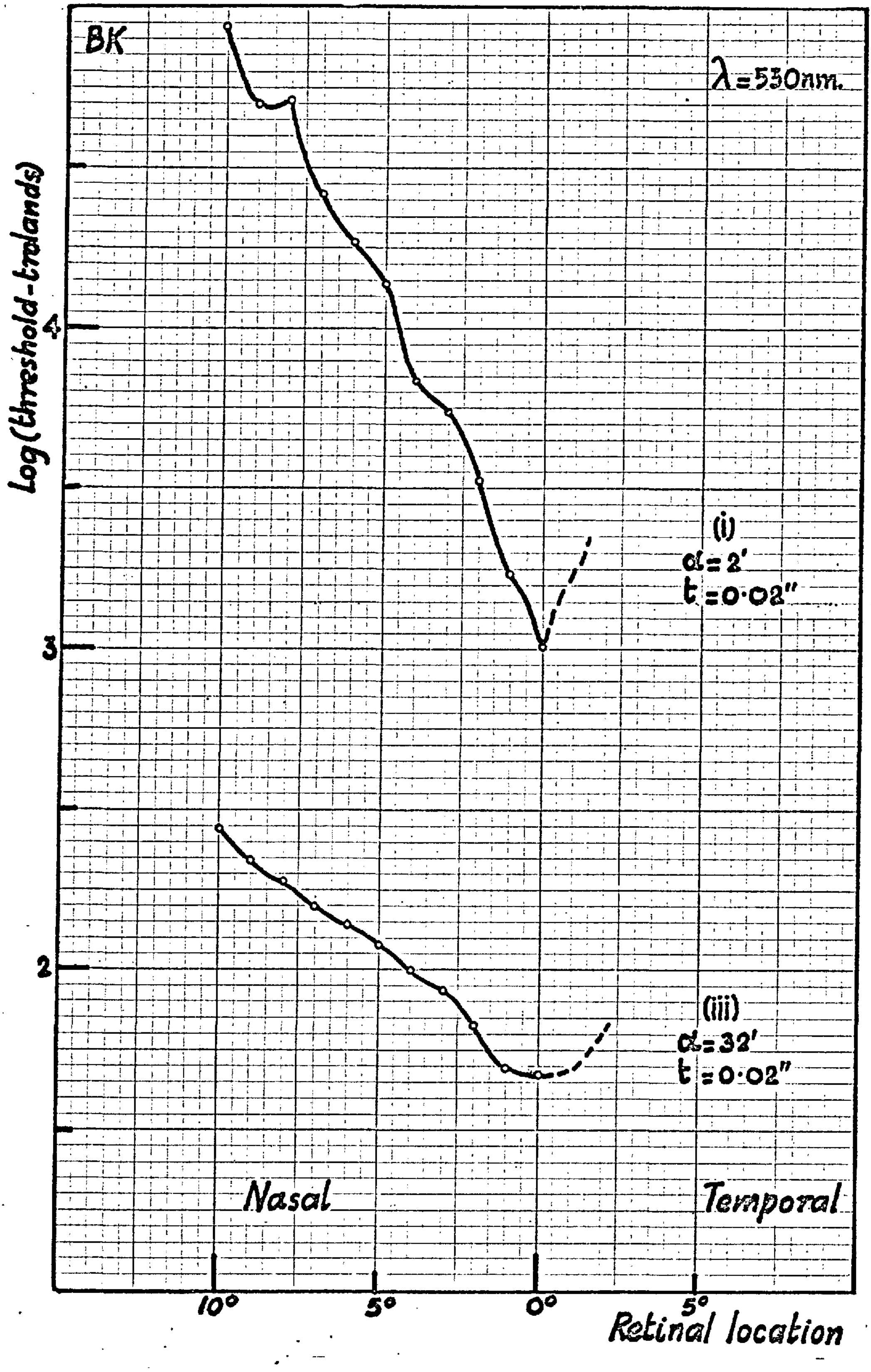


Fig. 70. Threshold variation for a green test flash against a white background of 1000 trolands (n = 1 c.p.s.).

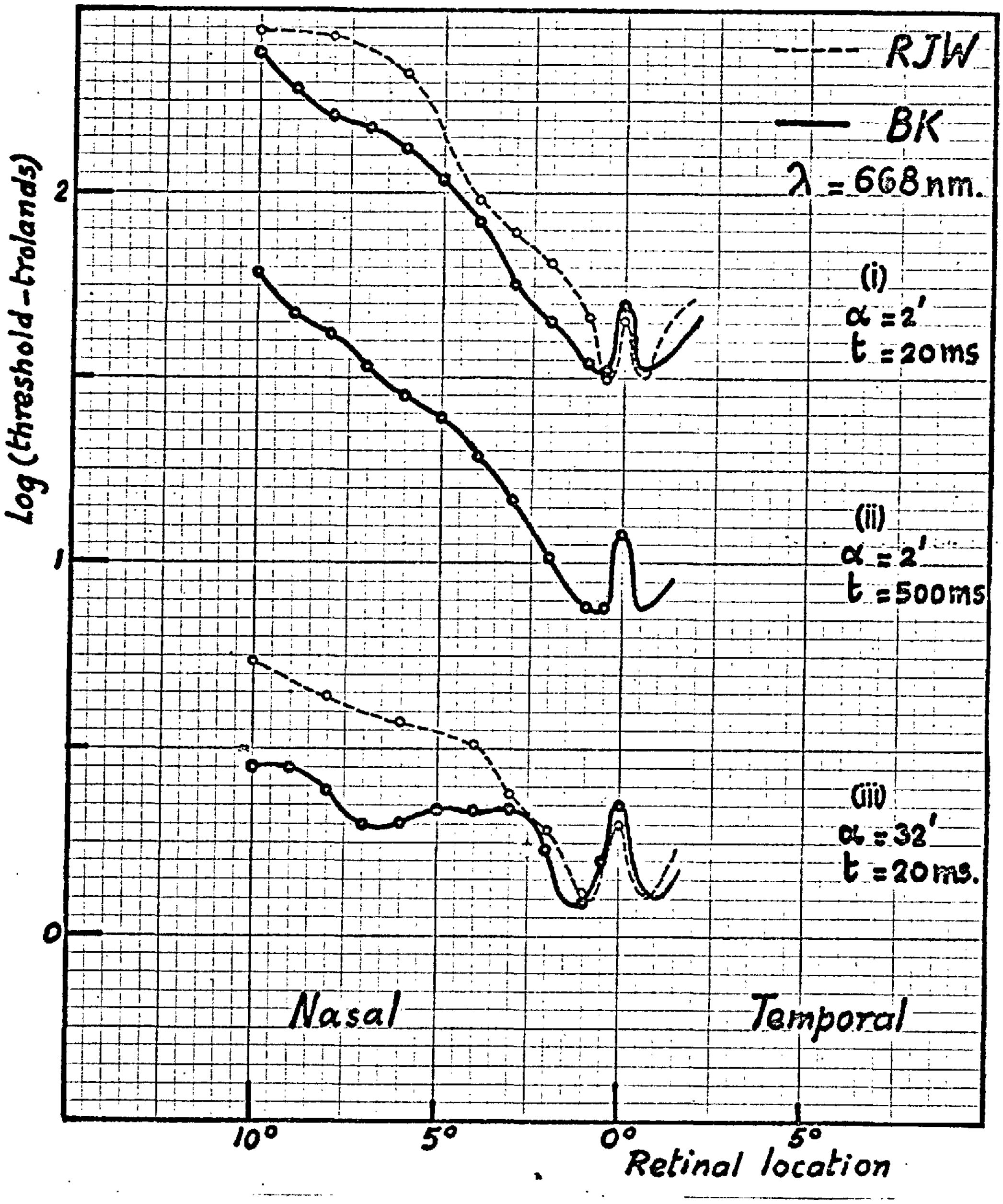


Fig. 71. Threshold variation for a red test flash against a dark background (n = 1 c.p.s.)

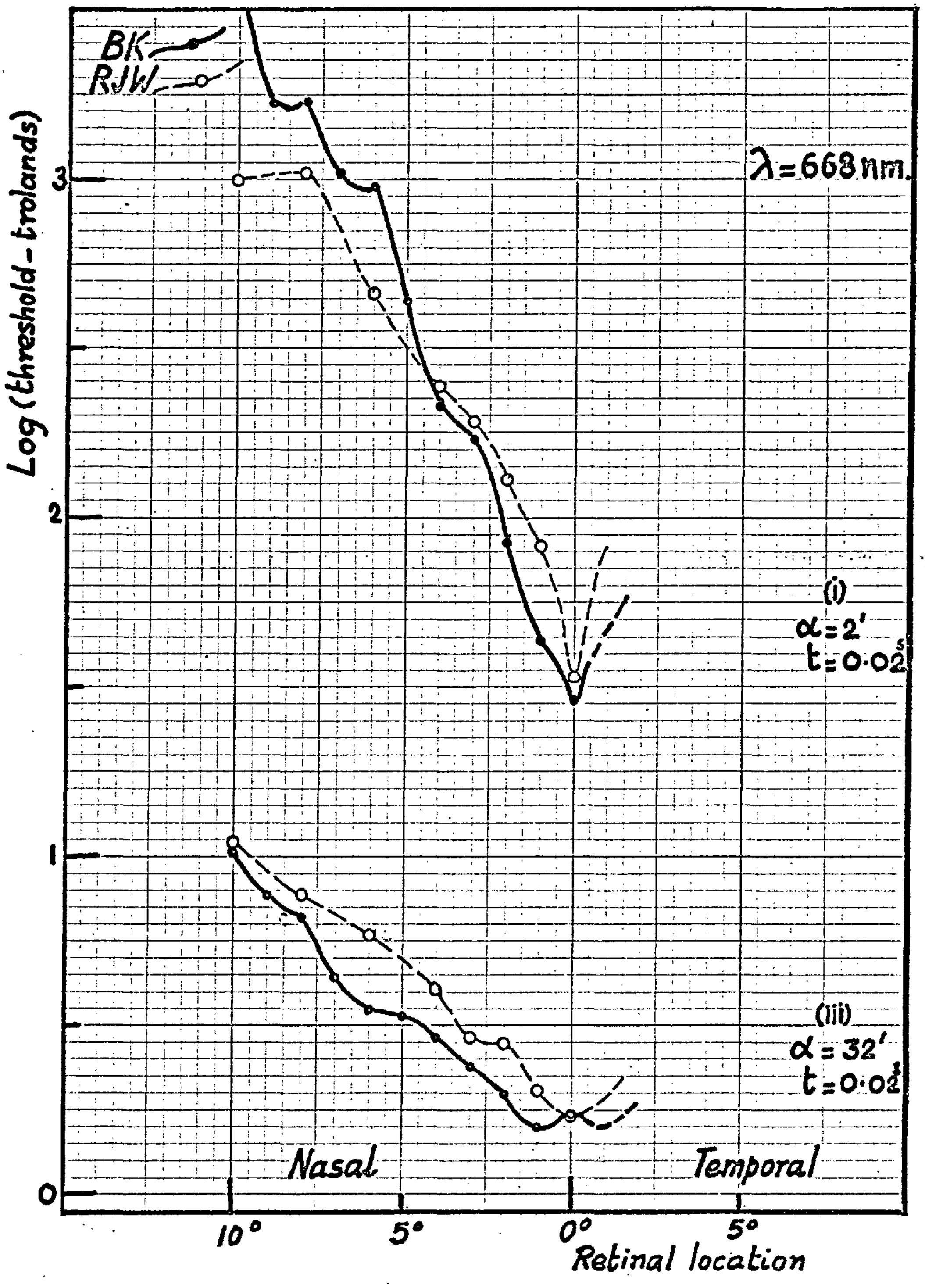


Fig. 72. Threshold variation for a red test flash against a white background of 1 troland (n = 1 c.p.s.)

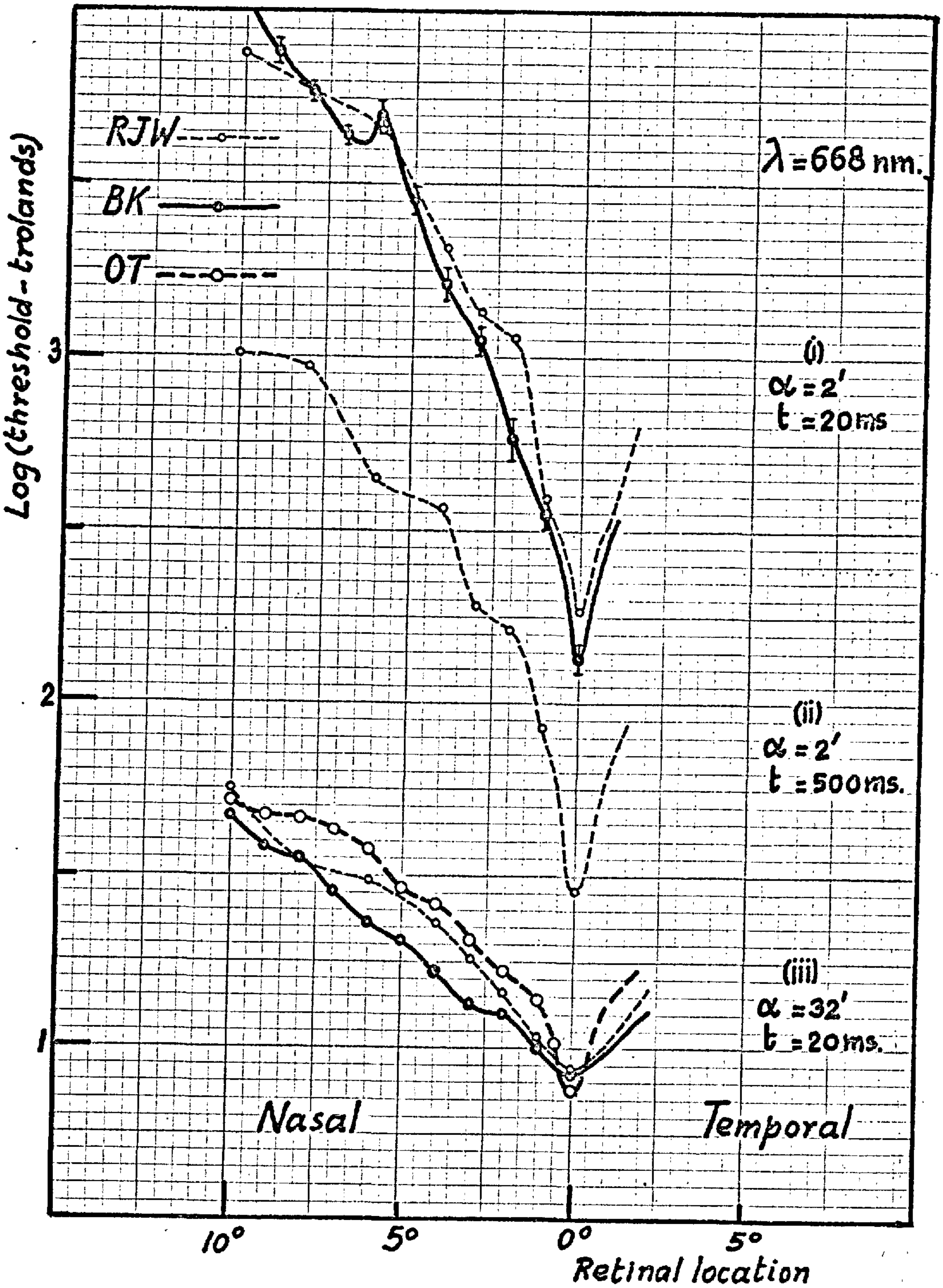


Fig. 73. Threshold variation for a red test flash against a white background of 100 trolands (n = 1 c.p.s.)

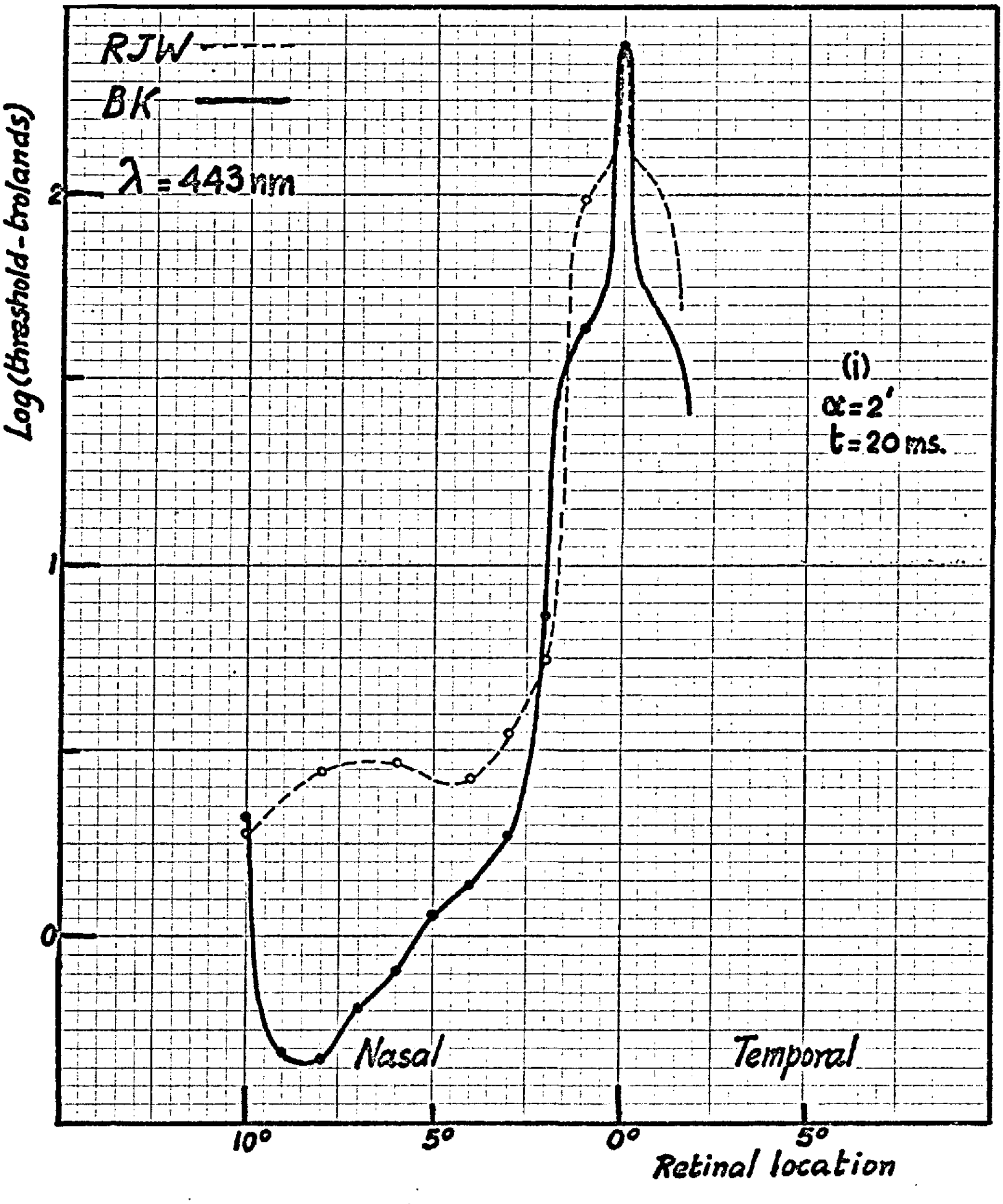


Fig. 74. Threshold variation for a blue test flash against a dark background (n = 1 c.p.s.)

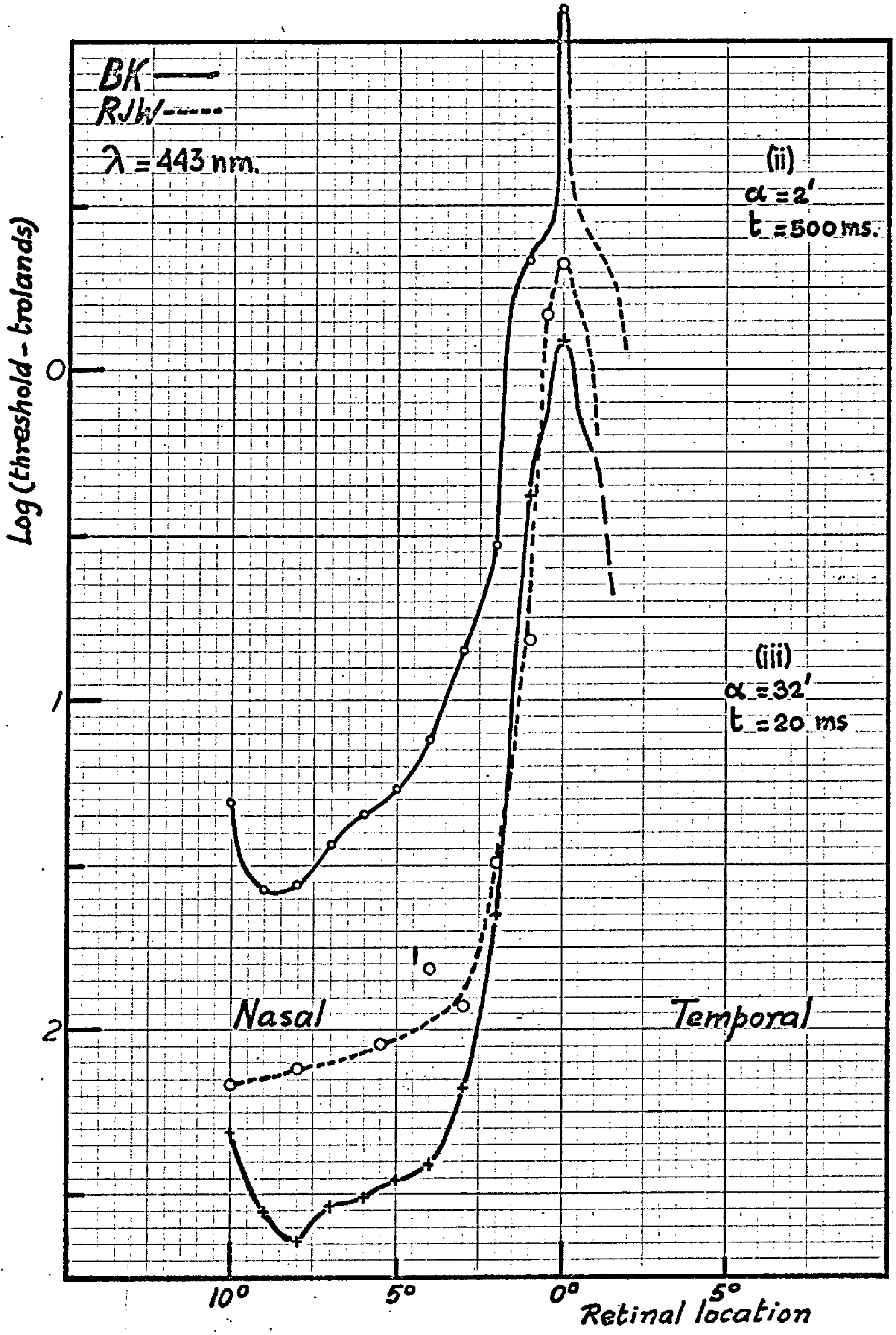


Fig. 75. Threshold variation for a blue test flash against a dark background (n = 1 c.p.s.)

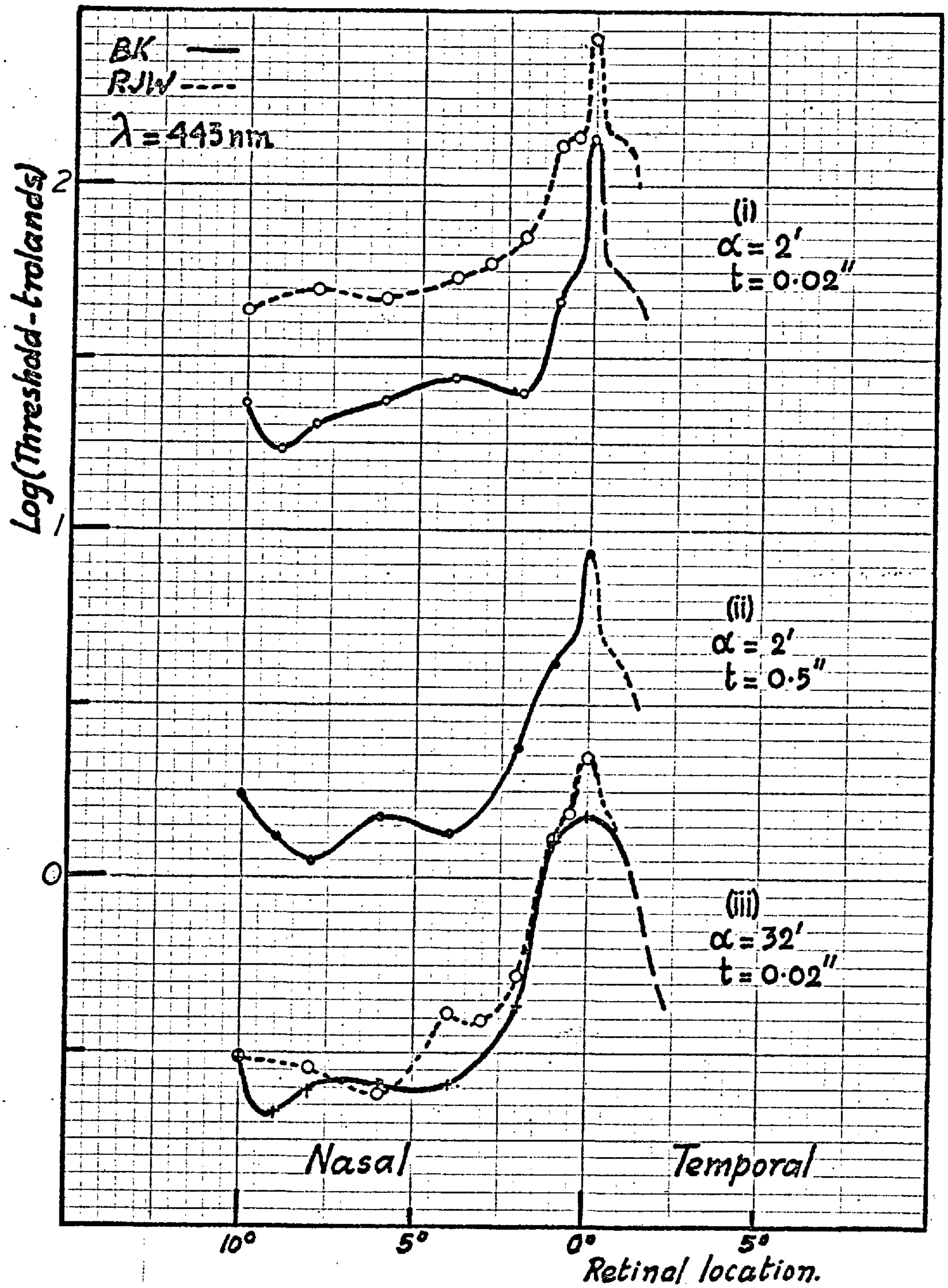


Fig. 76. Threshold variation for a blue test flash against a white background of 1 troland (n = 1 c.p.s.)

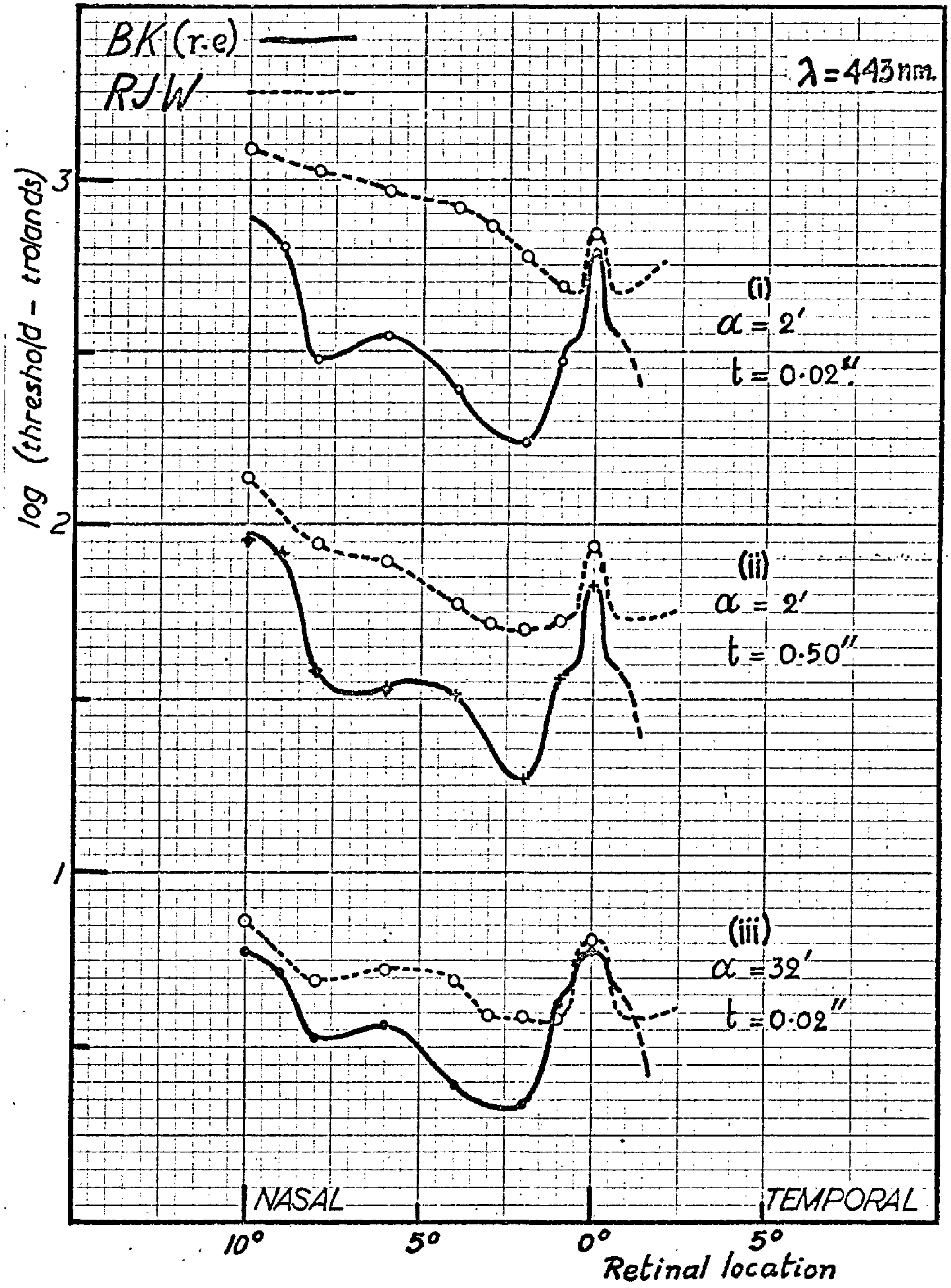


Fig. 77. Threshold variation for a blue test flash against a white background of 100 trolands (n = 1 c.p.s.)

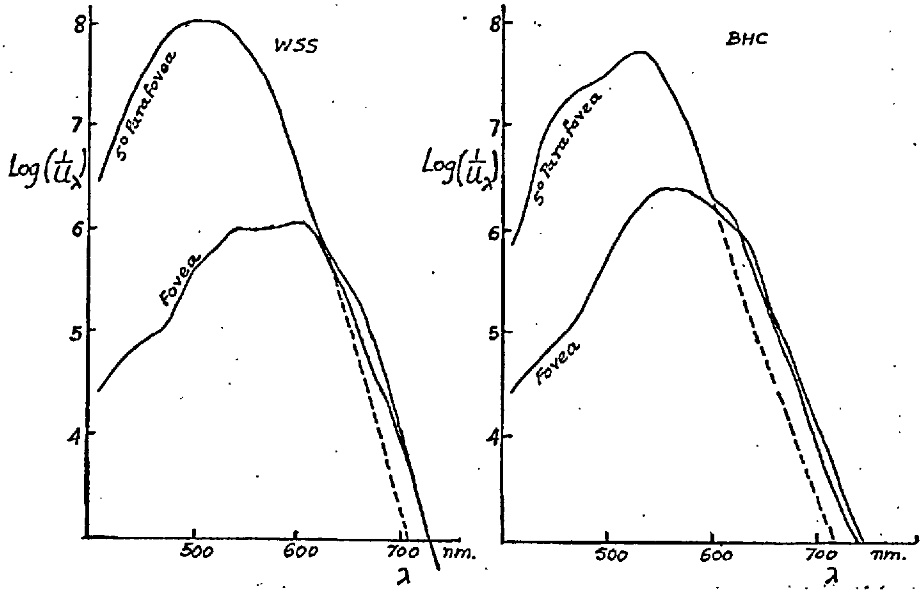


Fig. 78. Log $(1/U_\lambda)$ against λ for the dark adapted eye, where U_λ is the threshold energy flux received by the eye per unit angular area of the test spot. (Stiles and Crawford).

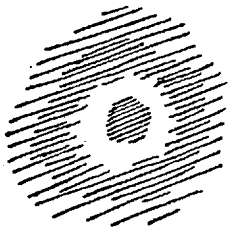


Fig. 79. Appearance of the Maxwell spot as seen by the author.

location as red and green thresholds against white backgrounds of high luminance and at eccentricities greater than 5° to 7°. Large observer differences may however occur in the foveal region. All the curves for $\lambda = 443$ nm. (fig. 74-76) show a sharp peak at the very centre of the field and within $\frac{1}{2}$° from the visual axis, but observer BK shows a broad hump across the fovea (2° to $2\frac{1}{2}$° from axis) which is absent for observer RJW (fig. 76). It seems very likely that the narrower central peak is associated with small field tritanopia (Willmer and Wright, 1945) whereas the broader maximum is attributable to greater absorption by the macular pigment. Ruddock (1963) concluded from colour matching data that there was sufficient evidence for the existence of a macular pigment in the living eye and deduced a curve in good agreement with the absorption curve for xanthophyll. Wald (1949) compared the absorption curve for extracted macular pigment with results derived from visual observations by taking the difference in cone threshold on the axis and at eccentricity $\theta = 8°$. This assumes that the cone response is constant as far as 8° from the centre. If an observer establishes a flicker match between a blue test field and a reference white at different retinal locations, a higher luminance is required for the blue in the foveal match. Assuming a certain uniformity in the response of the receptors, the differences observed are presumably due to screening by the macular pigment. Hough (private communication) has deduced "macular pigment" absorption curves from such experiments at $\theta = 0°$ and $\theta = 7°$, and according to him, the use of fields of luminance higher than about 100 trolands may give the effective optical density of the macular pigment to within 0.1 log unit. The experiment described below was therefore carried out.

Three observers made flicker matches at different retinal locations between a blue test field ($\alpha = 32'$, $\lambda = 443$ nm.) and a reference white of about 100 trolands, using a photometric field as in fig. 37 against a white background of 100 trolands. The results are given in fig. 80 (upper curves) in which the height of the ordinate above the horizontal portion of the curves presumably gives the optical density of the macular pigment at the position of the ordinate and at the chosen wavelength. The lower curves in the same diagram give the thresholds for a similar test field ($\alpha = 32'$, $\lambda = 443$ nm.) against a white background of 100 trolands for the observers. Correcting the threshold curves for "macular pigment absorption" yeilds the curves of fig 81, which shows better overall agreement among the observers.

The extent to which fig. 81 represents the actual receptoral response in absence of screening by the macular pigment is debatable. Studies on enucleated eyes (Polyak 1941; see p. 143) show that the macular pigment is absent over the foveola, a disc of about 70' in diameter centred on the axis, so that the upper curves of fig. 80 become difficult to explain. If one views the Maxwell spot, the entoptic projection of the macula with a purple filter, the appearance is of a dark ring surrounding a clear zone with a much darker central spot (fig. 79). Walls and Matthews

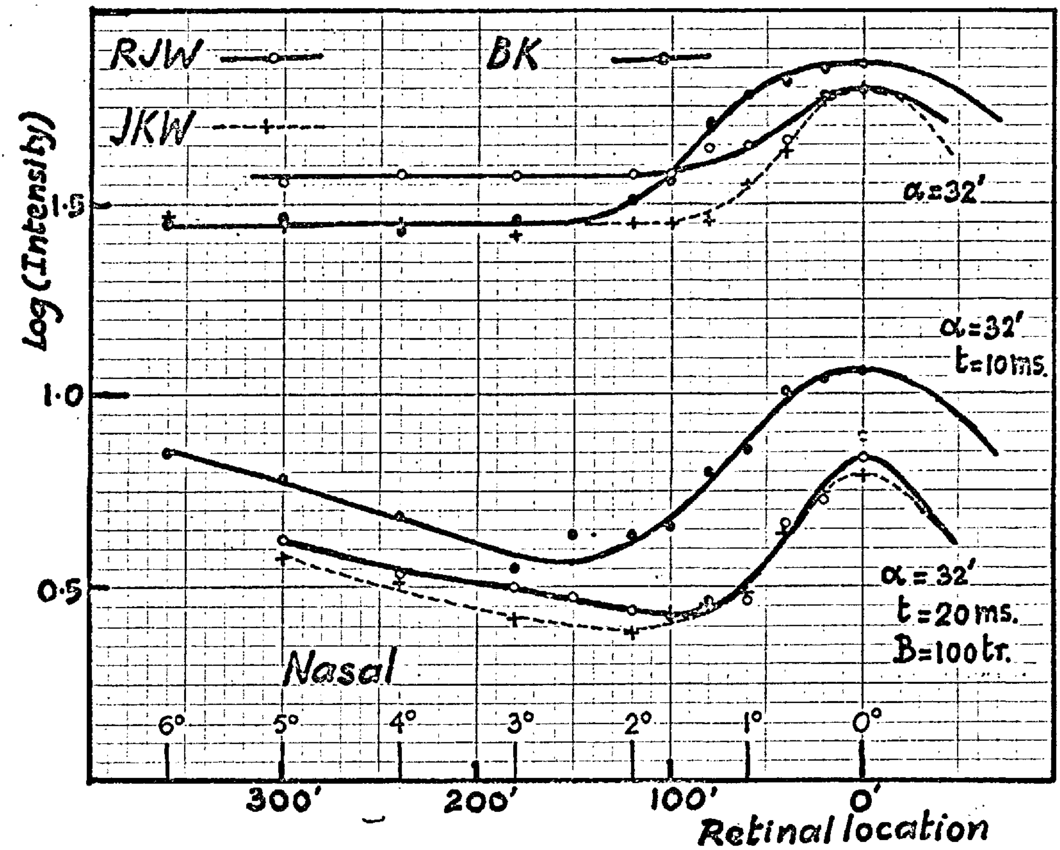


Fig. 80. Amount of blue light (443 nm) required in a flicker match against a reference white (upper curves) and thresholds (trolands) for a similar blue test field against a white background of 100 tr.

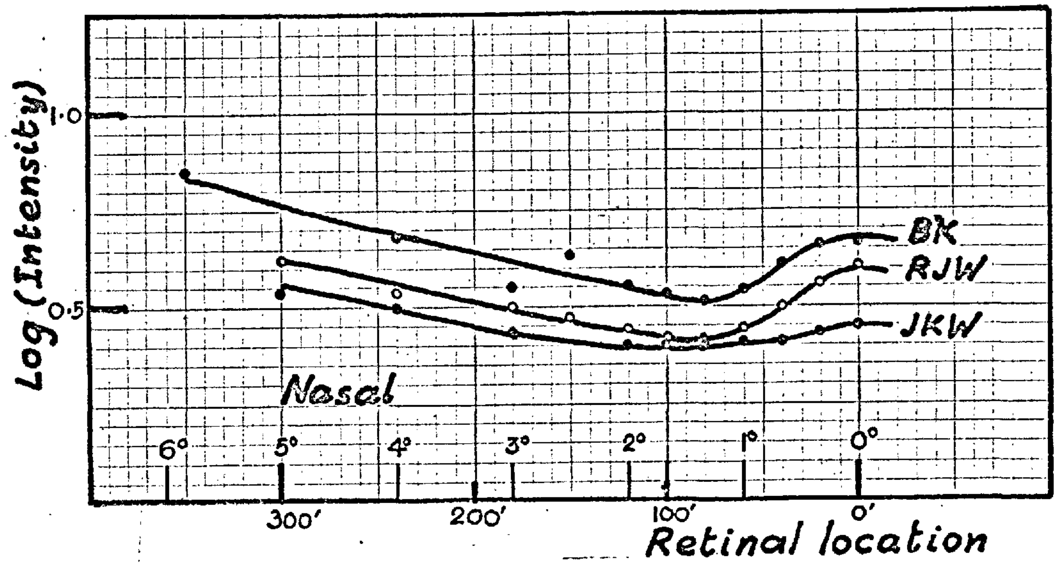


Fig. 81. Thresholds of fig. 80, corrected for "macular pigment absorption".

(1952) found that protan subjects saw the spot with characteristic colourings whereas deutan subjects do not see it at all and concluded that the spot owes its origin to a non-uniform distribution of the colour receptors in the fovea and not to pigment absorption. According to Marriott (1962), observations on the Maxwell spot by Stiles in fields arranged for metameric matches with different combinations of pairs of spectral lights would indicate that the Maxwell spot is produced by foveal pigmentation. It seems more likely that the dark ring in the Maxwell spot arises through pigment screening whereas the darker central spot is caused by the scarcity of the blue receptors in the axial region, often quoted in explanation of small field dichromatism; this would be in good agreement with the threshold observations using small test stimuli. The use of the larger field size in the above experiments would confuse the two effects and yield a spurious value for the optical density of the pigment at the centre of the visual field.

The screening due to the macular pigment would also in part be responsible for the much steeper fall in the threshold for the blue as compared with the green stimulus in dark adaptation (fig. 68, 74, 75), though a more important factor may be the relative sensitivities of the cone and the rod mechanism at the two wavelengths.

The variation of the threshold across the fovea for small red and blue test stimuli.

At all levels of background luminance difficulty was experienced in determining the threshold at the centre of the field when using small stimuli. With high background luminances, and red, green or white stimuli, there would appear to be a small region, estimated by the observers to be only two or three minutes of arc in diameter, where the threshold has a lower value than in the surrounding area, and once fixation has wandered from this region it is not easy to find the test flash again. In dark adaptation and with green, blue or white stimuli, a position can similarly be found by careful fixation where the threshold is a maximum, and any small eye movement will make the light appear well above threshold. It was therefore decided to measure the threshold at smaller intervals across the fovea with red and blue stimuli of 2' angular subtense to find the nature of the gradient in this region. The experiment is not easy as very careful fixation must be maintained and the observer must decide at the instant of recording an observation whether the degree of fixation was adequate. Often, an experiment has had to be abandoned half way as the observer started feeling symptoms of fatigue, but with care it seems quite likely that fixation may be maintained to within 2' or 3' of arc, and the results of such determinations against backgrounds of 100 and zero trolands are shown in fig. 82 and 83. The larger exit pupils have been used for observations against the dark background to reduce errors introduced by the Stiles-Crawford effect.

The correlation between the curves for the red and the blue thresholds against a background of 100 trolands would point to definite variations in the retinal structure.

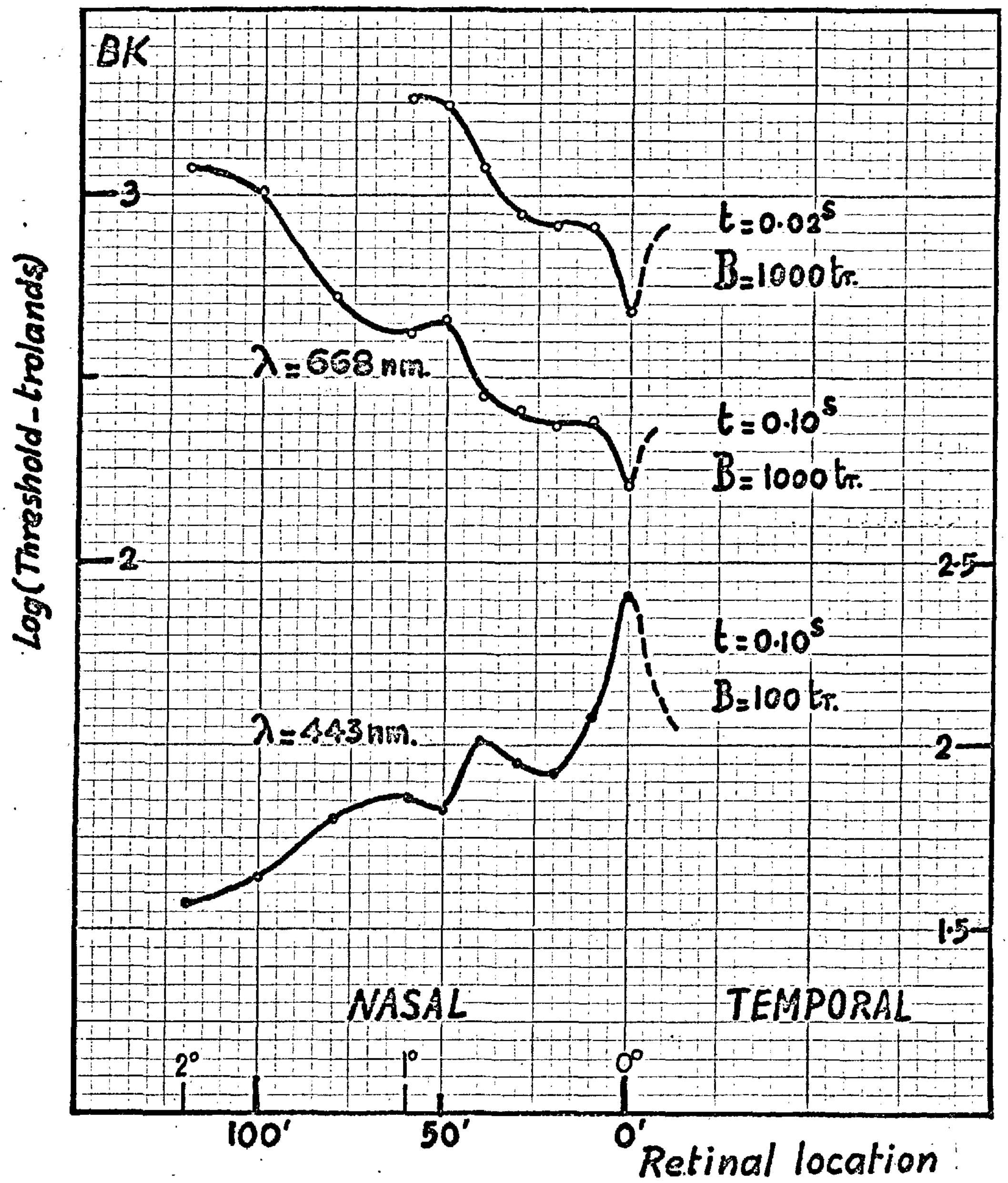


Fig. 82. Variation of threshold across the fovea for blue and red test fields of 2' angular subtense against white backgrounds of 100 and 1000 trolands (n = 1 c.p.s.)

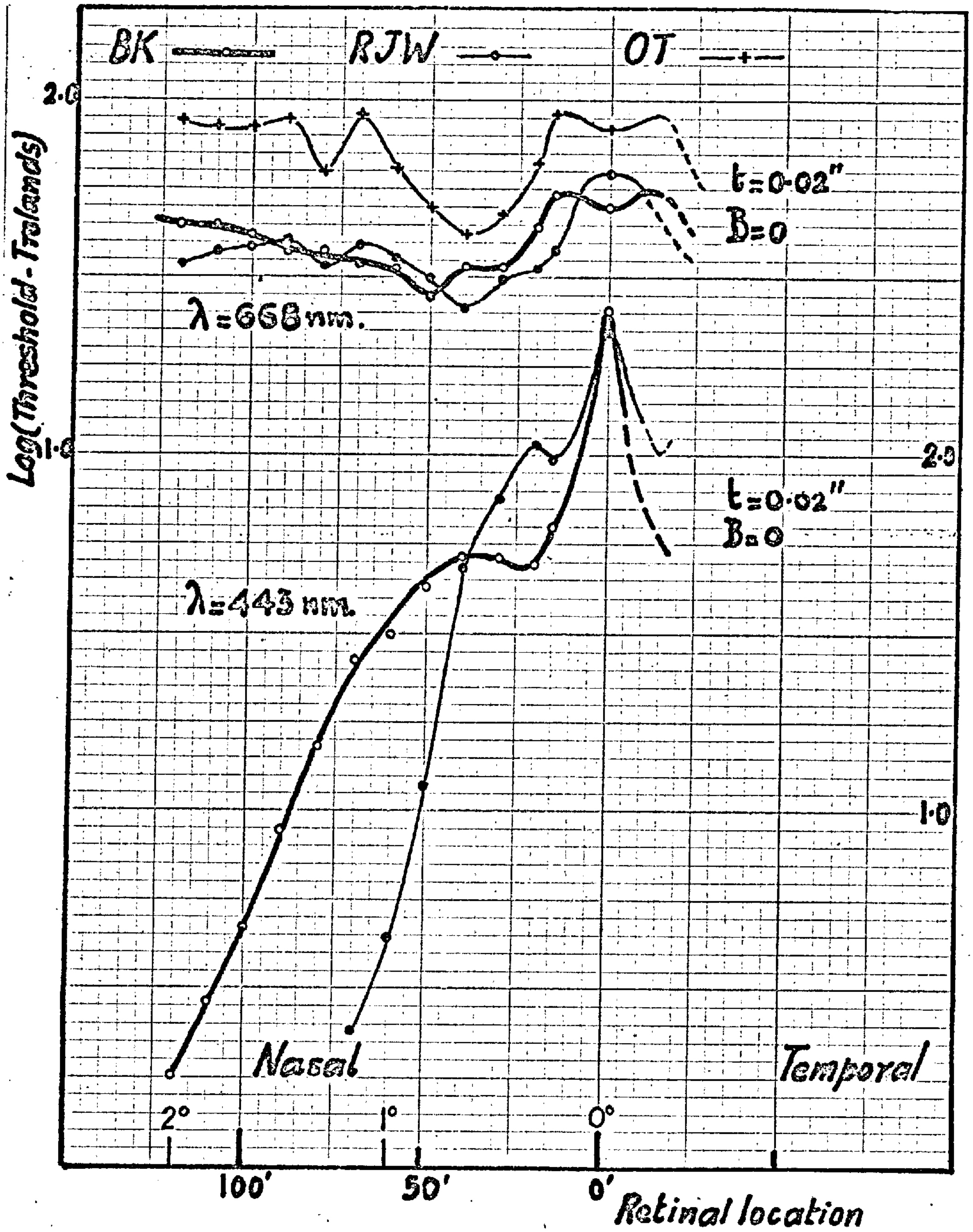


Fig. 83. Variation of threshold across the fovea for blue and red test fields (α = 2') against a dark background (n = 1 c.p.s.)

Steep threshold gradients occur within 10' to 15' from the visual axis. Miles (1949), from experiments with coloured filters, concluded that the central region of the fovea about 30' in diameter was very different from the rest and that there was evidence for concentric zonation within the fovea. In dark adaptation there is a very steep fall in the blue threshold within 2° of the visual axis and this sets in at about 40' for observer BK and at 20' to 25' for observer RJW (fig. 83). It seems fairly reasonable to assume that this originates from rod activity and that the eccentricities are related to the positions where rods start to make their appearance for these observers (cf. Cabello and Stiles; fig. 67). The central peak is about 20' half-width for BK and 15' for RJW and shows good correlation with the width of the central maximum for the red thresholds of these observers (upper curves, fig. 83). The deuteranope OT is again in good agreement with the other two observers. Moreover, the curve for the absolute threshold for a small green stimulus for observer BK (fig. 68) would indicate that the peak in this case may also be restricted to a similar area. It could be expected that an area of such dimensions might show up in ophthalmoscopic examination, but photographs taken of the fundi of the observers (e.g. plate 4) have been very inconclusive.

The curves obtained would indicate that at all wavelengths there is a reduced sensitivity over the central 30' to 40' of the fovea in the dark adapted state. Under these conditions the greater sensitivity of the periphery as compared to the fovea, except at the long wavelength end of the spectrum, is due to rod activity, but this explanation cannot apply to the increase in sensitivity with eccentricity at the very foveal centre, where the rods are absent, and another explanation must be sought for within the cone mechanism itself. Close to the visual axis the cones are very slender and the image of a test field only 2' in diameter may fall on an appreciable number of cones. On the hypothesis that spatial summation is absent at all levels of adaptation for the very central cones which define the visual axis, but starts occurring within a few minutes from this axis, the increase in summation at low levels of adaptation may lead one to expect higher thresholds in the centre. The peak in the blue threshold which has the same half-width in light and dark adaptation is of different origin, but its greater height in the dark adapted eye would be ascribable to summation. It seems very probable that this region is identical with the central zone of Miles and corresponds to the "bouquet of central cones" of Rochon Duvigneaud (p. 143). Hartridge (1947) has put forward the theory that cones near the visual axis may be grouped into small clusters, each cluster responding to one colour, and forming the point of fixation for that colour. He deduces from his experiments that this area of maximum acuity may be only 3' to 6' in diameter and may contain between 10 to 40 cones. The suggestion is ventured that fixation is maintained in photopic vision by the small central group of a few cones corresponding to the foveola fundi of Schwalbe, Kuhnt (p.143) and Dimmer (1894). Incidentally, owing to the rather flat nature of the central maximum for red light in dark adaptation, a very dim red fixation spot may not be as effective in maintaining fixation as is generally imagined. In view of the complex function of the central fovea, some of these results may not be too surprising and similar experiments with stimuli of different wavelengths in conjunction with histological evidence may lead to a better understanding of problems associated with fixation, visual acuity and possibly colour perception.

From the practical point of view, some of the results given in this chapter may be applied to the formula of Stiles, Bennett and Green (p.44) for calculating the finding time for a flashing light in the field of view, and similar experiments extended to the whole field of view can give valuable information in assessing the performance of a flashing signal in the stages of design. It has in general been the opinion of the observers that a safety margin of 0.5 to 1.0 log unit should be allowed above the experimentally determined values to ensure near 100% probability of detection.

CHAPTER VI.

SPATIAL AND TEMPORAL SUMMATION AND THE BLONDEL-REY LAW.

SPATIAL AND TEMPORAL SUMMATION.

Ricco's law and certain aspects of spatial summation have been considered in chapter II (pp. 82-84). The Bloch-Charpentier law (p.27) represents the ideal case of temporal summation, when the threshold luminance L is inversely proportional to the flash duration t; for very long flashes the threshold is independent of the duration. Blondel and Rey (p.33) were among the first to study the nature of the transition from Lt = const. to L = constant and concluded that this was gradual (eq. 4-6, fig. 84). The problem has been taken up by other investigators since and most results obtained under controlled laboratory conditions have been at variance with the Blondel-Rey law and often with one another. There seems, however, to be fairly general agreement that the Bloch summation time decreases with the level of light adaptation and that under given conditions of adaptation there is an interaction between spatial summation and temporal summation. It would appear that in attaining threshold the visual system can use either spatial or temporal summation, but not a large degree of both - very brief exposures would favour area summation, especially in the peripheral retina, and the use of small test spots increases the Bloch summation time. The manner in which the results of some investigations have differed is now indicated.

Graham and Margaria (1935) studied the intensity-time relation at 15°eccentricity in the parafovea and found an abrupt transition

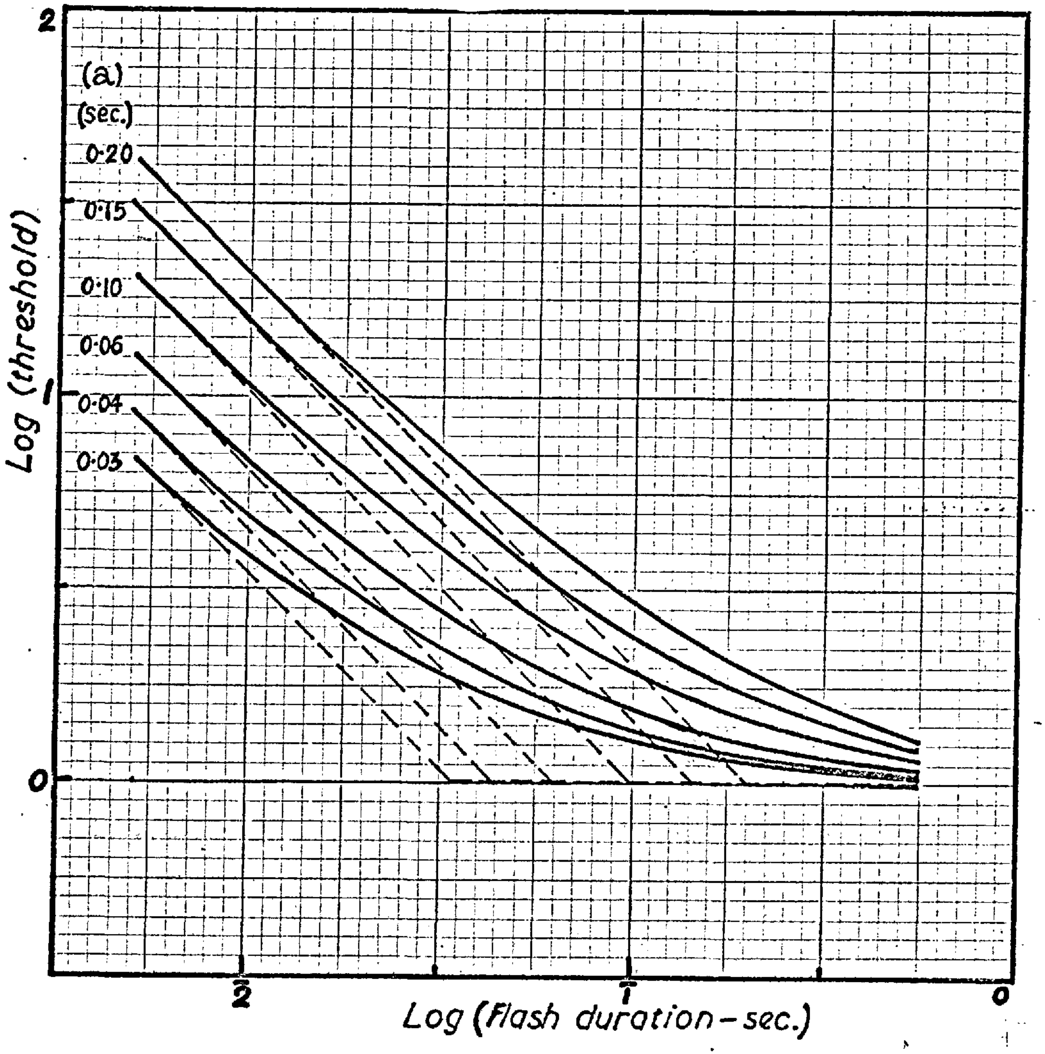


Fig. 84. Change of threshold with flash duration according to the Blondel-Rey equation, $I_e = It/(a+t)$, Each curve corresponds to one value of 'a' and the dotted lines at a slope of -1 would be expected on the basis of Bloch's law (It = const). The vertical scale is arbitrary and the horizontal line through the ordinate 0 is the threshold for a steady source, I = const.

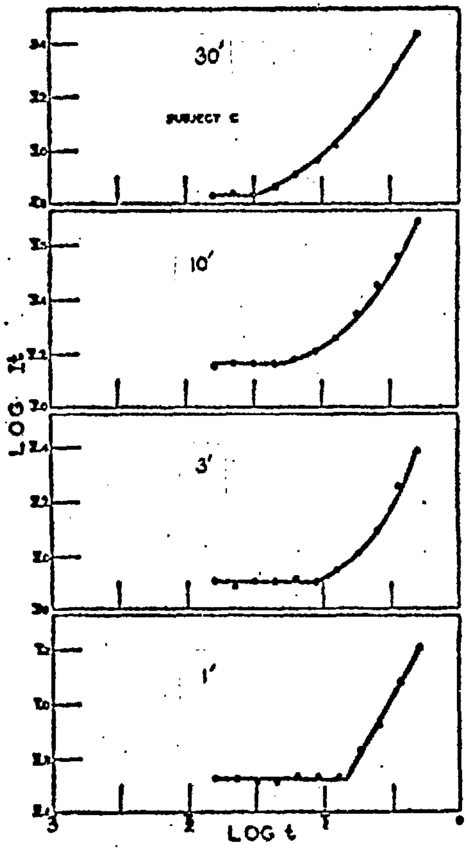


Fig. 85. Karn's curves for a typical subject showing the effect of increasing the size of the retinal image on the intensity-time relationship in the fovea.

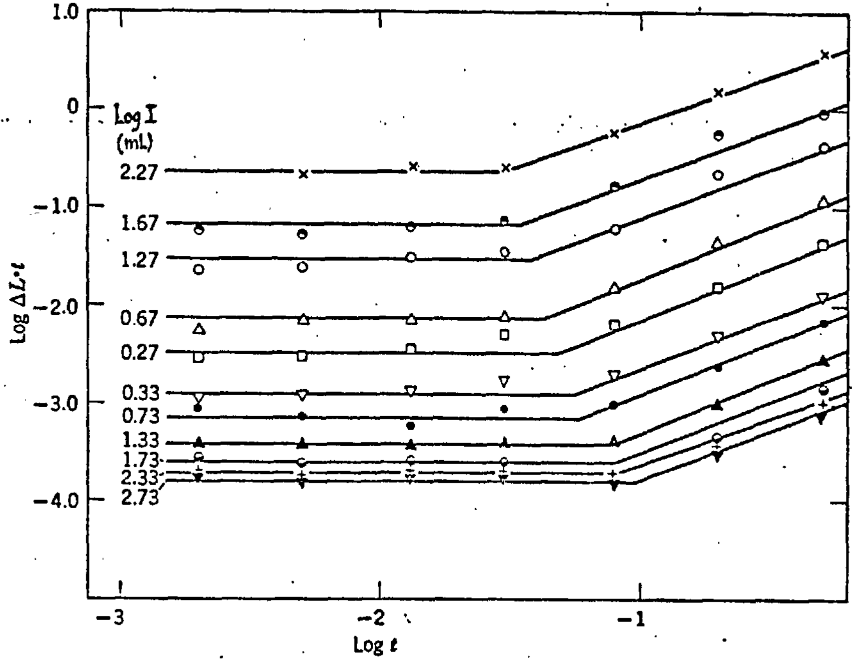


FIG. 86. The relation between ΔL and t for the various levels of luminance used in these experiments. The horizontal lines represent the equation $\Delta L \cdot t = const$, the inclined lines, $\Delta L = const$. (From Graham and Kemp, 1938.)

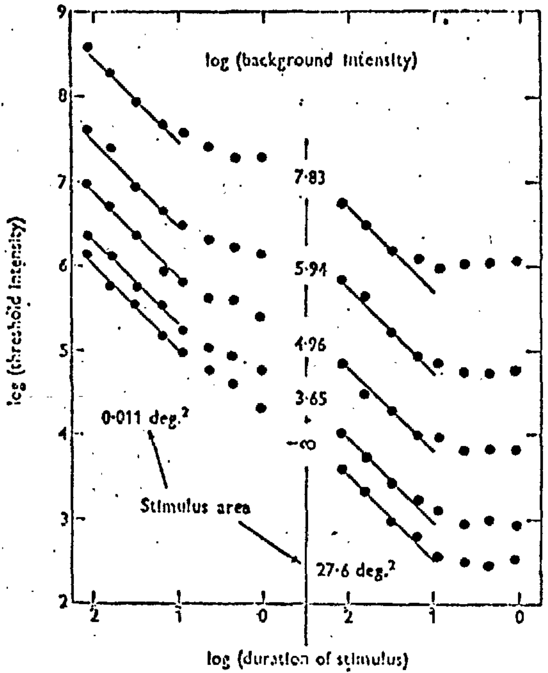


Fig.87a. Temporal summation at incremental and absolute threshold for a circular field centred 6° 30′ from the fixation point. Durations in seconds. The straight lines have gradient −1. Note that the greatest duration at which complete summation occurs (gradient −1) is slightly shorter, and the amount of summation between 0.1 and 1 sec much less, for large fields than for small (from Barlow, 1958).

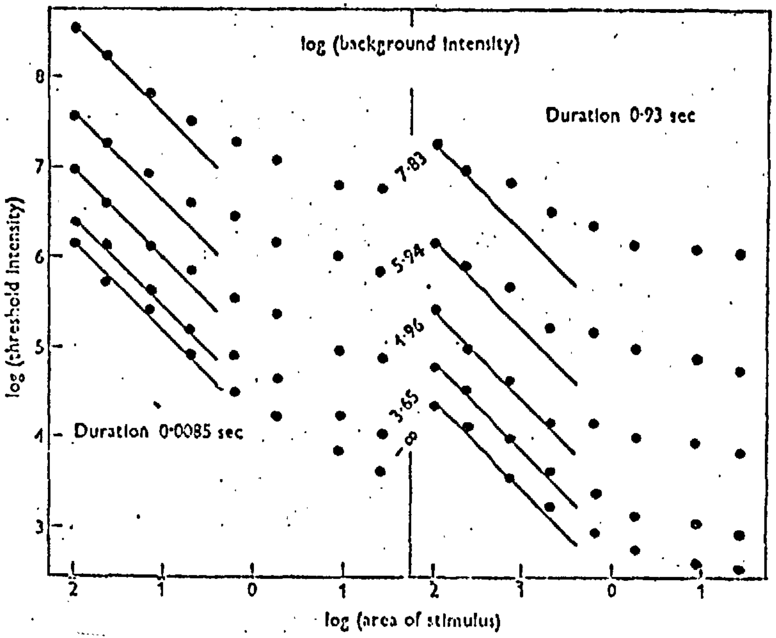


Fig. 87b. Spatial summation at incremental and absolute threshold for a circular field centre 6° 30′ from the fixation point. Areas in degrees. The straight lines have gradient −1 (from Barlow, 1958).

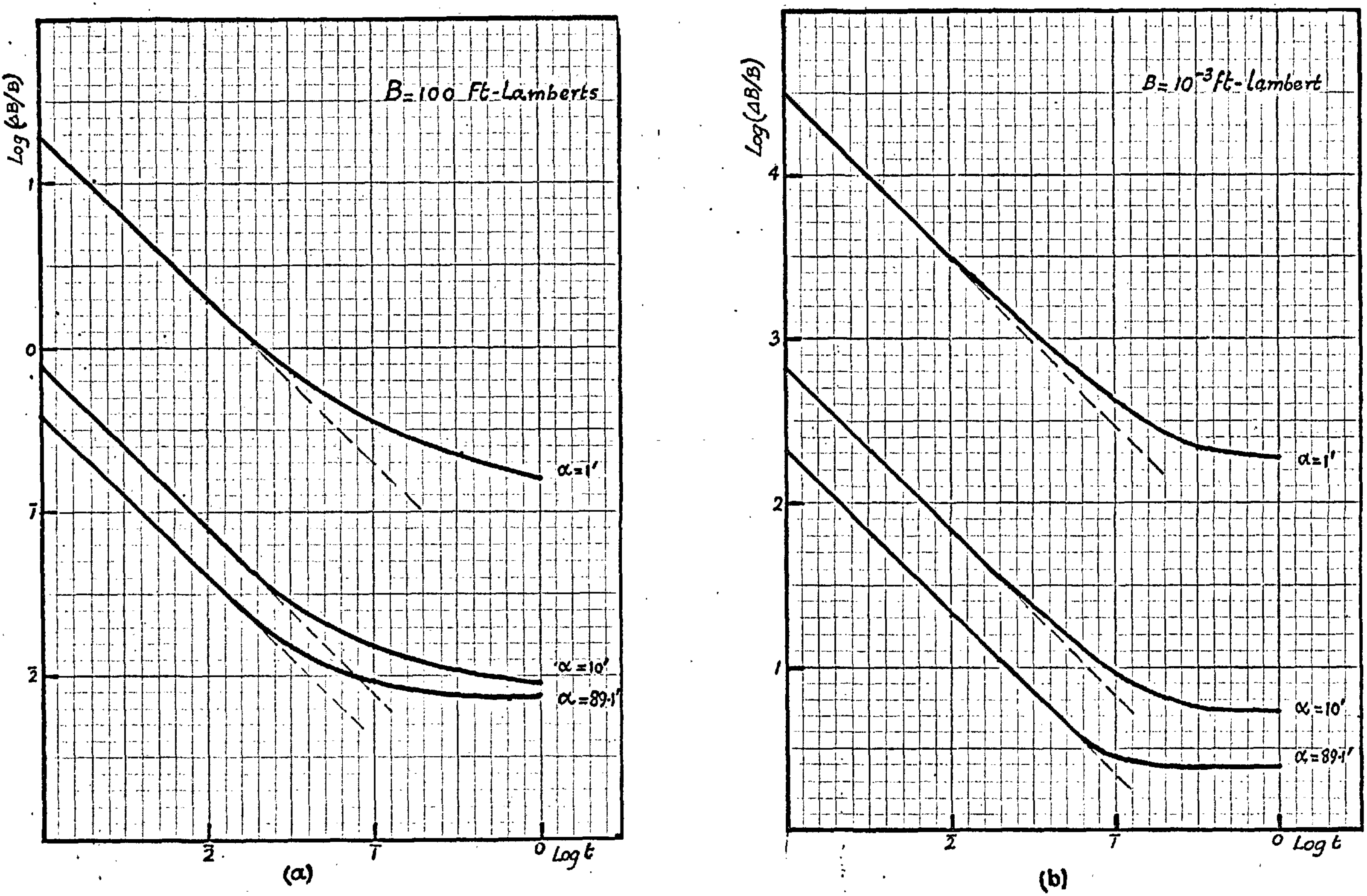


Fig. 88. Log threshold contrast (ΔB/B)/log duration curves against backgrounds of luminance B for stimuli of angular subtense α, in central fixation (plotted from smoothed data of Blackwell & McCready)

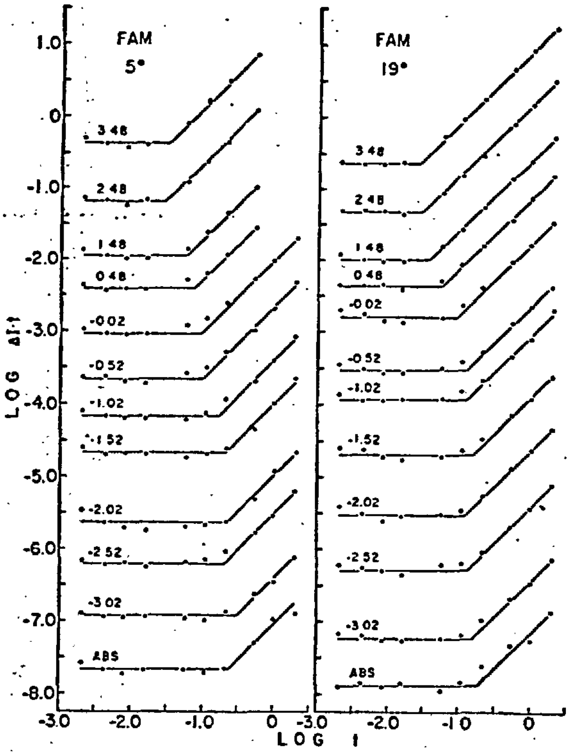


FIG.89. Mean thresholds for subject FAM for the 5° and 19° incremental area conditions. The parameter is the log luminance of the surround. For the 5° area, the curve for log surround = 0.48 is plotted directly against the ordinate, while those curves above are lowered toward it in multiples of 0.2 (e.g., 1.48 lowered 0.2, 2.48 lowered 0.4, etc.). Those curves below 0.48 are lowered away from it in multiples of 0.5 (e.g., −0.02 lowered 0.5, −0.52 lowered 1.0, etc.). For the 19° area, the curves are plotted similarly, except those below 0.48 are lowered in multiples of 0.4.

(BIERSDORF)

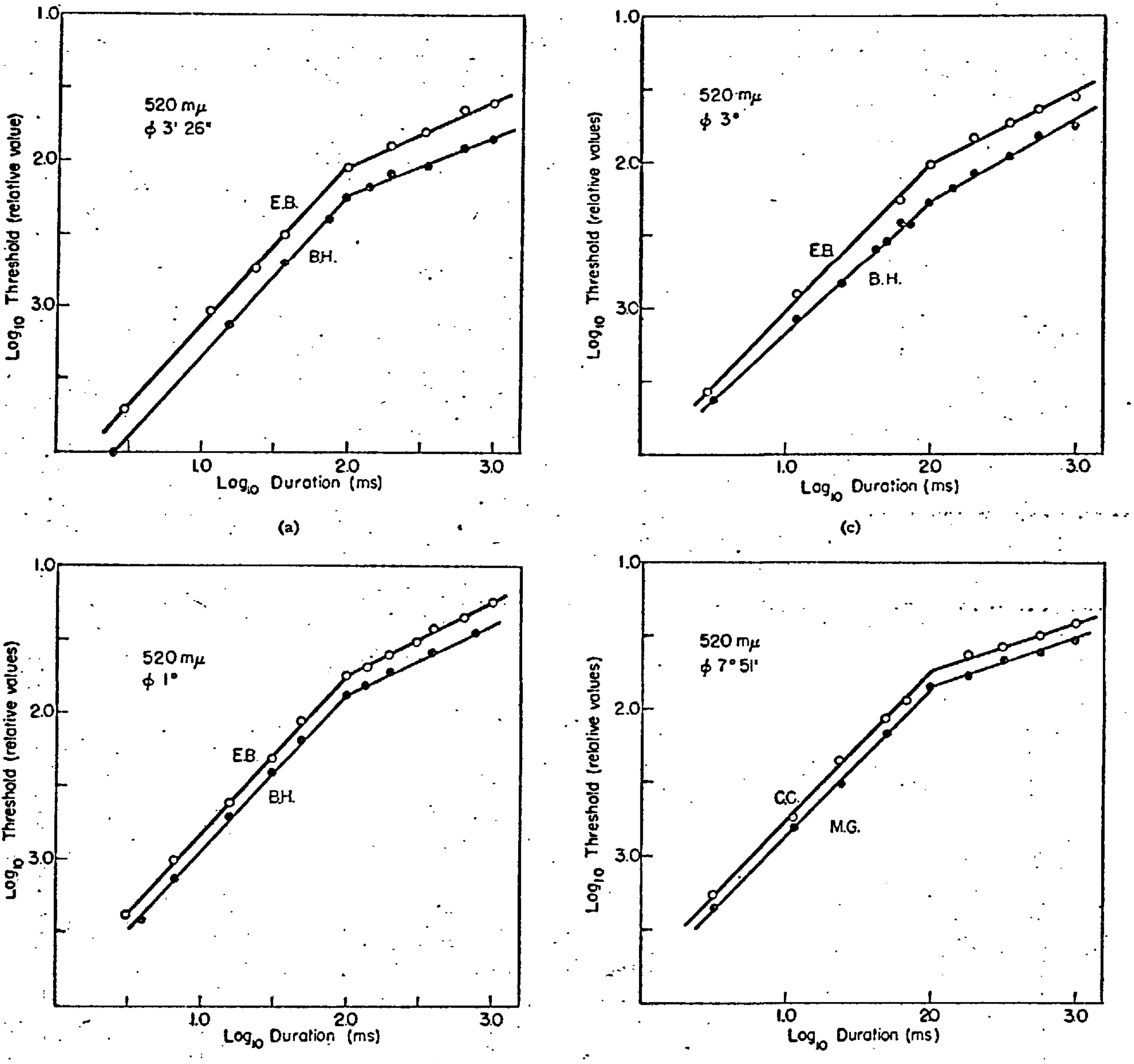


Fig. 90. (a)–(d). The intensity-time relation for four test sizes at 520 mμ. Subjects are identified by initials beside their respective data. (BAUMGARDT and HILLMAN)

Ø is the angular subtense of the test flash.

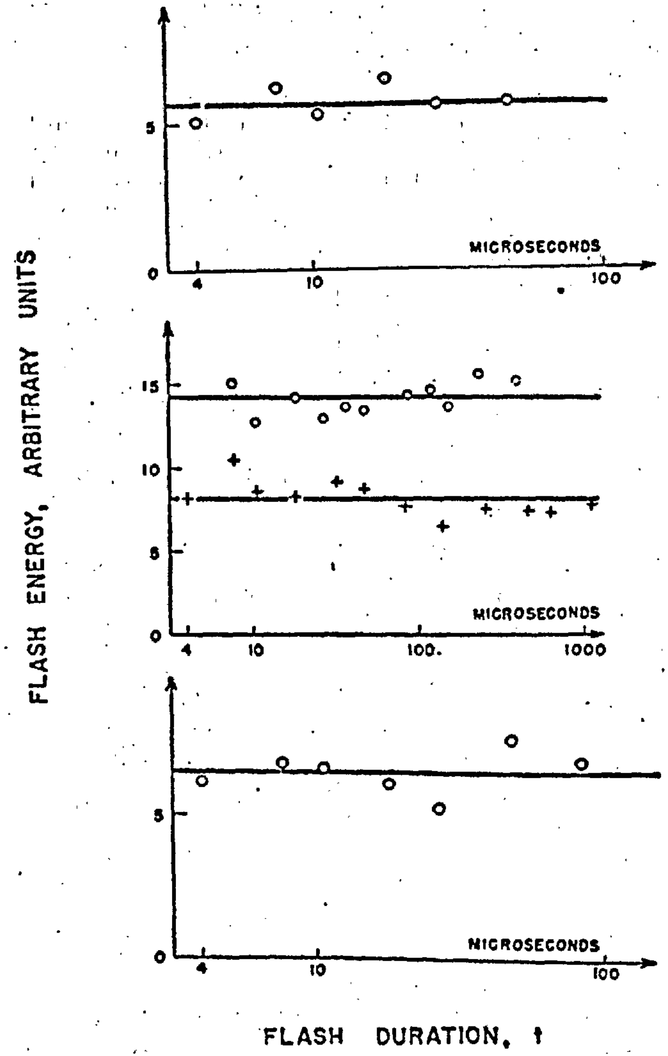


Figure 91. Flash energy required for threshold excitation 12° from the fovea as a function of flash duration, *t*, for values of *t* between 4 microseconds and 1 millisecond. Data for four observers. (Baumgardt)

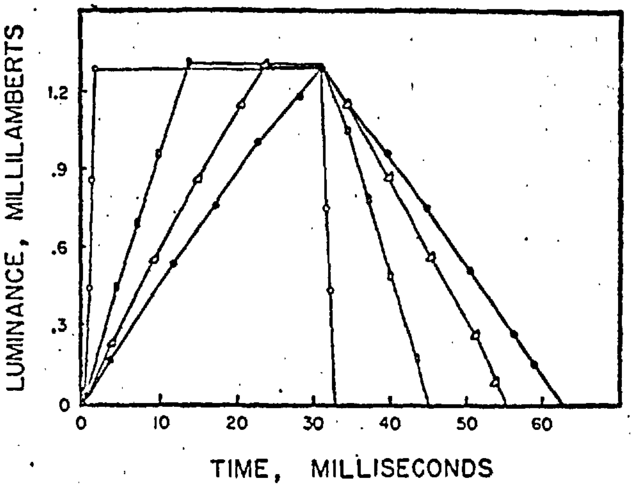


Figure 92a. Curves showing four of the seven wave forms used by Long in determining the relation between wave form of a flash and effective intensity. The wave forms are so designed as to provide equal total flash energies.

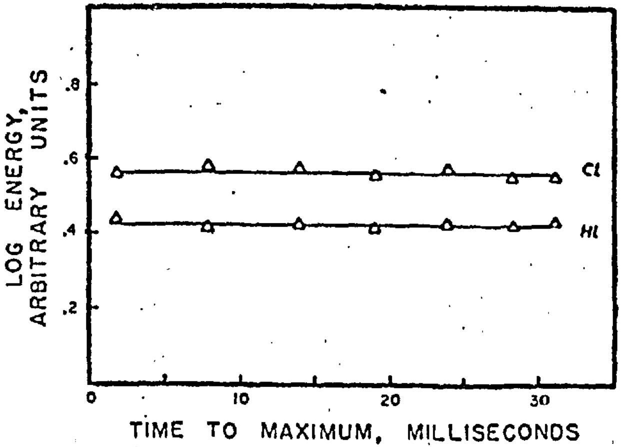


Figure 92b. Flash energy required for threshold excitation for flashes of seven wave forms (four of them shown in Fig. 5) by two observers. The seven wave forms are distinguished by the time required for the intensity to rise to a maximum. (Long).

from It = const. to I = const. with small field sizes (2') and a more gradual increase in the threshold energy for larger stimulus sizes (1° and 3°). Karn (1936, fig. 85) obtained similar results in central fixation. These findings are in agreement with the fairly abrupt transition found by Hartline (1934) in the discharge of impulses in a single fibre of the optic nerve of Limulus at the critical duration. The authors have interpreted the effect of area in masking this critical duration as due to "the statistical distribution of properties among a large number of sense cells, and to the increased interaction effects associated with large areas". Graham and Kemp (1938, fig. 86) however, in their experiments on brightness discrimination, obtained a fairly sharp transition for a larger area of stimulation in central fixation (84' field with the incremental brightness added to half the field), but in line with earlier observations by McDougall (1904) and by Graham and Cook (1937), found that the critical duration decreased with increase in intensity. Galifret and Pieron (1946) represented their results over a limited range by an expression of the type

$$It^{n} = \text{constant} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (34)$$

where the value of the exponent n varies with the retinal location, being 2/3 for all wavelengths at the fovea. Rouse (1952) also demonstrated the absence of any effect with wavelength, but obtained a sharp transition from I = const. to It = const. in central fixation with an adaptation brightness just above the cone threshold.

More complete investigations of the interdependence of spatial and temporal summation have been made by Bouman (1950, 1952) and

Barlow (1958, fig. 87) at about 7° eccentricity; apart from showing that critical duration decreases with high luminance and large area of stimulus, an examination of their results would indicate a relatively sharper transition to a constant threshold value with large size stimuli as compared with the results of Graham and Margaria. Similar remarks would apply to the results of Blackwell and McCready (1958, fig. 88) in central vision, as opposed to those of Karn. Using fairly large centrally fixated fields of angular subtense 1°20', 5° and 19°, and surround luminances from log L = 3.48 to -3.02 mL, Biersdorf (1955) found a relatively sharp transition to a constant threshold under all conditions, regardless of field size and luminance level, and obtained critical durations, depending on field size, ranging from 0.02 - 0.06 sec. at high luminances to 0.20 - 0.34 sec. at scotopic luminance levels (fig. 89). Luizov (1958) using 5.5' fields obtained results fully confirming the Blondel-Rey law. Baumgardt and Hillmann (1961) repeated the experiment of Graham and Margaria at 20° eccentricity and with near monochromatic light of wavelengths 520 nm. and 692 nm. and obtained a sharp transition from It = const. to It^n = const. at about 100 ms. where $n = \frac{1}{2}$ for small fields and $\frac{1}{3}$ for the largest field used (fig. 90); they ascribe the discrepancy between their own observations and those of Graham and Margaria to the fact that these authors used white light, but the close agreement between their own results at the two wavelengths would hardly make this a plausible explanation. The work of Glezer (1965) has generally confirmed the findings of Bouman and Barlow.

It may be of interest to enquire what happens at very short flash durations and when the wave-form of the flash is not square. Beams (1934), Brindley (1952) and Baumgardt (1949, fig. 91) have experimented with flashes down to 10^{-8} sec. duration and all agree in finding that the visual response depends only on the total amount of light in the flash and is independent of the flash duration. Long (1951) investigated the nature of the pulse shape (fig. 92) on the threshold and found that the latter depended only on the total energy in the flash and not on its distribution in time, provided the flash duration was below the Bloch summation time. The related work of Davy (1952, p. 74) extended these conclusions to multiple flashes.

Summation in the incremental threshold against backgrounds of high luminance.

An attempt was made at finding out to what extent the summation laws held against backgrounds of high luminance. The threshold was measured with stimuli of different diameters (2' to 32') against a background of 1000 trolands (a) at eccentricities of 0°, 5°, 10° with a constant flash duration and (b) with different flash durations at 0° and 5° eccentricity. Some results obtained by the author with the earlier form of the apparatus are given in fig. 93 - 94, 96 - 99, fig. 97 and 99 being derived from the curves of fig. 96 and 97 respectively; fig. 95 is from a more recent experiment by JKW.

To what extent the curves for spatial summation may be considered to be made up of two linear parts as would be indicated by fig. 94 is difficult to say; similar pairs of straight lines could possibly have been drawn in many cases in fig. 96, 98, and on this issue the

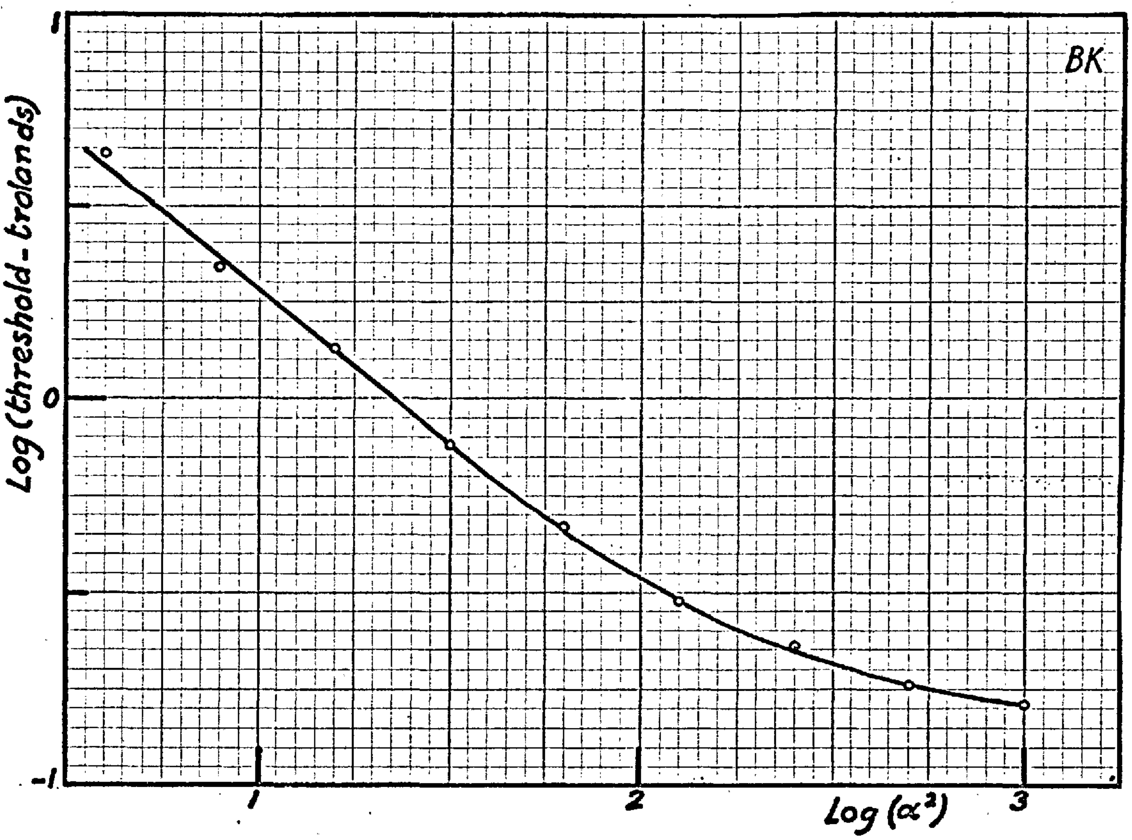


Fig. 93. Variation of threshold with area of test-field for a white test flash (t = 100ms, n = 1 c.p.s.) viewed against a dark background in central fixation. α is the angular subtense of the test flash.

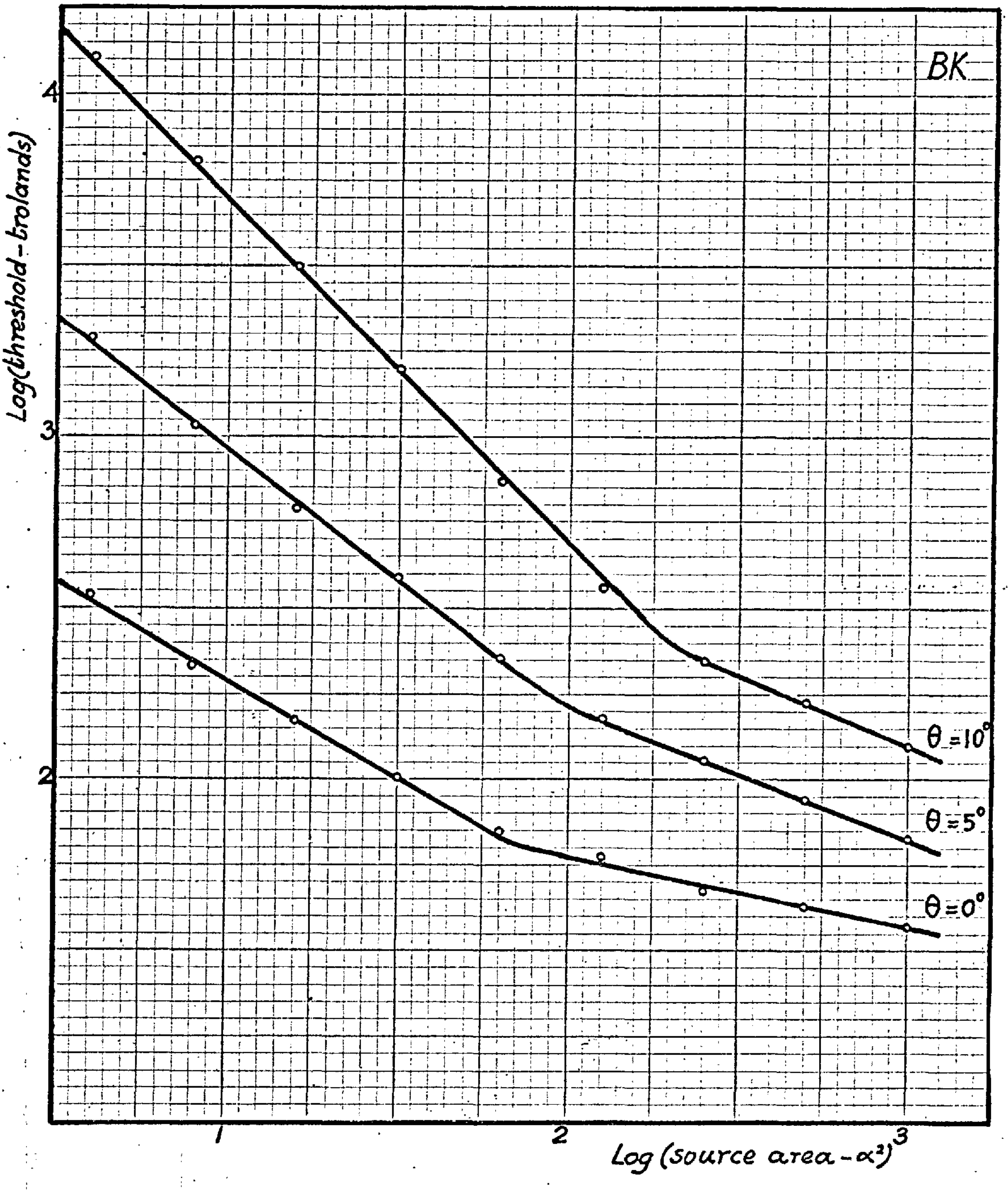


Fig. 94. Variation of threshold with source area for a white test flash (t = 100 ms, n = 1 c.p.s.) viewed against a background of 1000 trolands, at different eccentricities θ° (temporal retina).

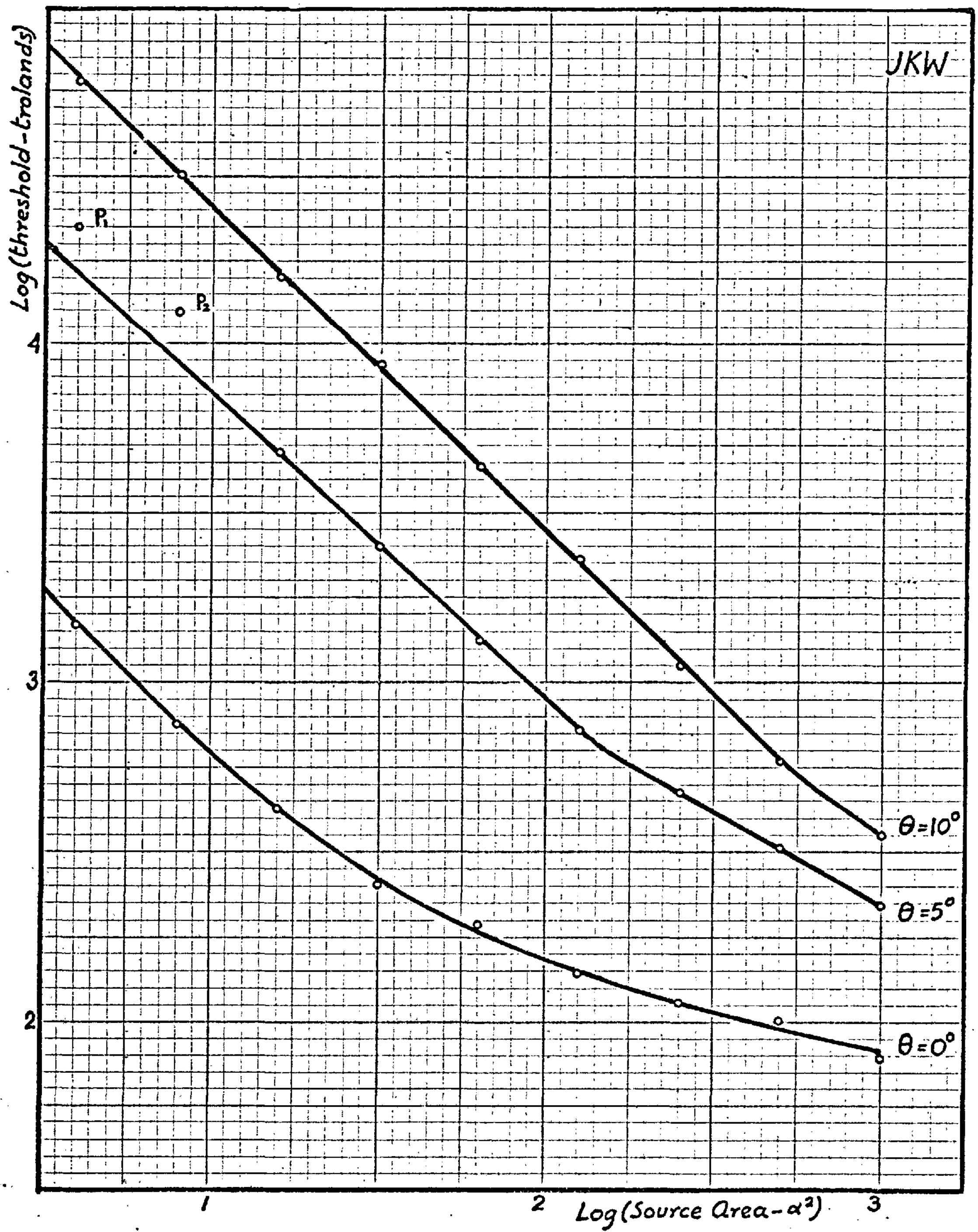


Fig. 95. Variation of threshold with source area for a white test flash ($t = 20$ ms, $n = \frac{1}{2}$ c.p.s.) viewed against a background of 1000 trolands, at different eccentricities θ (nasal retina)

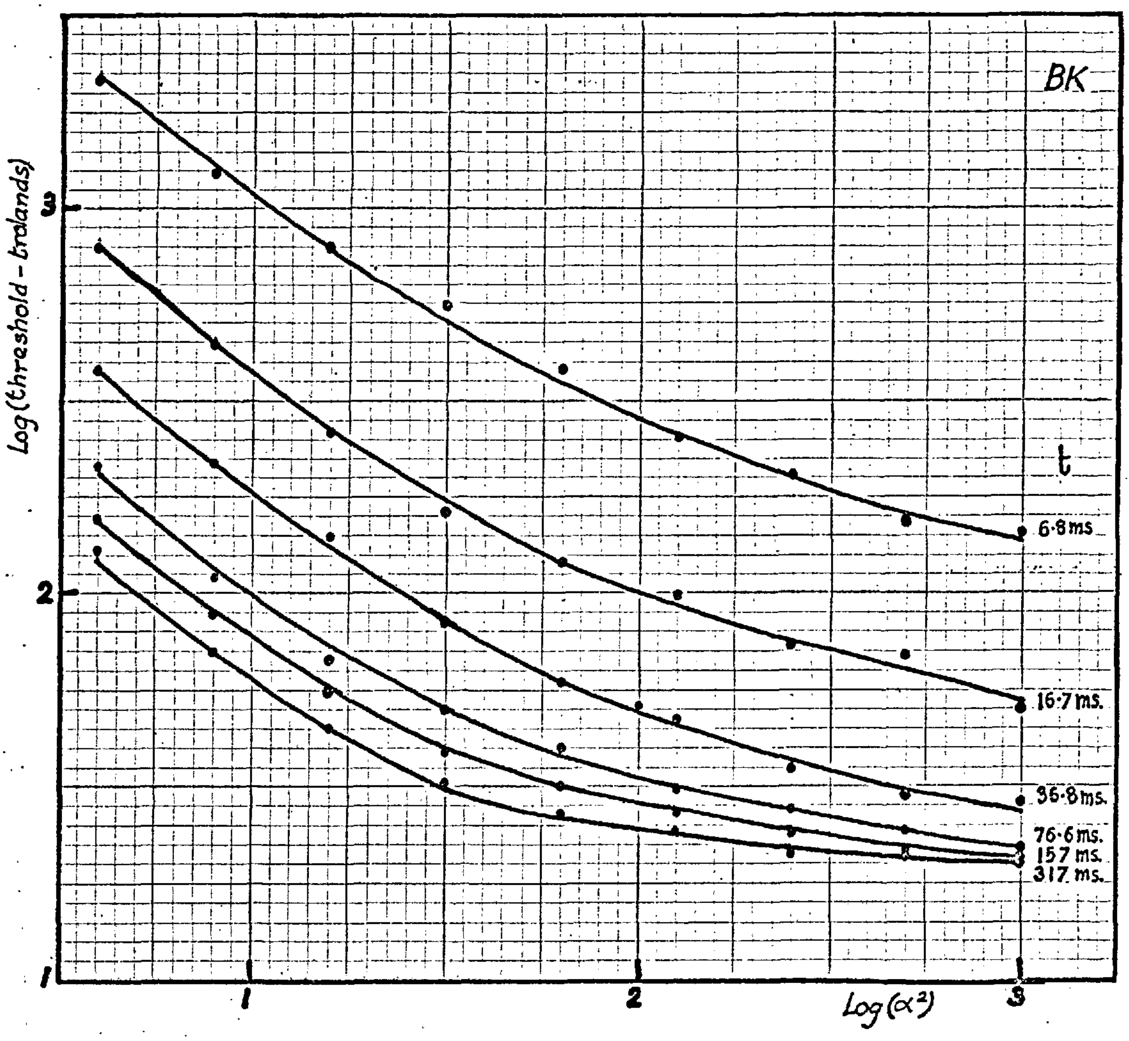


Fig. 96. Variation of threshold with source area for white test flashes of duration t viewed against a background of 1000 trolands in central fixation (n = 1 c.p.s.)

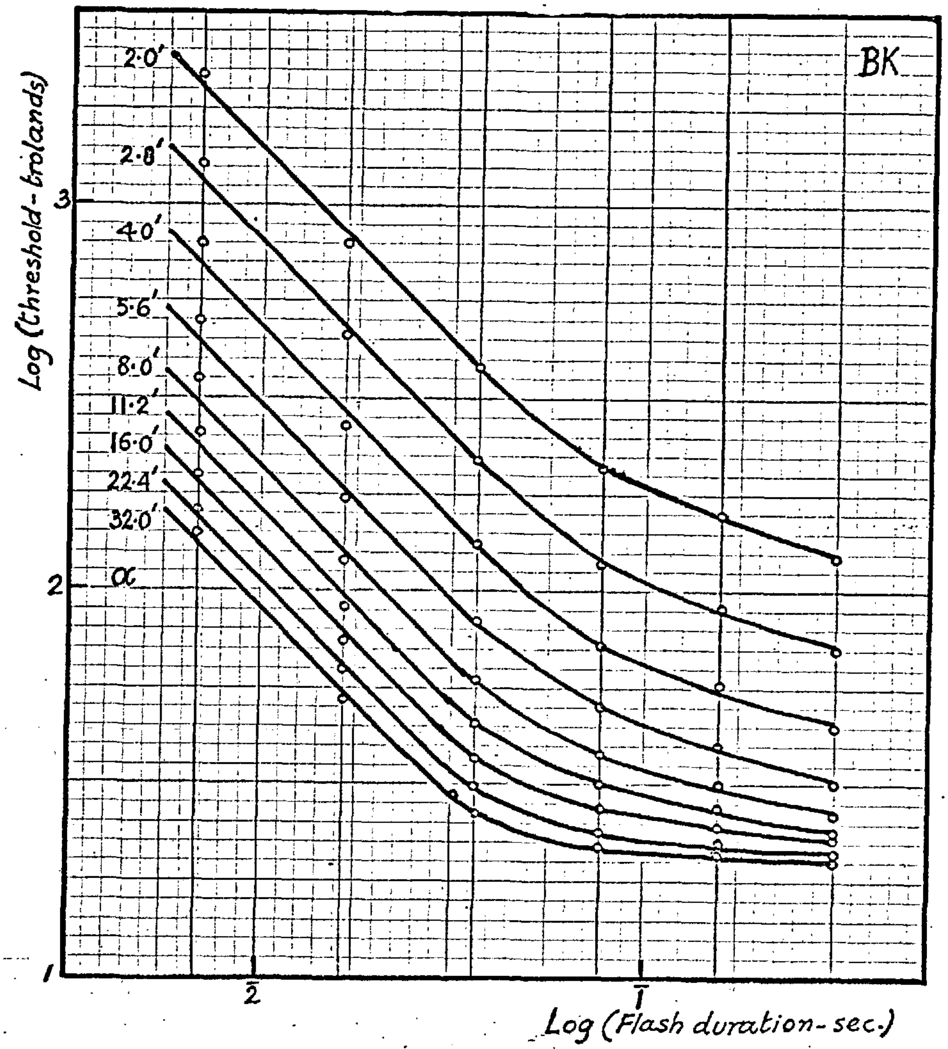


Fig. 97. Variation of threshold with flash duration for white flashes of angular subtense α viewed against a background of 1000 trolands in central fixation (n = 1 c.p.s.)

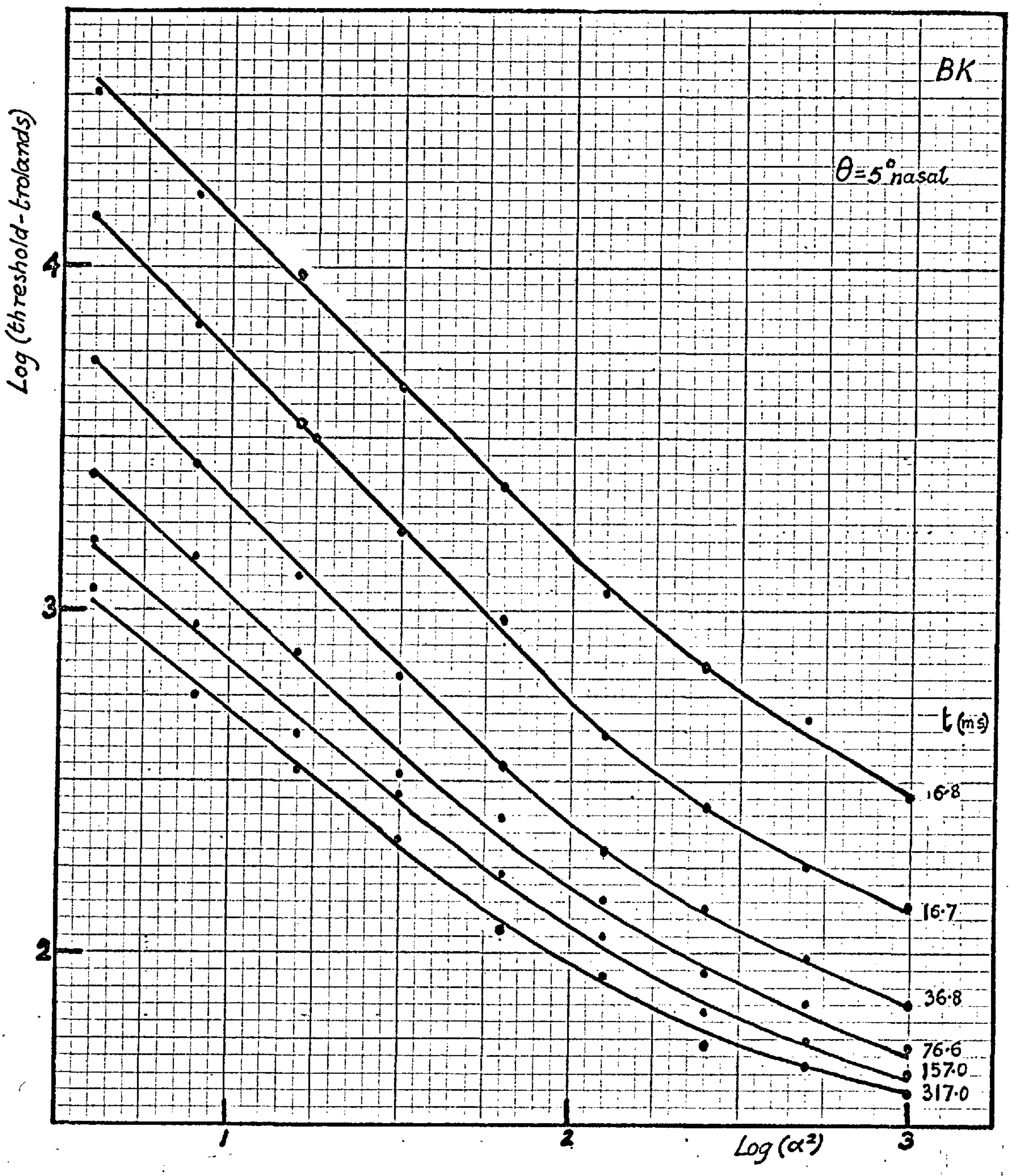


Fig. 98. Variation of threshold with source area for white test flashes of duration t viewed against a background of 1000 trolands at 5° eccentricity (nasal retina); (n = 1 c.p.s.)

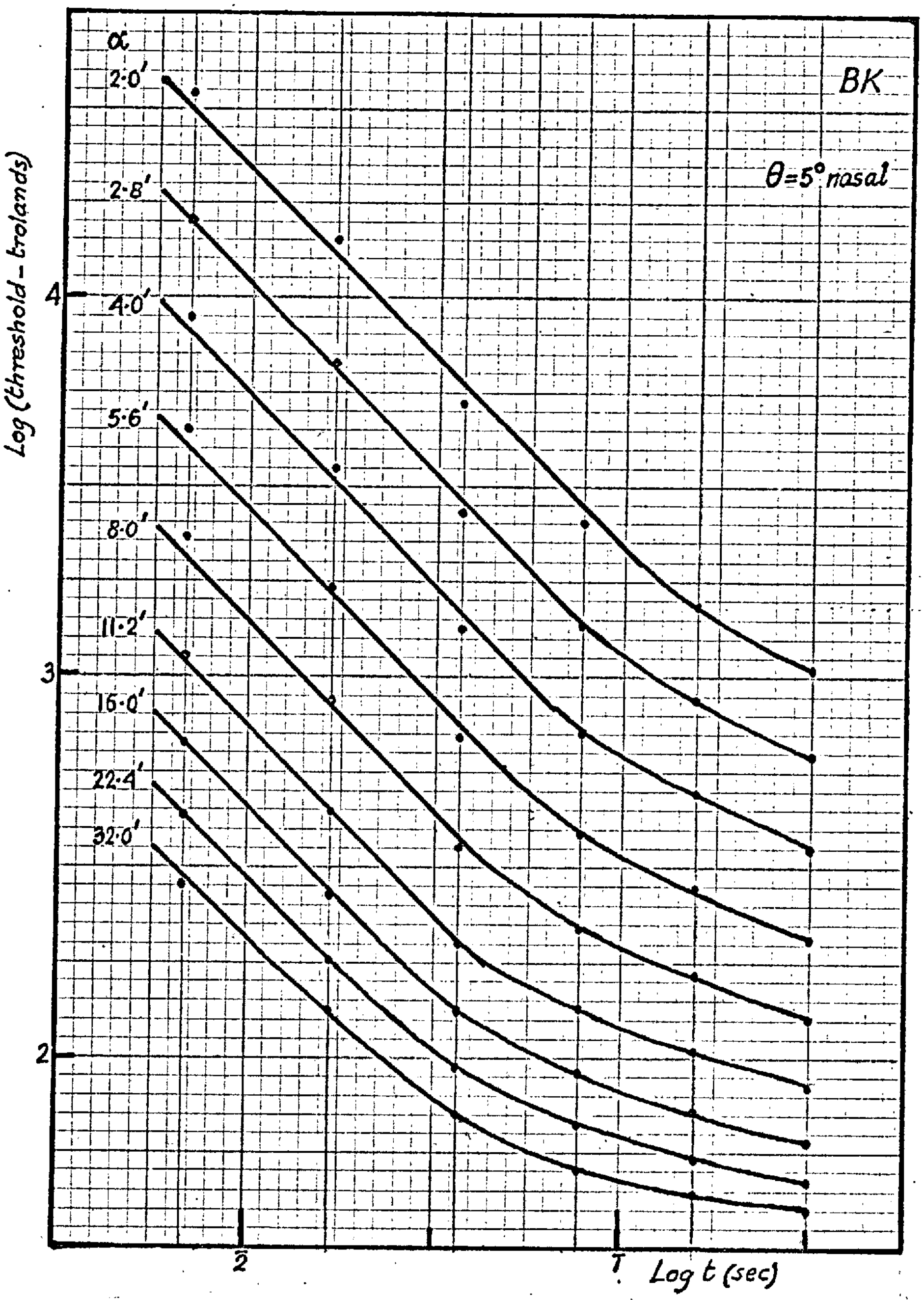


Fig. 99. Variation of threshold with flash duration for white flashes of angular subtense α, viewed against a background of 1000 trolands at 5° eccentricity (nasal retina), n = 1 c.p.s.

experiment is indecisive. The results would indicate however that complete spatial summation (slope of -1) does not occur in central fixation under any state of adaptation (cf. p.83,187) with the field sizes used; the Ricco' area must be less than 2' in diameter. Away from the visual axis, the degree of summation increases with eccentricity (fig. 94-95.) and at 10° eccentricity near complete summation may be occurring with angular subtenses of 10' - 20' according to the flash duration employed. The dependence of the degree of area summation upon the duration of the flash is clearly shown in fig. 96 and 98; at 5° eccentricity, area summation may be near complete up to α = 10' at the two shortest flash durations used, but the slopes of the curves are less than unity for the longer flashes.

On the other hand, fig. 97 and 99 would indicate a reasonably well defined slope of -1 for the temporal summation. The degree of summation decreases with increase in the field size and the transition to a constant threshold tends to become relatively sharper at larger field sizes (cf. fig. 87a, 88). There is also some indication that more summation may be occurring off axis than in central fixation. One of the aims of the experiment had been to find out whether the Blondel-Rey law was applicable to incremental thresholds against backgrounds of high luminance; in view of the change in the value of the constant $\underline{a}$ of the Blondel-Rey equation with increase in intensity, very little complete summation might have been expected at the background luminance used here (fig. 84), and the result of the experiment was rather surprising. The manner in which Blondel and Rey's results were arrived at by averaging the data for 17 observers (p.34) would no doubt smooth out observer differences, but this would be hardly likely to account for the discrepancies observed. Before passing on to what may have been a major cause of disagreement, some other factors which may conceivably influence threshold determinations and which came to light during the course of the above experiments may be mentioned.

In fig. 95, the two points P_1 and P_2 at small field sizes are well off the curve; in a repeat experiment at the same eccentricity, this observer obtained four points on a well defined straight line of slope about - 1.3 at the smallest field sizes. This was traced to the image of the source falling upon a small blood vessel, thereby raising the threshold. As the size of the stimulus is increased relative to that of the blood vessel the curve approaches the correct gradient. It does not seem unlikely that the result reported by de Groot et al (p.53) may be of similar origin. Under normal circumstances, one is not conscious of the presence of the vascular system owing to the fading of the stabilised image and possibly some degree of "psychological filling-in" (see below), but they may seriously interfere with threshold determinations, especially with small test fields. One experiment which was performed was the following:

A test field of about 40' to 60' angular diameter (λ = 443 nm) was viewed in central fixation with the dark-adapted eye and the luminance adjusted to be somewhat below the threshold. Keeping the luminance constant, the size of the field was increased to 10°-12°

when the whole field appeared filled uniformly with light with the colour appearance characteristic of scotopic vision. With a 1° field very little spatial summation would occur in the centre of the field so that area summation effects cannot explain the bright appearance there. Besides, a dark disc of 1° diameter introduced into the centre of the field was quite invisible whereas a larger opaque disc of about 2°- 3° diameter such that the edge of the disc is at a position in the field where the background luminance is above the visual threshold (see fig. 75) is clearly seen. Fixating on the edge of the 12° field still gives the appearance of a disc of light, though the edge may be slightly blurred near the point of fixation. This would clearly indicate that there is some "psychological" filling-in process by which the centre of the field appears luminous when the stimulation is subliminal or even when there is no stimulation at all, and which also fills up the contour of the test object when over a certain region of this contour the light stimulus is insufficient for perception. A similar explanation is generally given for the failure of the optic disc to appear in ordinary vision. Schaeffer (1915) had made the observation that a white spot viewed foveally but too feebly illuminated to stimulate the cones is not seen as black, but is not seen at all. It would appear therefore that with large test fields it is the contrast at the edge over the greater part of the field which may determine what is perceived when the stimulation is subliminal at other regions within the area considered. Caution must therefore be exercised in interpreting the results obtained with large test fields in terms of spatial summation, and similar remarks would apply even with smaller fields in the presence of small scotomata. It may be interesting to speculate on the role played by spatial and temporal facilitation as studied by Van den Brink (1964) and by van den Brink and Reijntjies (1965) in visual perception under such conditions.

In the experiments described in chapter V (fig. 57-60, 68-76) with white and coloured stimuli, there is very little difference in the threshold on axis against backgrounds of 0 and 1 troland, yet such small differences as have been obtained would generally indicate that this threshold is lower in mesopic vision than in the dark-adapted eye. This may be an artefact of the technique of measurement, but if the threshold at the very centre of the field is independent of the background luminance over the range considered, the subliminal luminance of the background of 1 troland may add up to that of the test stimulus to give an effectively lower threshold than in dark adaptation.

Eye movements and threshold determinations, temporal summation.

The study of eye movements can be traced back almost a century and a condensed summary of earlier work has been given by Lord and Wright (1950). These investigators used a system developed by Lord (1948) in which an ultra-violet beam reflected from the cornea is partially intercepted by a straight edge and eye movements are detected by measuring the amount of radiation passing the straight edge with a photo-multiplier coupled to an oscilloscope (1948, 1949). Subsequent investigations using a beam of light reflected from a mirror fixed to a contact lens or cap fitting over the cornea have been described by Ditchburn and Ginsborg (1952, 1953), Riggs, Armington and Ratliff (1954), Ditchburn (1955), Ditchburn and Fender

(1955), Yarbus (1965).

According to Ditchburn (1955) even when a subject is fixating as steadily as possible on a well defined point, the following eye movements occur:

i.) a rapid tremor of frequency 30 to 80 c.p.s. which vibrates the image with an anplitude of 5 to 15 seconds, approaching the intercone distance,

ii.) flicks at intervals from 0.03 to 5.0 sec, the amplitude ranging from 1 to 20 min. of arc.,

iii.) slow drifts up to 5 min. of arc during the interflick period.

The effects of these movements is to allow the image of the fixation point to wander over an area about 20' in diameter over the central region of the fovea; whereas the drifts are random, the flicks are corrective and tend to occur towards the centre. Further Riggs et al (1954) have shown that under good experimental conditions, the retinal image is virtually stationary up to 0.01 sec. duration. Intervals of 0.1 second entail an average displacement of about 25 sec. of arc and intervals of 1 second one of about 3 min. of arc.

In the experiments described in chapter V, the difficulty encountered by the observers in maintaining fixation has been described (p.183). In view of the magnitude of eye movements, it seems quite conceivable that when there exists a steep threshold gradient across the retina, threshold determinations may be appreciably in error owing to such movements. Under certain conditions, it was found that when an observer was rather tired, increasing the flash duration beyond about 0.2 second gave a steady downward drift in the threshold which was relatively constant in other determinations by the same observer. Longer flash durations, and fatigue on the part of the observer, would lead to more wandering of the fixation and to lower values of the threshold. Thresholds as determined with large test fields on the other hand would be less susceptible to errors due to unsteady fixation, and some of the results described earlier in this chapter show that with large fields a sharper transition from Lt = const. to L = const. may be obtained in temporal summation. It seemed plausible therefore that the transition was relatively sharp, but that in many experiments the effect had been masked by poor fixation. It may be noted that in his experiments on velocity discrimination, Brown (1955; fig. 25, p.77) attributed the absence of an abrupt change to eye movements which may have masked the critical duration. With proper precautions however (p.183) it seemed likely that errors due to drift in fixation could be reduced, and the experiments described below were performed.

Four observers obtained temporal summation curves under conditions approximating as closely as possible to the original Blondel-Rey experiment as the apparatus would allow: white test stimulus of 2' angular subtense viewed in central fixation by the dark adapted eye. The results (fig. 100) indicate complete summation up to about 0.1 second after which there is no significant change in the threshold except for BK, (cf. fig. 84). Observer PD, who was the least experienced in this type of work, seemed to find it relatively easier however to maintain fixation and therefore carried out measurements leading to

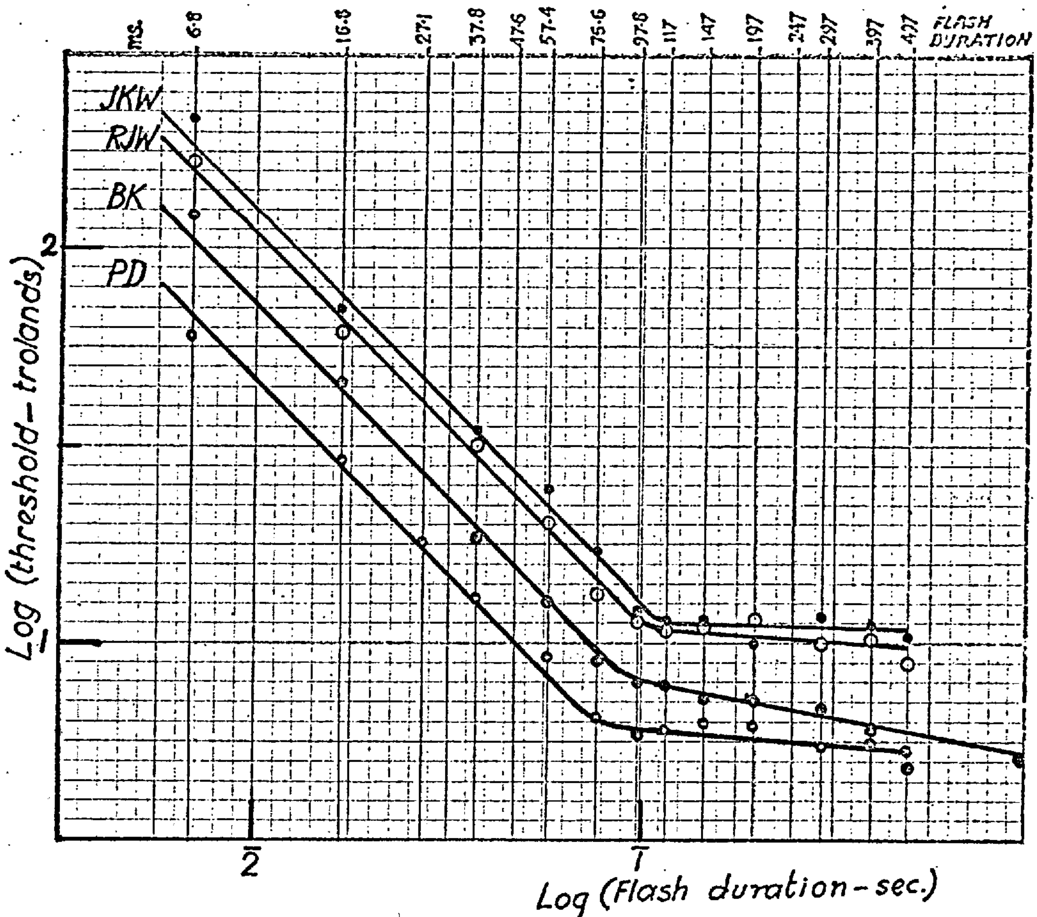


Fig. 100 Variation of threshold with flash duration in central fixation (B = 0, α = 2', θ = 0°).

In fig. 100-110, the colour of the test flash is white unless otherwise specified, and the symbols have the following meanings:

B = luminance of background (troland-value),
α = angular subtense of test-field (minutes of arc),
θ = eccentricity with visual axis (nasal retina),
t = flash duration.

The frequency of the flashes is ½ c.p.s.

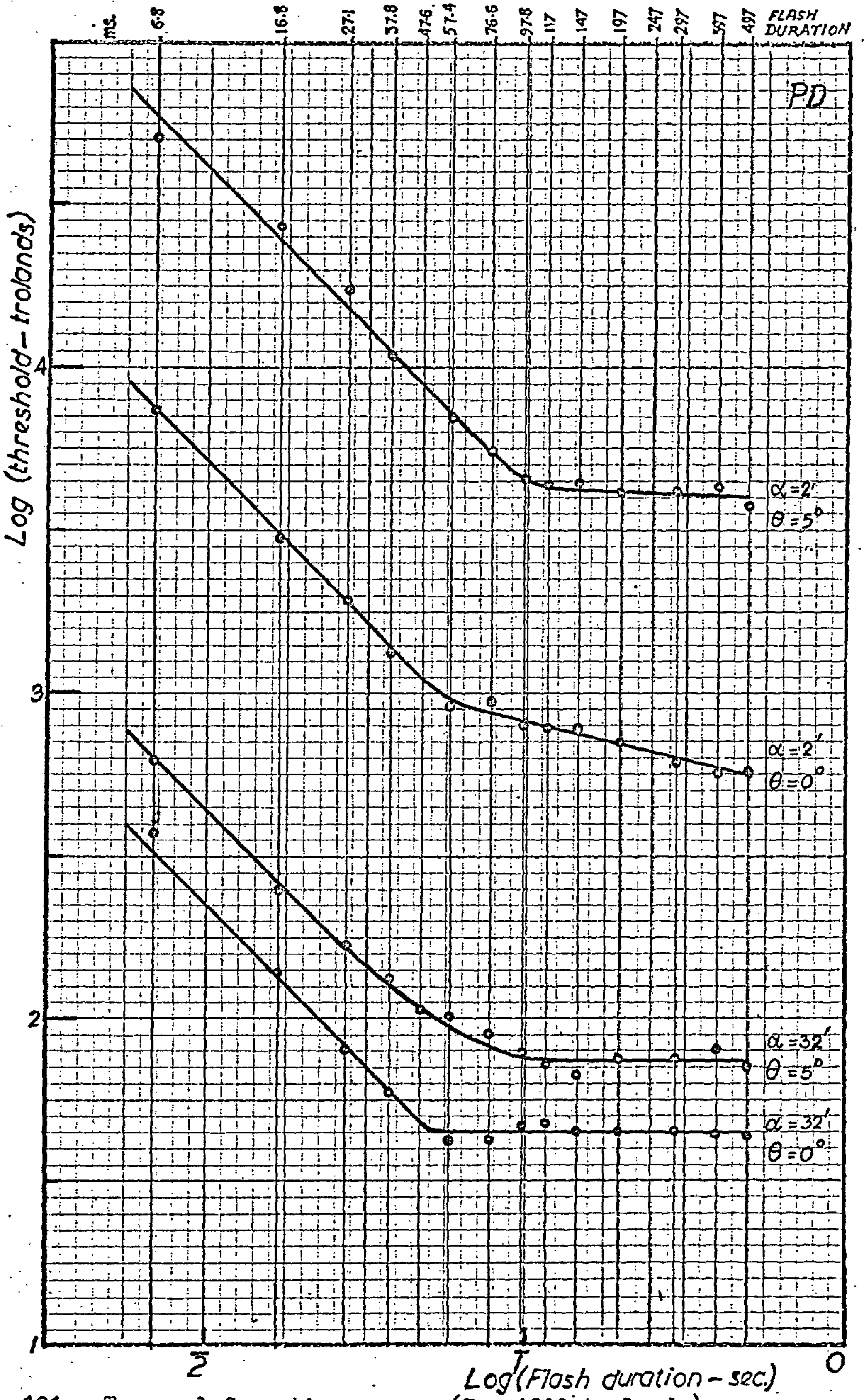


Fig. 101. Temporal Summation curves (B = 1000 trolands).

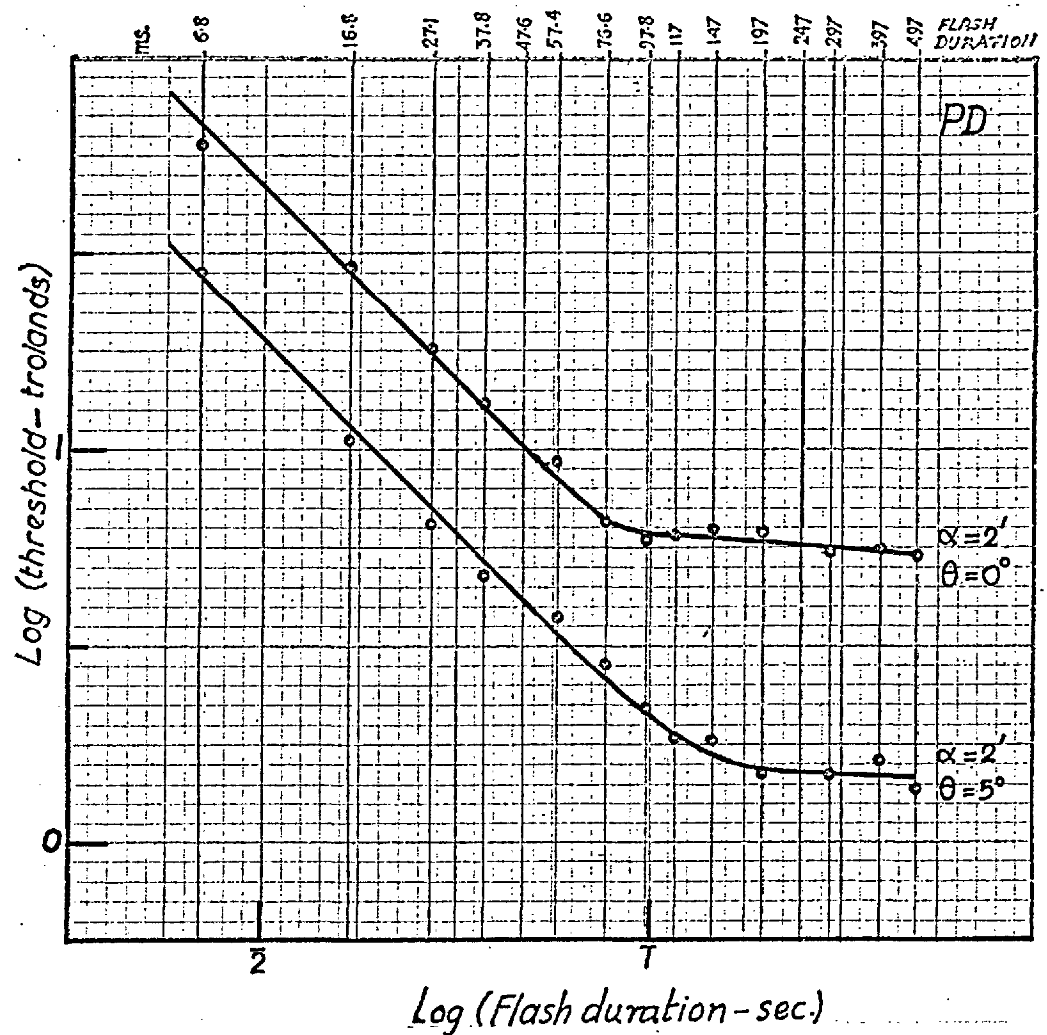


Fig. 102. Temporal summation in dark adaptation.

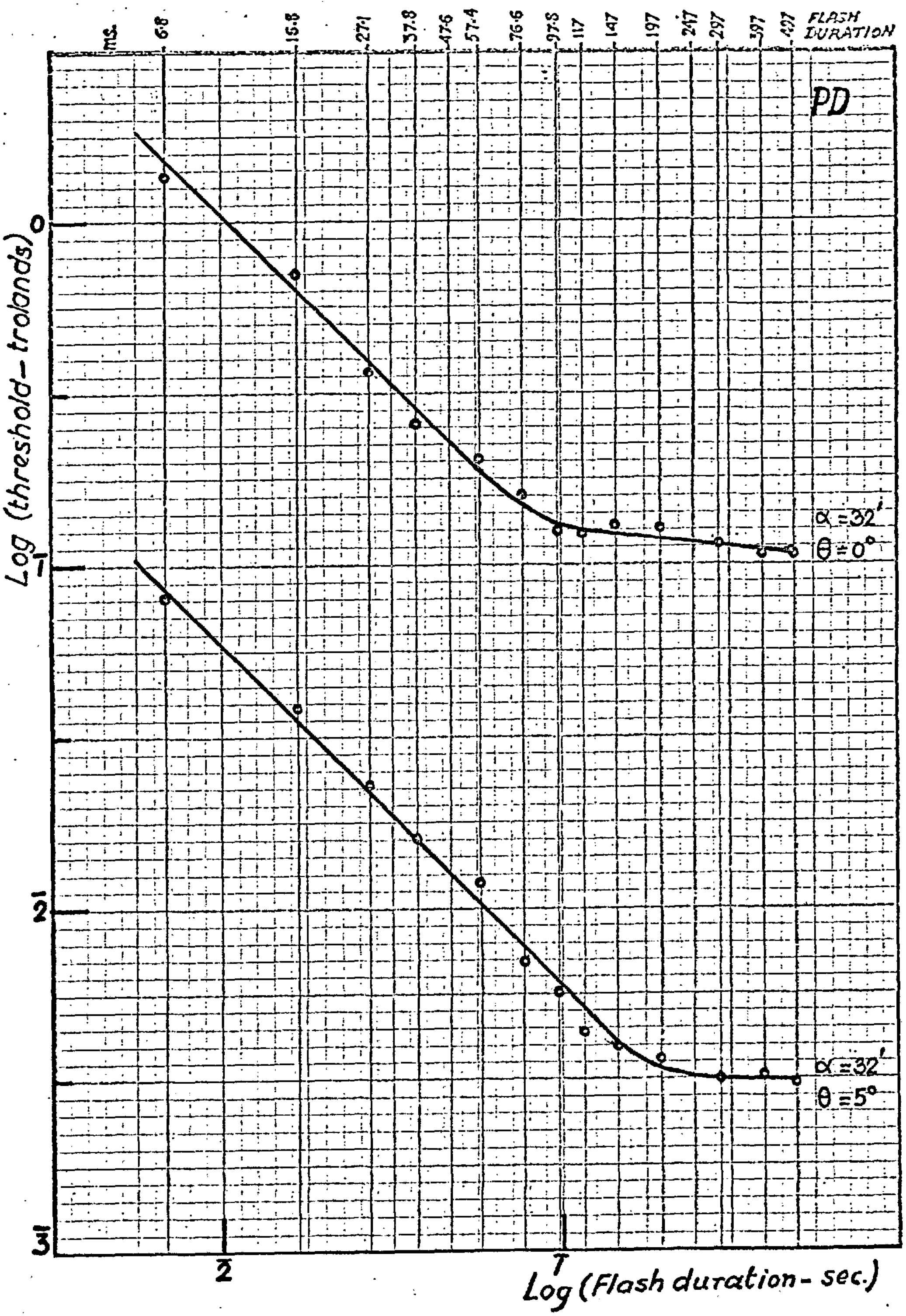


fig. 103. Temporal. summation in dark adaptation.

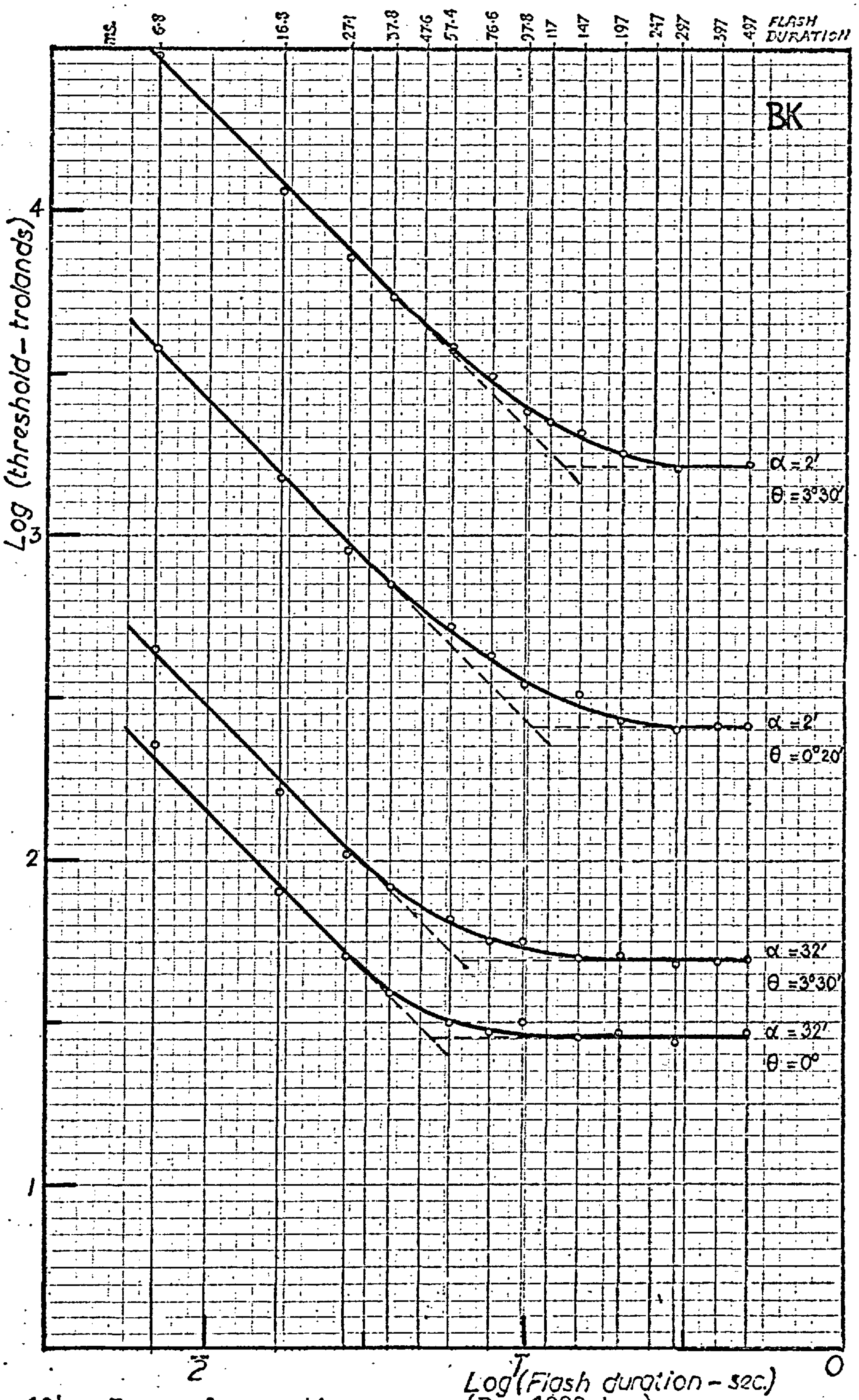


Fig. 104. Temporal summation curves (B = 1000 tr.)

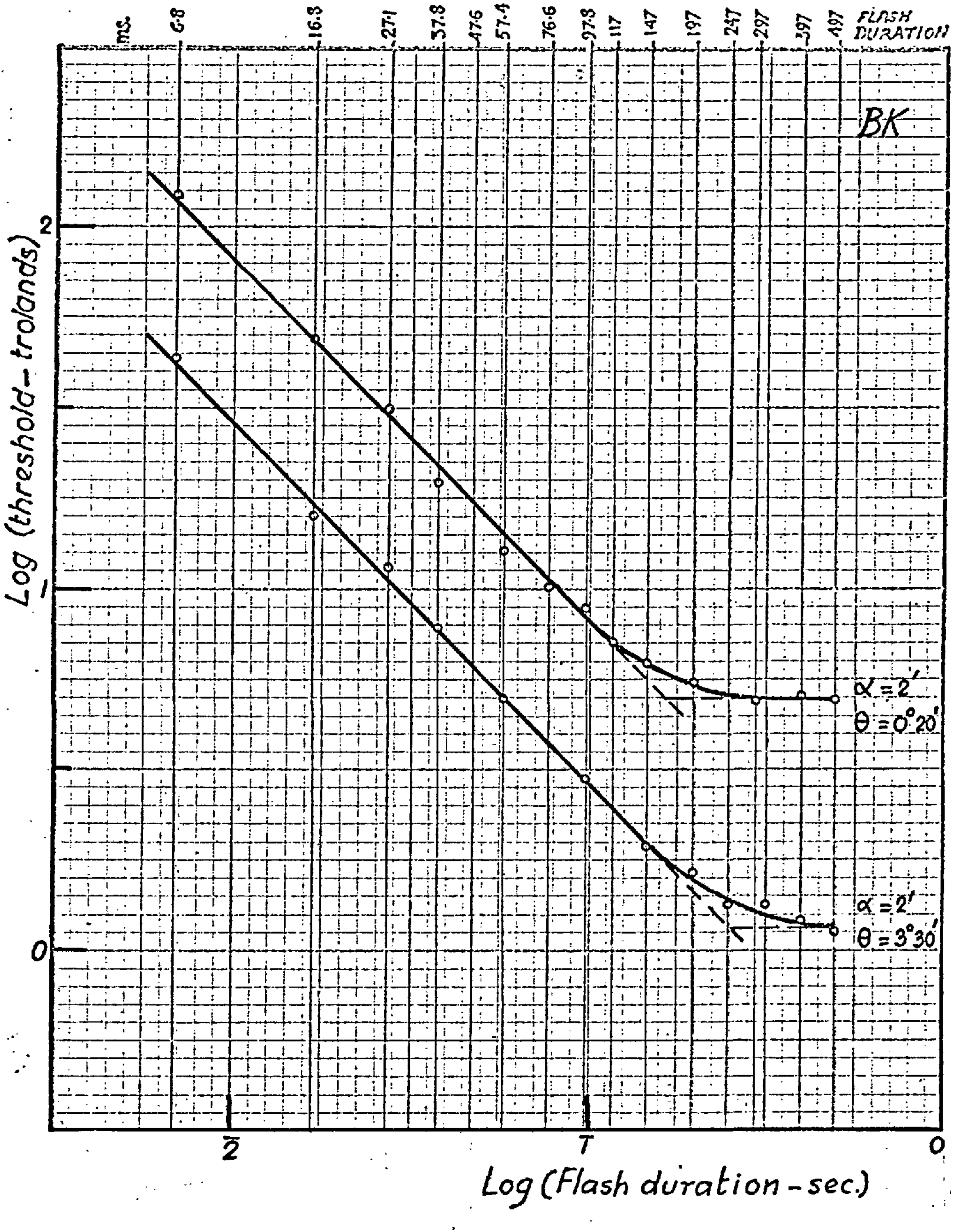


Fig. 105. Temporal summation in dark adaptation.

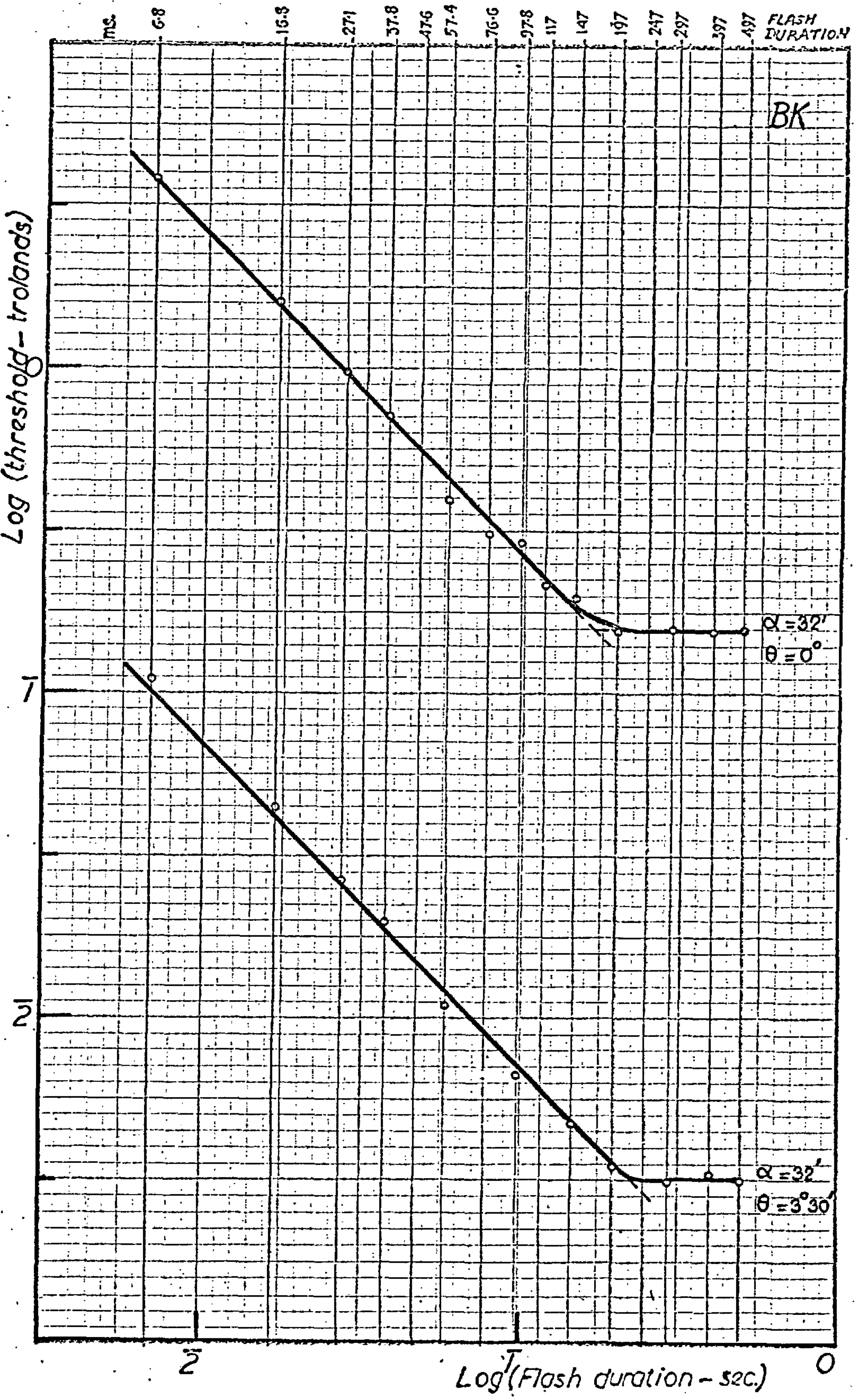


Fig. 106. Temporal summation in dark adaptation.

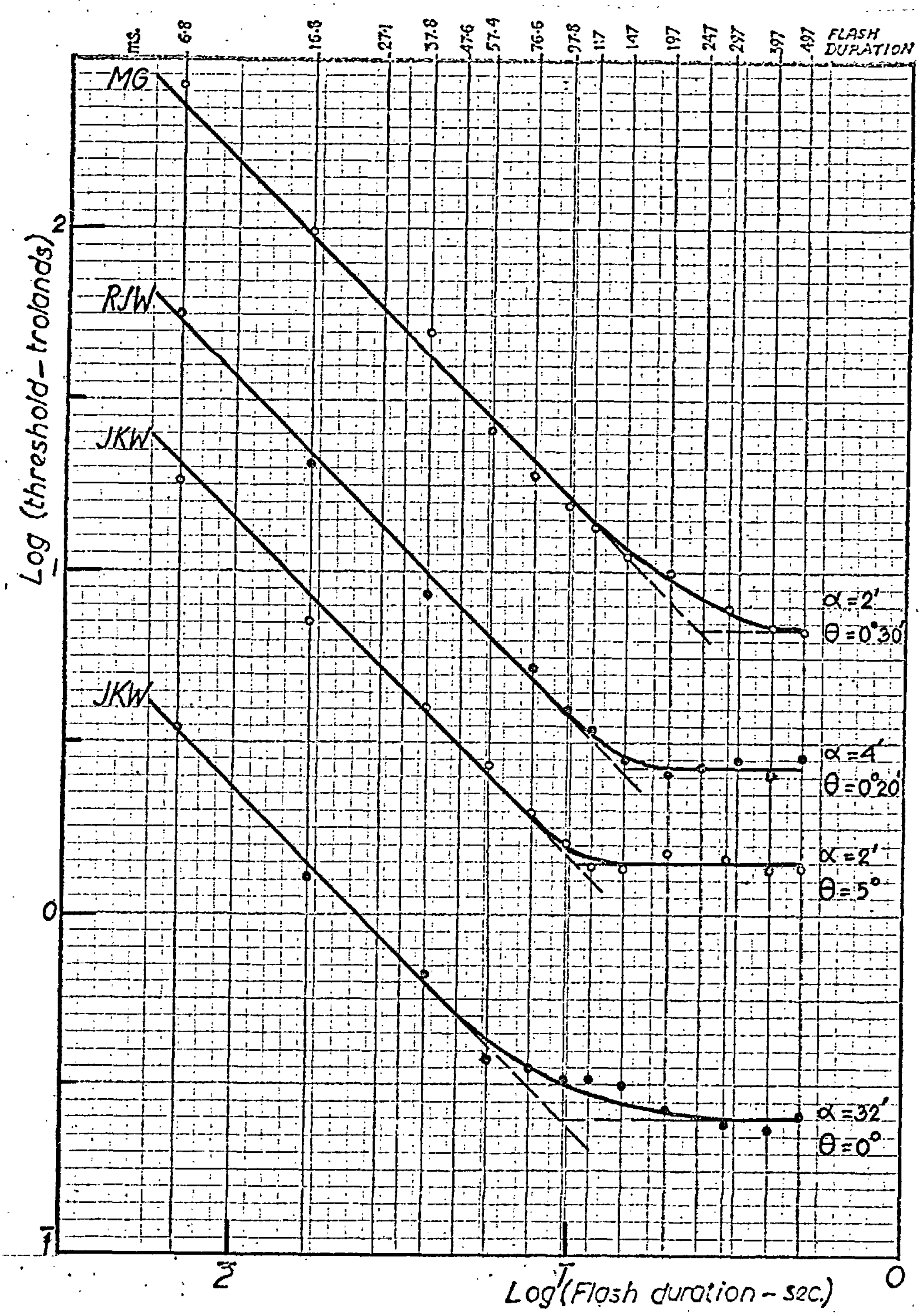


Fig. 107. Temporal summation in dark adaptation.

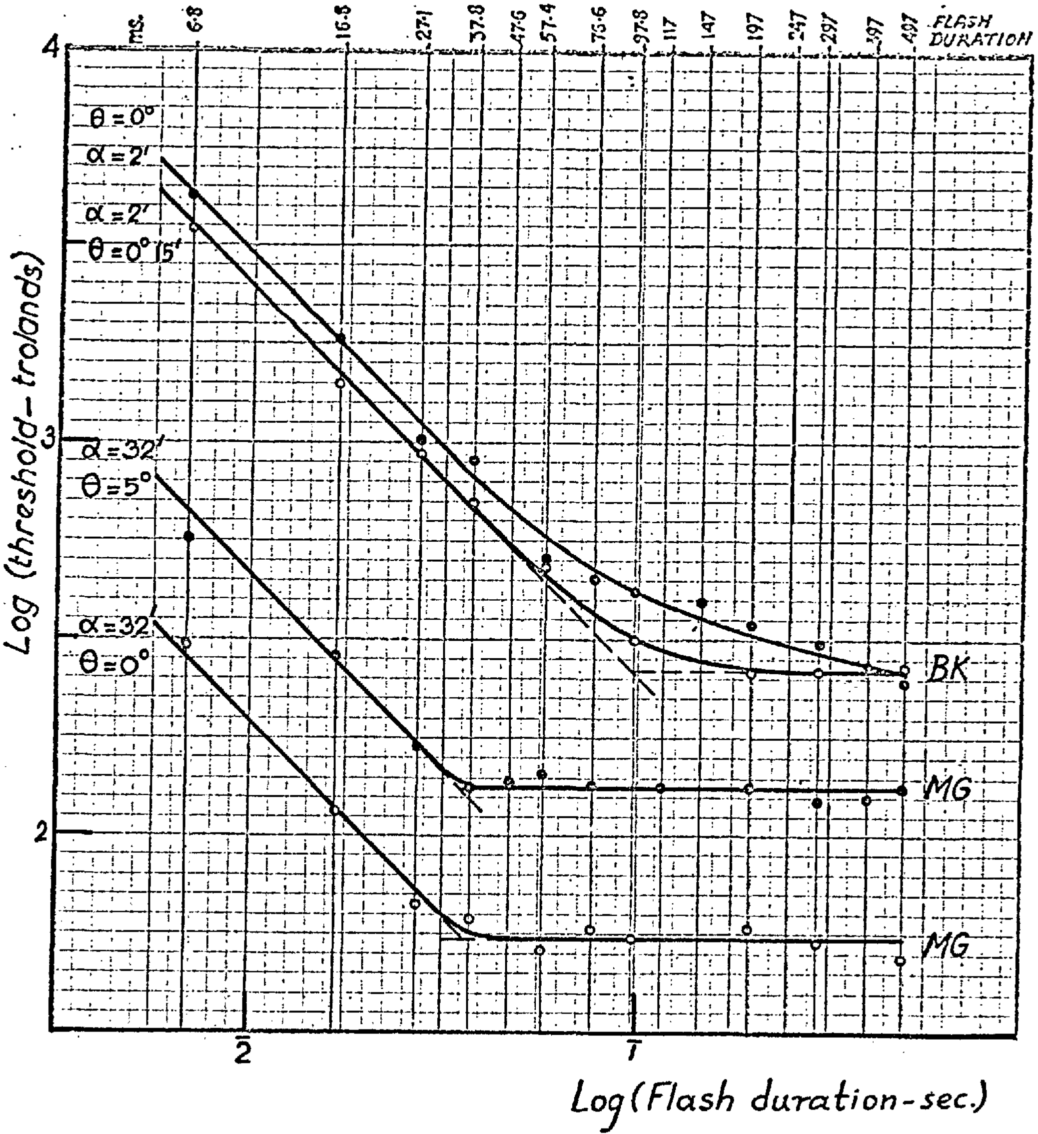


Fig. 108. Temporal summation curves (B = 1000 tr.)

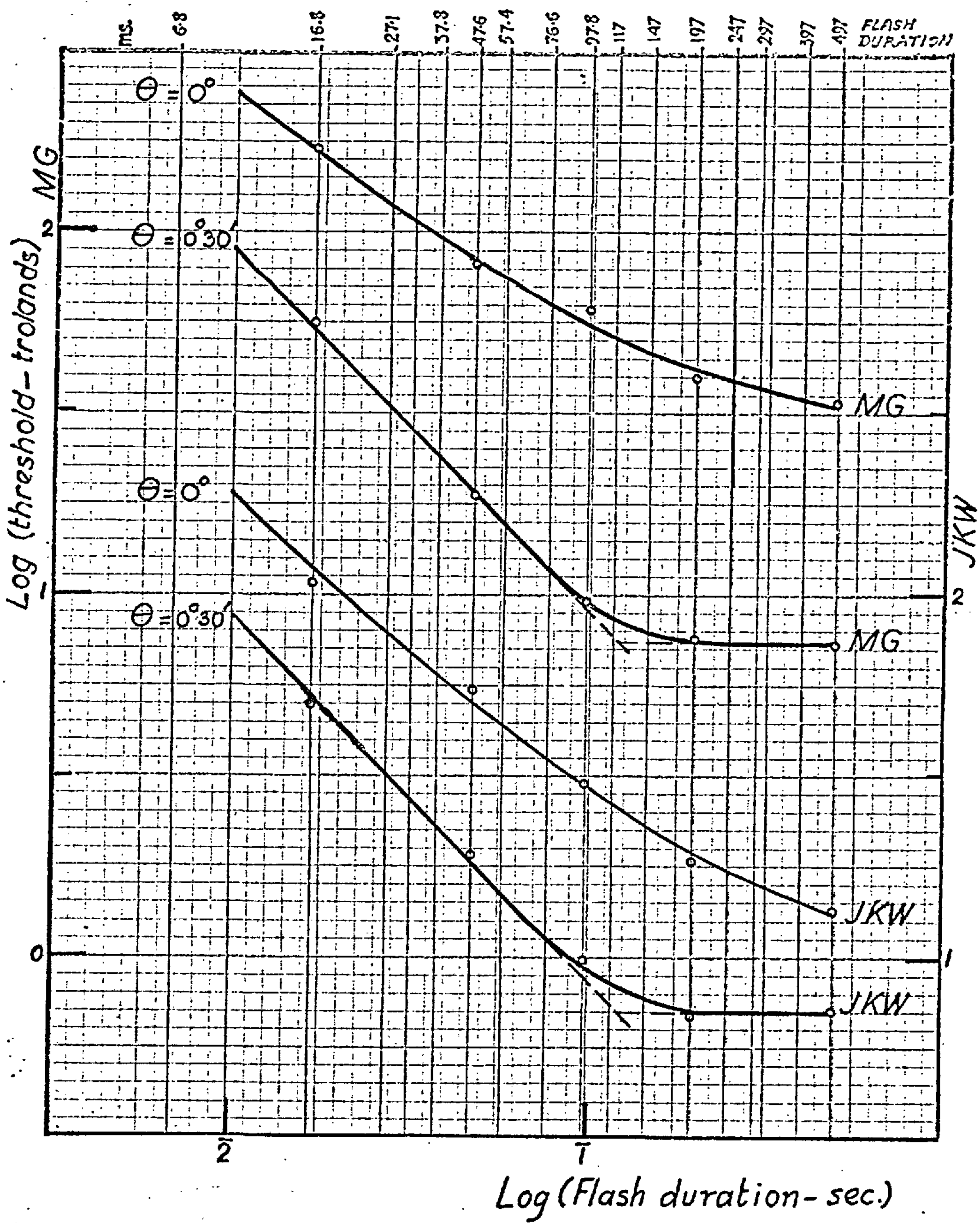


Fig. 109. Temporal summation curves in dark adaptation (α = 2')
See text.

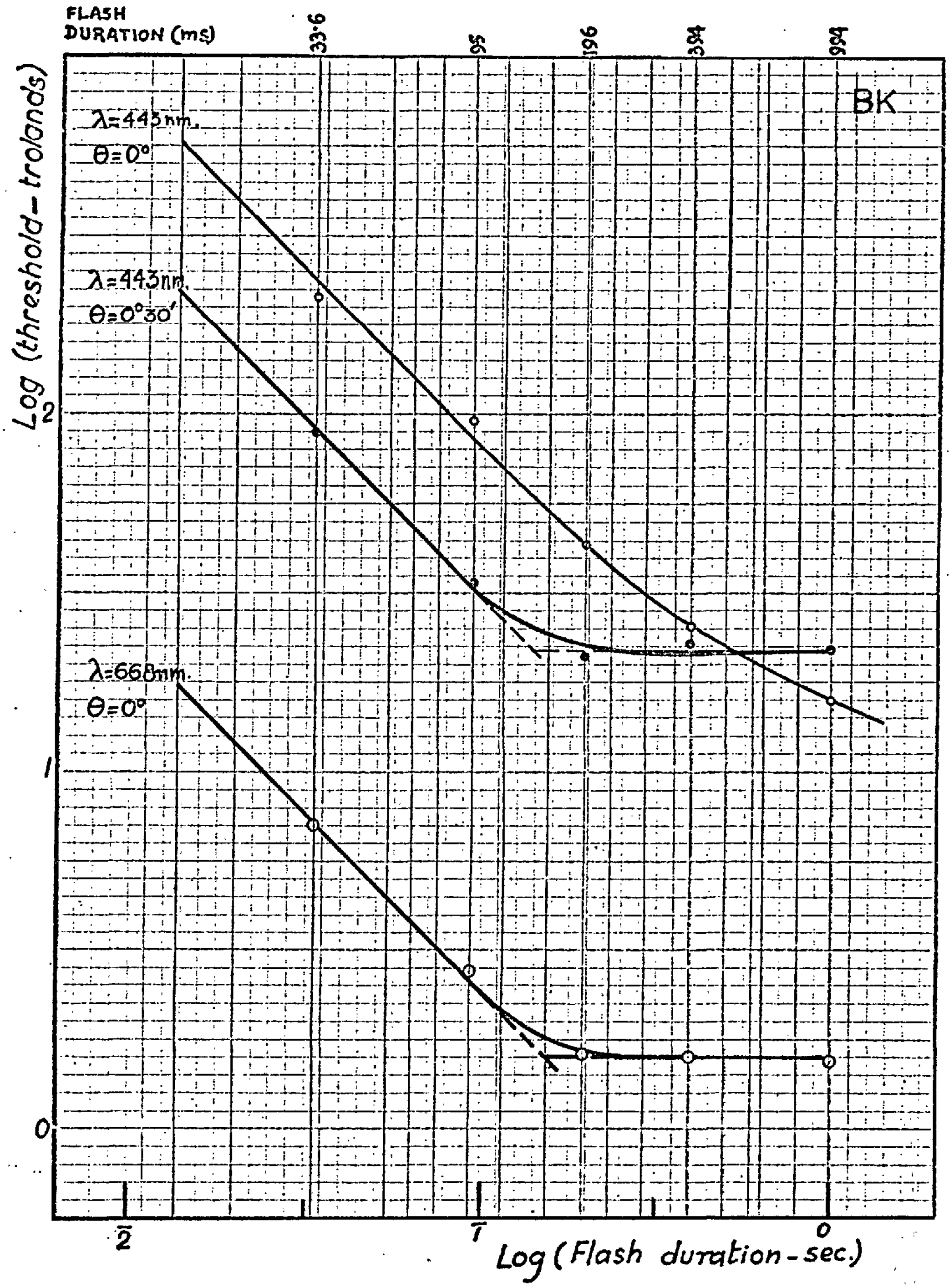


Fig. 110. Temporal summation curves in dark adaptation for blue (443 nm.) and red (668 nm.) test flashes (α = 2'). See text.

the curves in fig. 101-103, for white stimuli of 2' and 32' angular subtense viewed centrally and at 5° eccentricity against backgrounds of luminance 1000 and 0 trolands. The only case in which he obtained a significant decrease in the threshold after the inflexion in the curve was with the centrally fixated 2' field against a background of 1000 trolands, and this corresponds to a steep threshold gradient (fig. 61-63). The determinations were repeated by the author (fig. 104-106) at the fovea, but with a single fixation point 20' from the axis, as he found it relatively easier to maintain fixation with this arrangement than when having to judge the midpoint between two fixation spots, and at an eccentricity of 3° 30', as this region was quite free of blood vessels. Sundry determinations by other observers are given in fig. 107-108, and the results show that there is a relatively sharp transition to a constant threshold with increase of the flash duration, provided good fixation can be maintained.

It seemed desirable to find out whether by artificially creating conditions leading to poor fixation a more gradual change would be obtained. In central fixation, approaching the threshold by reducing the magnitude of the stimulus helps in maintaining fixation; moving the fixation spots further apart however (2° separation) and approaching the threshold from below lead to poorer fixation and a large spread in the results. The curves at $\theta = 0°$ for a 2' white test field for observers MG and JKW (fig.109) were obtained in this manner, each point being the mean of 50 determinations. With a single fixation spot at

0° 30' eccentricity the same observers obtain a sharp transition. The curve for observer MG at 0° 30' eccentricity should be compared with the corresponding curve obtained by the same observer on another occasion when she was tired and found difficulty in maintaining fixation (fig 107). Similar experiments were carried out by observer BK using small red and blue stimuli at the eccentricities indicated (fig.110); reference to fig. 83 would show that the top curve corresponds to a case of steep threshold gradient whereas in the other two cases a small drift in fixation would hardly affect the threshold.

The value of the threshold illumination at the eye for a white test field ($\alpha = 2'$, $t = 0.5$ second) viewed centrally in dark adaptation was found by the author to be 1.5×10^{-7} lux with moderate fixation and 4.6×10^{-7} lux with careful fixation. The corresponding mean value obtained by four observers with careful fixation was $4.6_2 \times 10^{-7}$ lux, (cf. p. 35,37).

Two other points about these experiments deserve mention. Four of the observers found that the 2' stimulus when viewed just above the threshold in central vision appeared reddish or orange, as has been originally reported by Broca and Polack (p.67). The curves of fig 101-106 all indicate that temporal summation occurs to a slightly greater degree in the peripheral retina as compared to the centre of the fovea for stimuli of the same size and under the same conditions of adaptation, in photopic as well as in scotopic vision. This is in agreement with earlier observations. (pp. 154, 207).

CHAPTER VII.

The recovery of summation during dark adaptation.

It has been seen in chapters V and VI that the luminance to which the eye is adapted influences the degree of spatial and temporal summation; the higher the background luminance, the smaller is the difference in threshold between large and small fields, long and brief exposures. Craik and Vernon (1941) and Arden and Weale (1954, fig. 111) found in threshold measurements during dark adaptation that a greater increase in sensitivity occurs with large than with small test fields, and interpreted their results as indicating that part of the increase in sensitivity during dark adaptation is due to an increase in the amount of spatial summation, the integrating power of the retina increasing with dark adaptation. By analogy, it may be expected that there is a similar progressive increase in temporal summation during dark adaptation, though there seems as yet no evidence in the literature that this happens.

Using the method indicated in fig. 50 (p.134) dark adaptation curves were recorded by the author in central fixation, after the eye had been pre-adapted for 3 minutes to a white 12° field of troland value 5000. Fig. 112 shows the results obtained with a white test flash, keeping the duration constant at 100 ms., and varying the angular subtense of the stimulus. There is no significant difference among the curves and this may possibly be attributed to the negligible degree of complete summation occurring in the centre of the fovea even in dark adaptation (p.207). On keeping the field

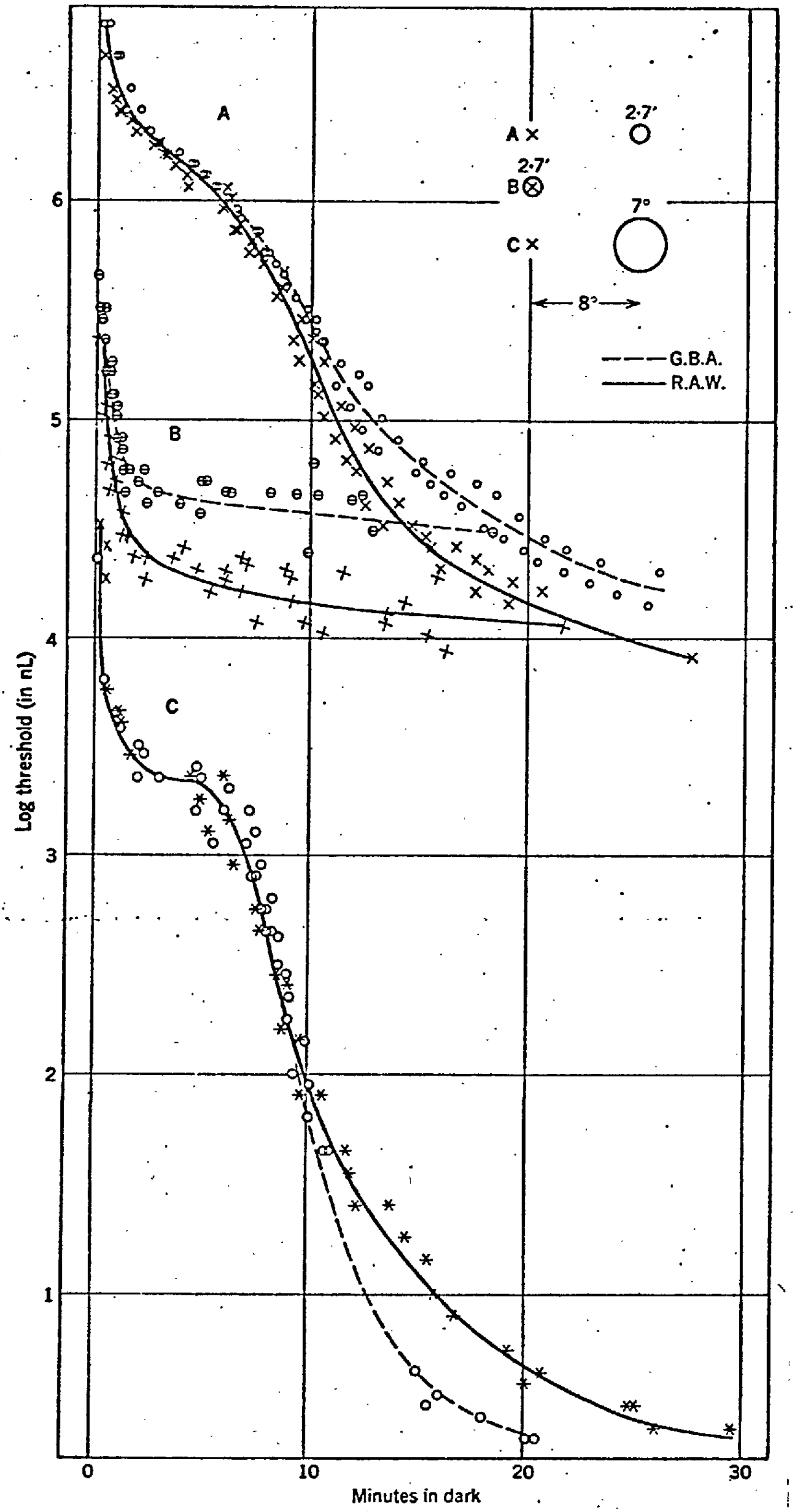


Fig. 111. Thresholds during dark adaptation showing the effect of test stimulus size: 8-*degree extrafoveal vision: A*, diam. 2.7′, *C*, diam. 7°; *foveal vision: B*, diam 2.7′ (Arden and Weale 1954).

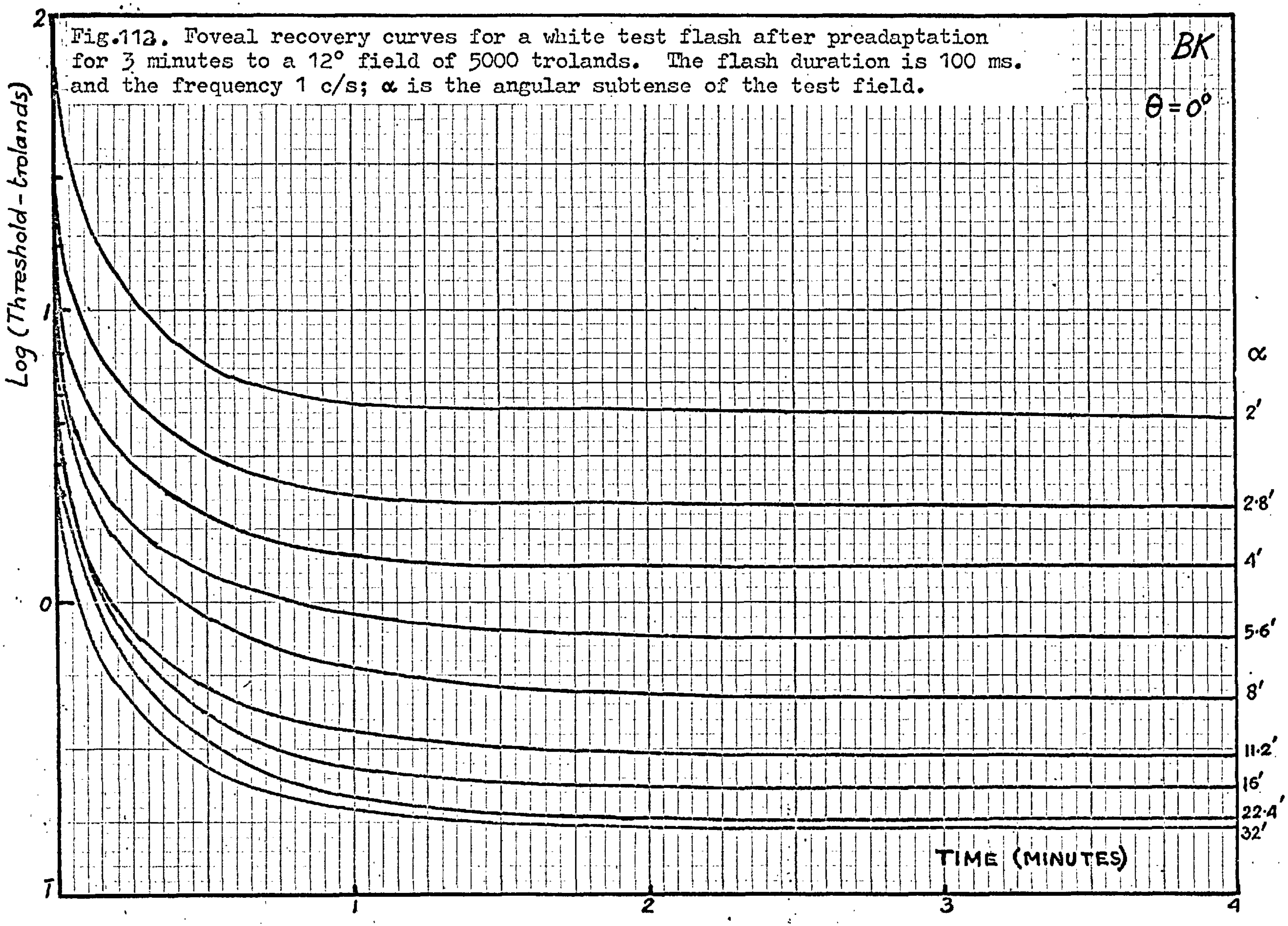


Fig.112. Foveal recovery curves for a white test flash after preadaptation for 3 minutes to a 12° field of 5000 trolands. The flash duration is 100 ms. and the frequency 1 c/s; α is the angular subtense of the test field.

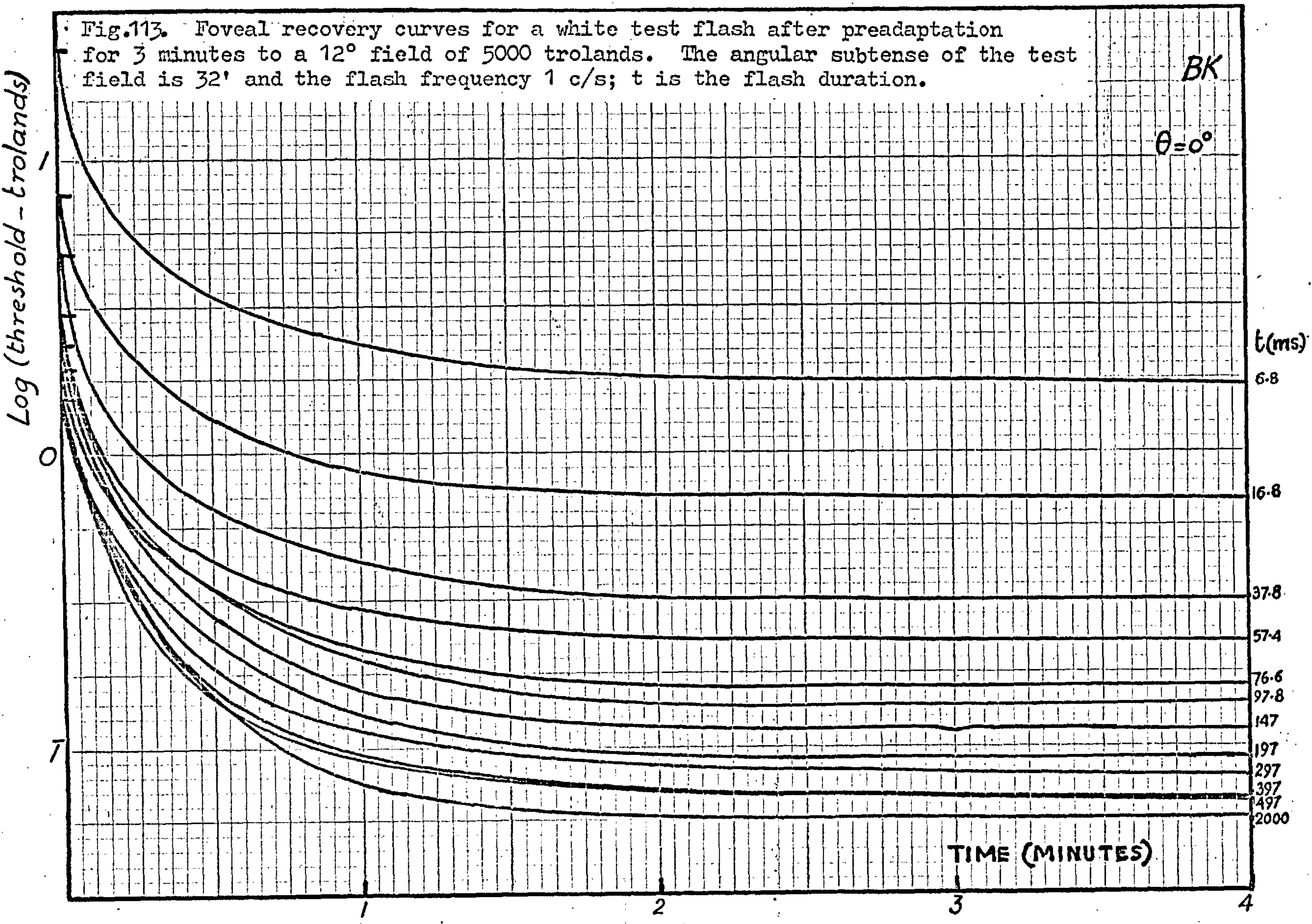


Fig.113. Foveal recovery curves for a white test flash after preadaptation for 3 minutes to a 12° field of 5000 trolands. The angular subtense of the test field is 32' and the flash frequency 1 c/s; t is the flash duration.

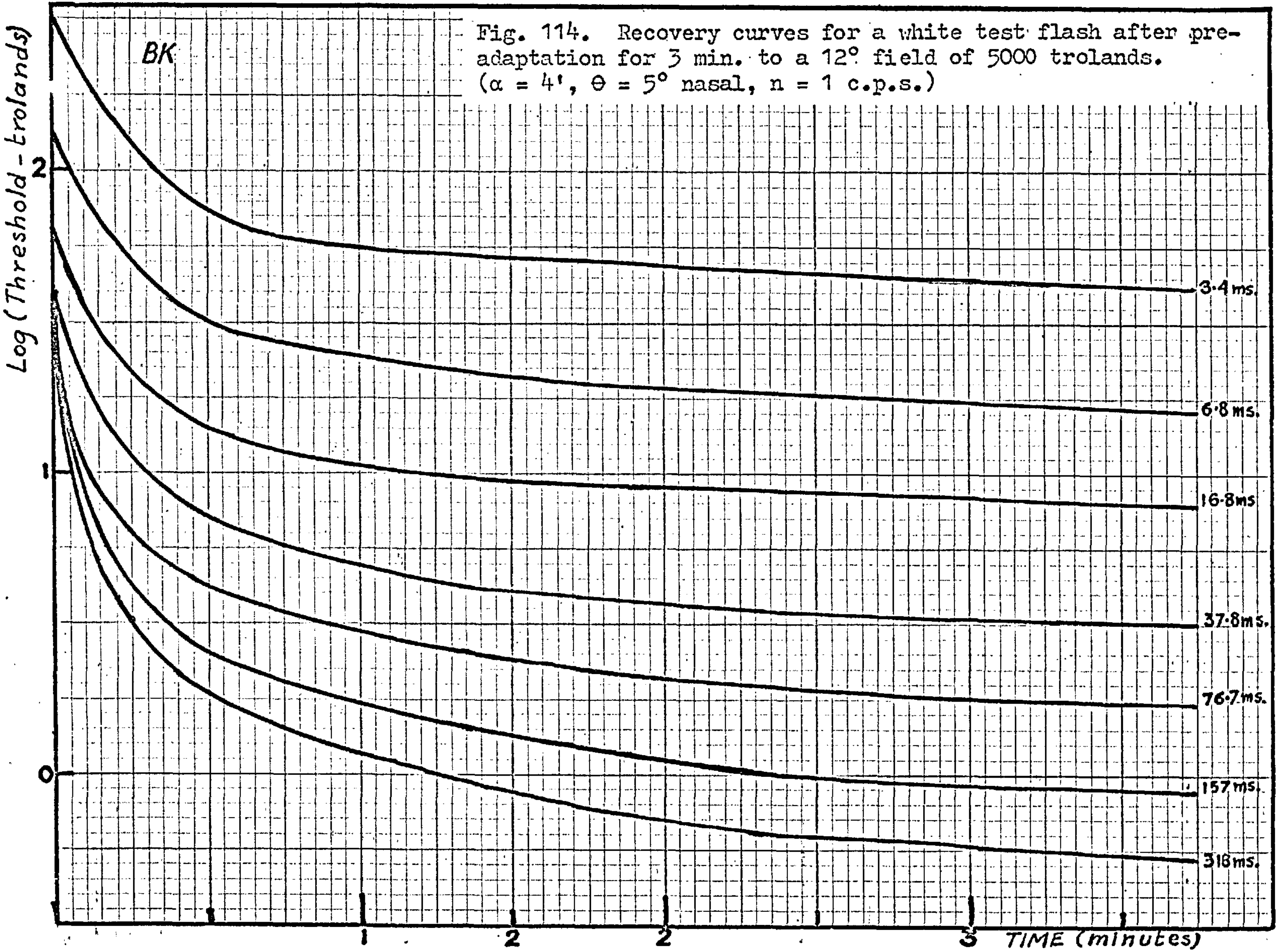


Fig. 114. Recovery curves for a white test flash after pre-adaptation for 3 min. to a 12° field of 5000 trolands. (α = 4', Θ = 5° nasal, n = 1 c.p.s.)

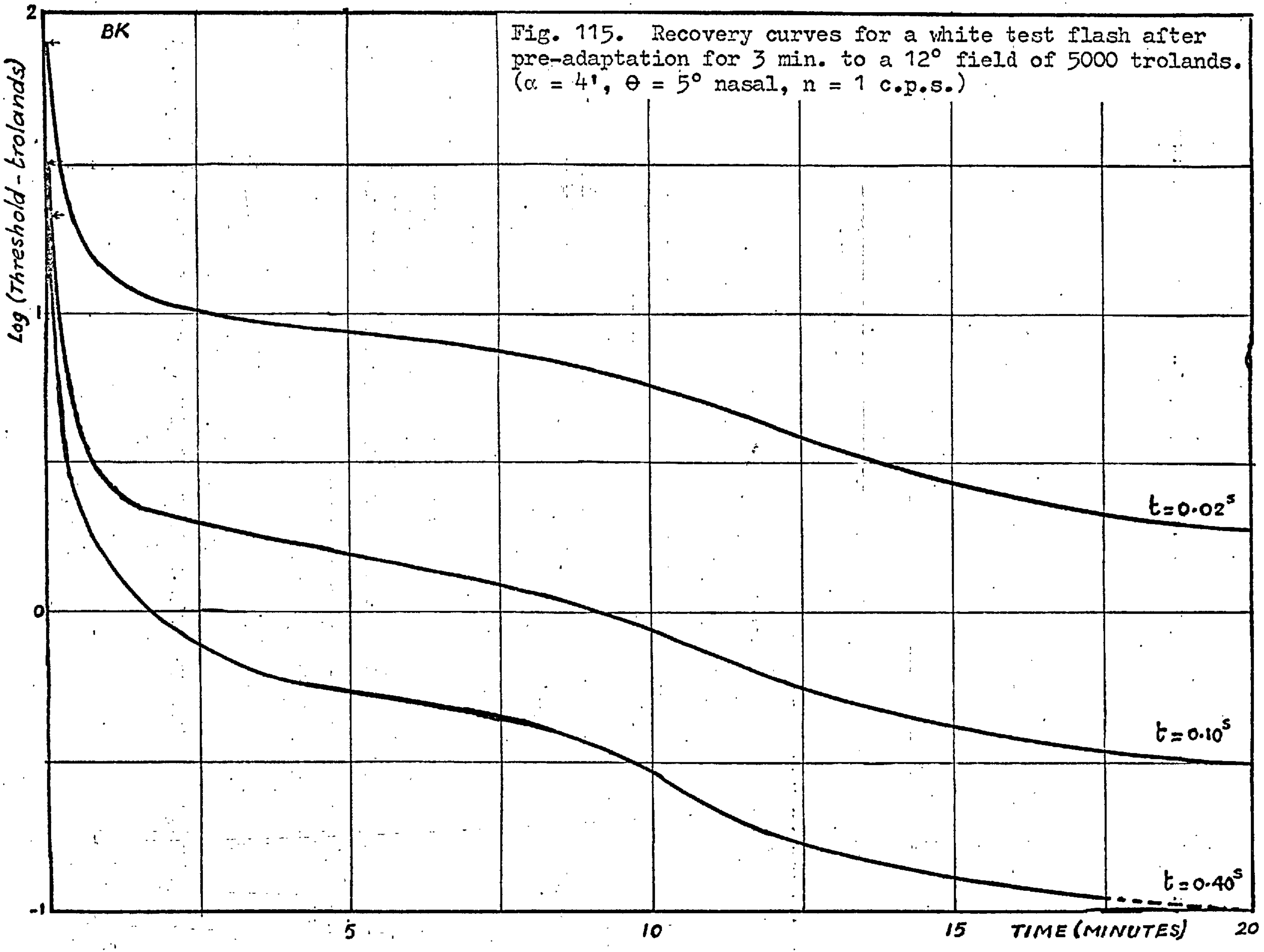


Fig. 115. Recovery curves for a white test flash after pre-adaptation for 3 min. to a 12° field of 5000 trolands. ($\alpha = 4'$, $\theta = 5°$ nasal, $n = 1$ c.p.s.)

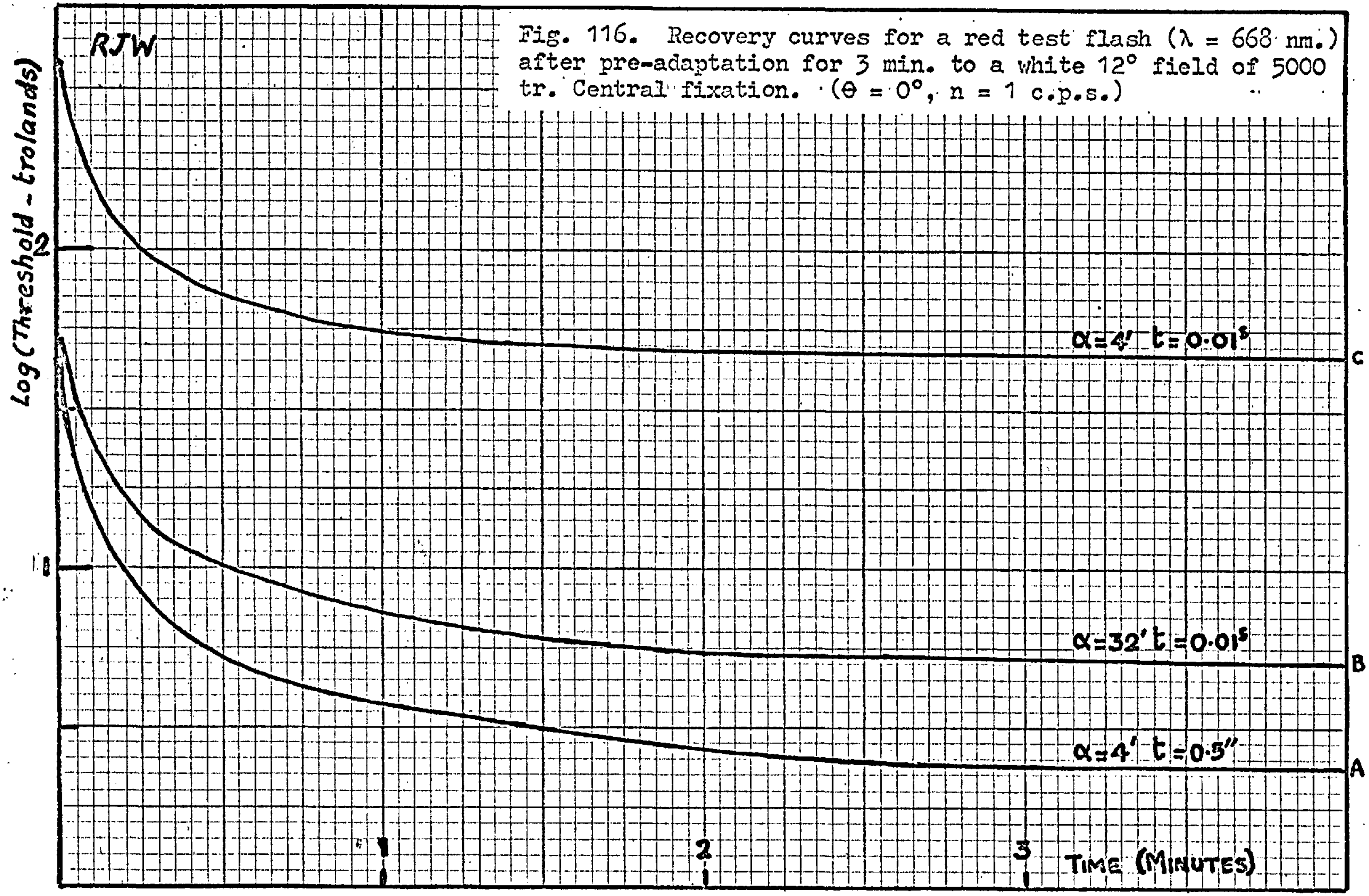


Fig. 116. Recovery curves for a red test flash (λ = 668 nm.) after pre-adaptation for 3 min. to a white 12° field of 5000 tr. Central fixation. (θ = 0°, n = 1 c.p.s.)

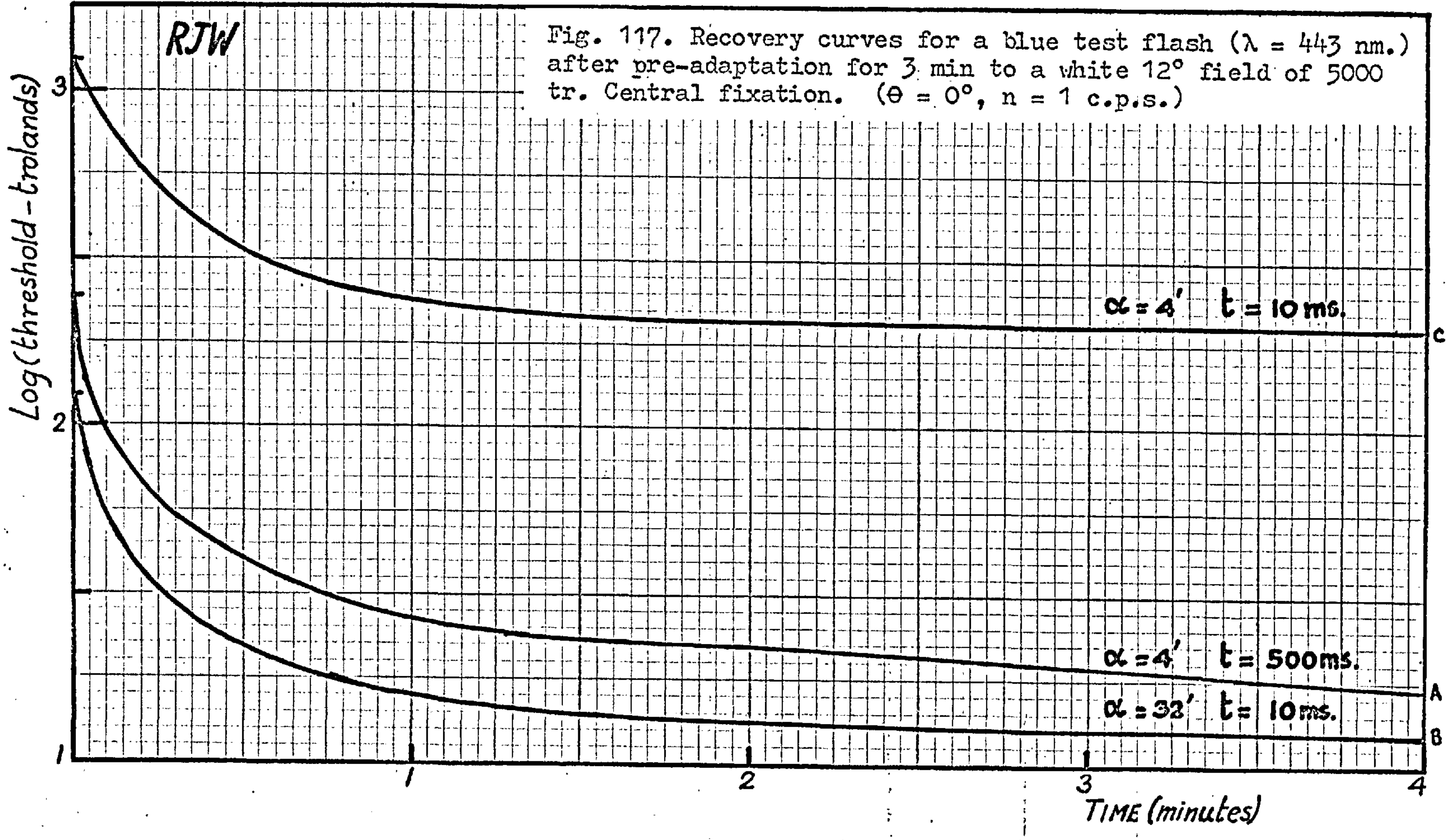


Fig. 117. Recovery curves for a blue test flash (λ = 443 nm.) after pre-adaptation for 3 min to a white 12° field of 5000 tr. Central fixation. (θ = 0°, n = 1 c.p.s.)

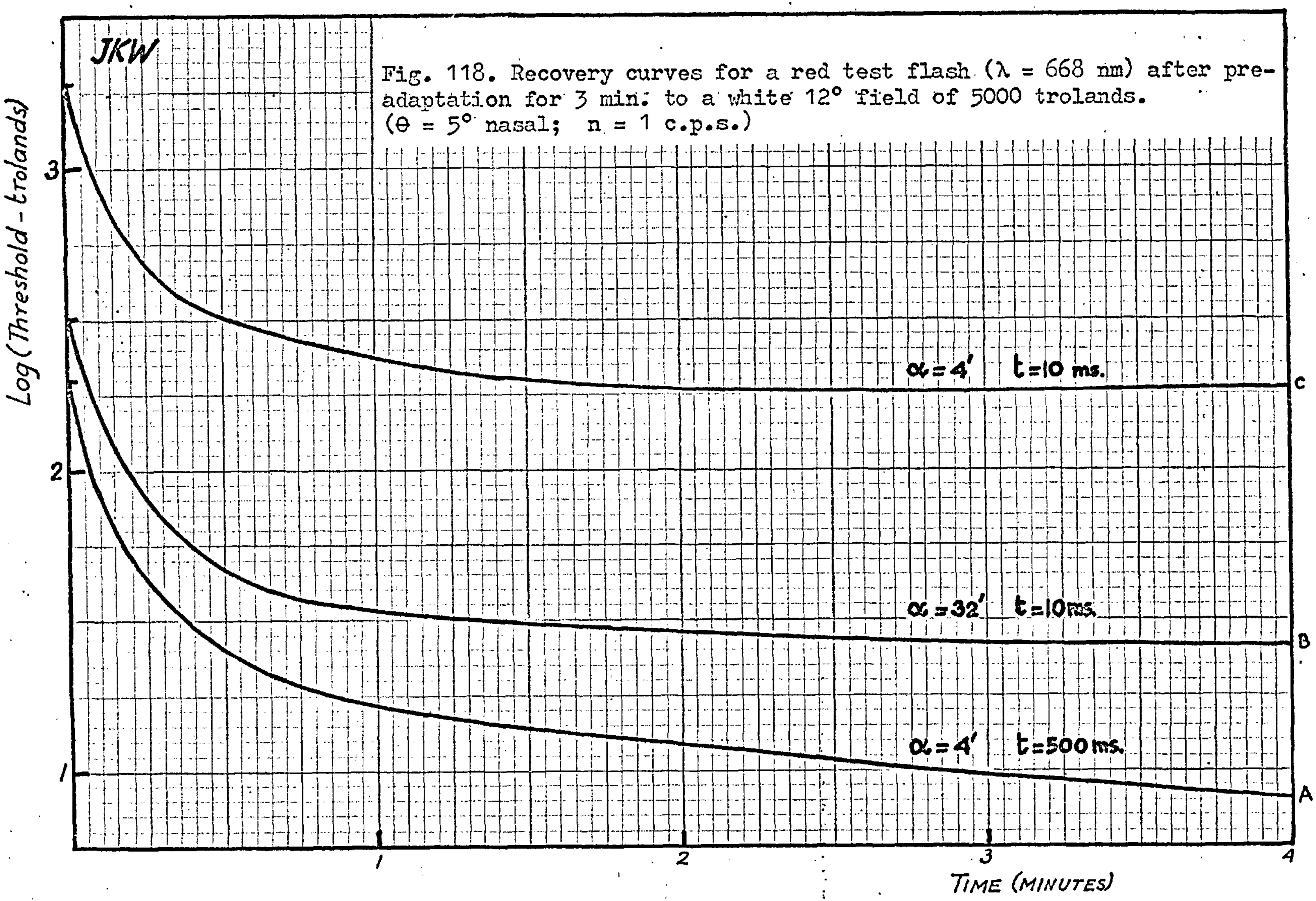


Fig. 118. Recovery curves for a red test flash (λ = 668 nm) after pre-adaptation for 3 min. to a white 12° field of 5000 trolands. (θ = 5° nasal; n = 1 c.p.s.)

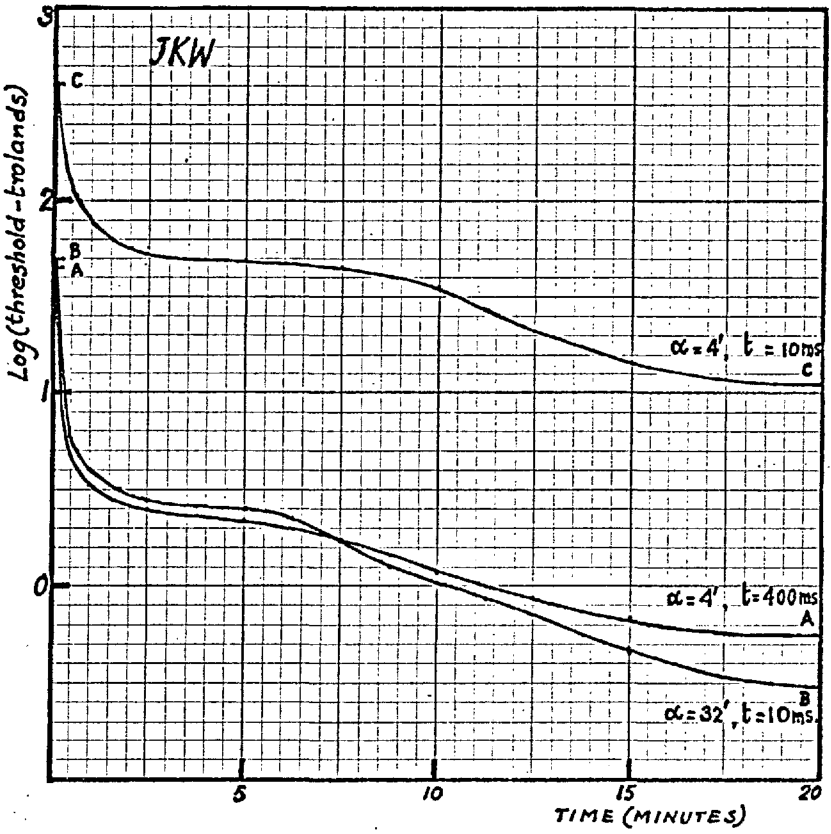


Fig. 119. Recovery curves for a white test flash after pre-adaptation for 3 min. to a 12° field of 5000 trolands. (θ = 5° nasal, n = 1 c.p.s.)

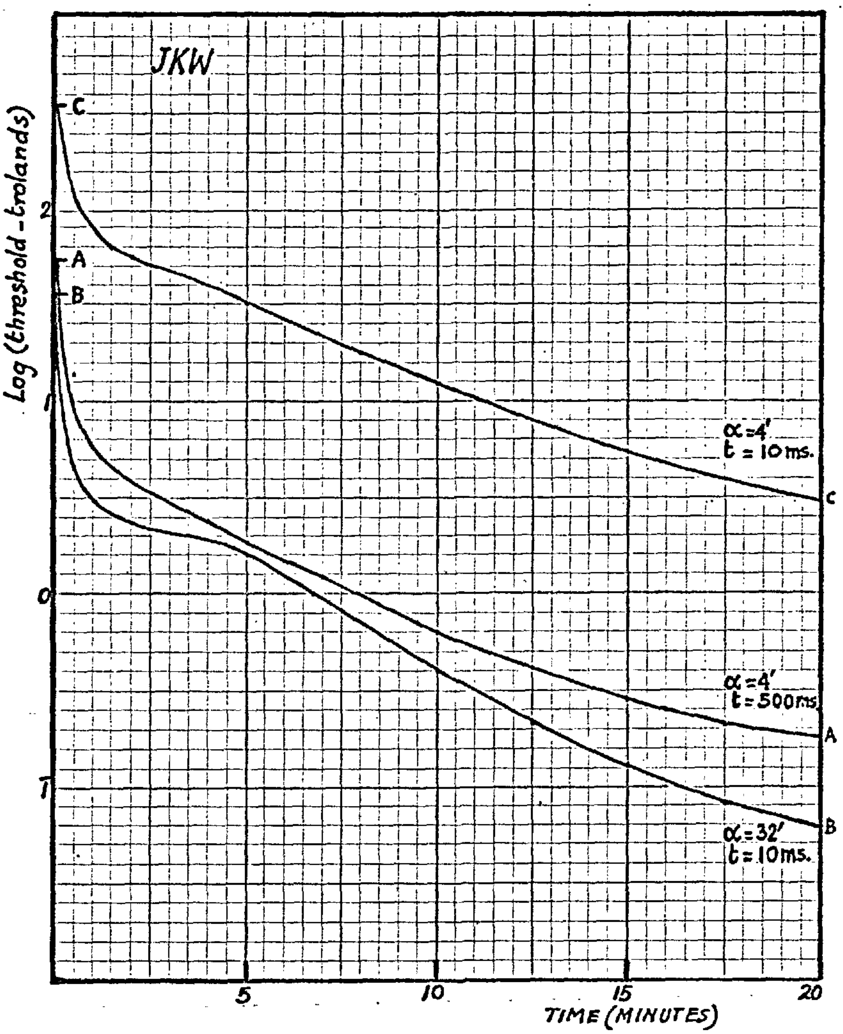


Fig. 120. Recovery curves for a blue test flash (λ = 443 nm.) after pre-adaptation for 3 min. to a white 12° field of 5000 trolands. (θ = 5° nasal, n = 1 c.p.s.)

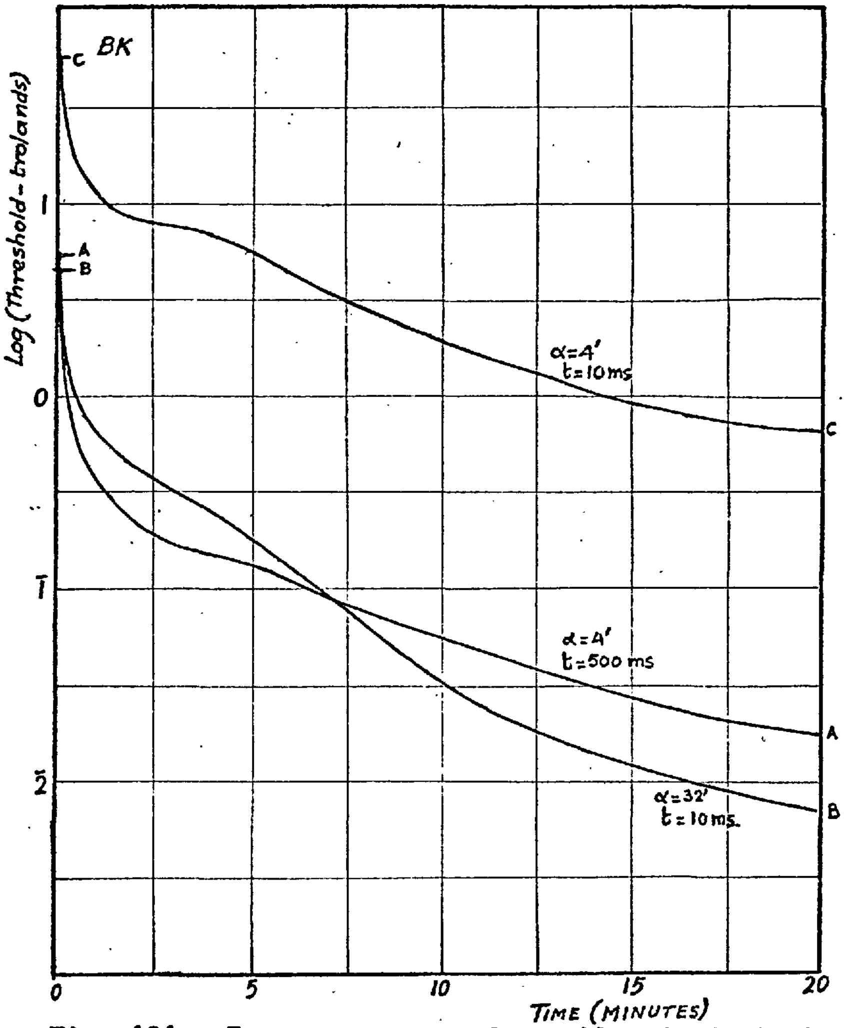


Fig. 121. Recovery curves for a blue test flash (λ = 443 nm.) after pre-adaptation for 3 min. to a white 12° field of 5000 trolands. (θ = 5° nasal, n = 1 c.p.s.)

size constant at 32' and varying the flash duration, ~~steeper~~ gradients are obtained at long exposures as anticipated (fig. 113), indicating an increase in the degree of temporal summation with dark adaptation; the curves are nearly parallel after a minute or so showing that the recovery of temporal summation is almost complete. These experiments were judged unsatisfactory as in the first case the exposure used may have been too long so that the recovery in sensitivity may in part have been due to recovery of temporal summation; the size of the test field in the second experiment may also have been too large. In subsequent experiments, stimuli of smaller diameter and briefer exposures were used and the method of recording the dark adaptation curve indicated in fig. 51 was employed as it proved more satisfactory; each curve is the mean of three to eight determinations. The initial conditions of light adaptation have been kept the same throughout all the experiments.

Measurements by the author at 5° eccentricity over the first 4 minutes of dark adaptation and with a white test flash of 4' angular subtense (fig. 114) show clearly the effect of increasing the exposure time. With the three shortest flash durations, the recovery of sensitivity follows much the same course as these durations may be below the summation time of the eye when adapted to the background of 5000 trolands, but with an increase in the flash length, a steeper initial gradient is obtained. The lowest curves start at the same point, indicating little difference in the initial degree of temporal summation, but separate with the course of dark adaptation, as more summation occurs with the longer flashes.

Curves recorded under similar conditions over more prolonged periods (fig. 115) run almost parallel after about two minutes, within the limits of experimental error, pointing to an almost complete recovery of the temporal summation within this interval.

Further observations were made by three observers at 0° and 5° eccentricity (nasal retina) using white, blue (443 nm) and red (668 nm) stimuli, and the following combinations of angular diameter of field α and flash duration t:

(A) $\alpha = 4'$, t = 400 or 500 ms.;

(B) $\alpha = 32'$, t = 10 ms;

(C) $\alpha = 4'$, t = 10 ms.

With the values of the variables chosen, it seems fairly reasonable to assume that the differences between A and C are solely ascribable to changes in temporal summation and the differences between B and C to changes in spatial summation. The results are shown in fig. 116-121; only the first four minutes of the record with the red stimulus in peripheral vision have been given (fig. 118) as no changes in the threshold could be detected after $5\frac{1}{2}$ minutes in more prolonged observation.

Examination of curves B and C in fig. 116-117 for observer RJW shows little change with increase in field size for the red stimulus as compared with the blue. This may be associated with the greater degree of spatial summation found by Brindley (p.84) with blue test fields as opposed to red. Similar remarks would apply to the curves obtained by JKW at 5° eccentricity (fig. 118, 120), though in this case the course of adaptation with the blue stimulus may have been influenced by rod activity. In fig. 119-121 the slopes of the curves B are greater than for A and C even after 15 minutes of dark adaptation, showing that recovery of spatial summation is still going on within the rod mechanism. This is in agreement with the findings of Arden and Weale. On the other hand temporal summation is completely recovered within about two minutes, the greater part of the recovery occurring during the first minute of dark adaptation. One feature of these curves is that for both observers, the branch generally associated with scotopic adaptation starts earlier with blue than with white stimuli, and the blue curves are steeper and show up better the differences involved.

The conclusion is that the recovery of temporal summation is a relatively rapid process as compared with the recovery of spatial summation and is largely complete within the first minute of dark adaptation. There seems to be little change in spatial summation during the course of dark adaptation when using red stimuli.

CHAPTER VIII.

Some investigations on the Broca-Sulzer effect.

Researches on the Broca-Sulzer phenomenon have been reviewed in chapter II (pp. 28-31). Certain preliminary experiments carried out by the author which, it is hoped, will be followed by more detailed investigations, are described in this chapter.

In the attempt to measure the magnitude of the visual response in a transient sensation the method used may seriously bias the outcome of the experiment and it is not easy to decide upon the best conditions of observation. The original measurements of Broca and Sulzer were obtained with contiguous fields, and at high levels of luminance the steady half of the field may conceivably affect the appearance of the other half. A binocular method of comparison in which the test and comparison stimuli are presented to different eyes seems clearly indicated, but attempts at using this method gave a large spread in the readings, though it seems possible that the accuracy may be improved. The experiments of Katz (1964) indicate that similar results are obtainable through monocular and binocular matching; it was therefore decided to restrict these preliminary experiments to monocular observations. In experiments involving peripheral viewing it is necessary to keep the two fields separate and distinct; two circular separated fields were therefore used in all the experiments as even in foveal vision it was considered that this approximated more closely to conditions as met with in practical applications. A flashing light away from the visual axis may be

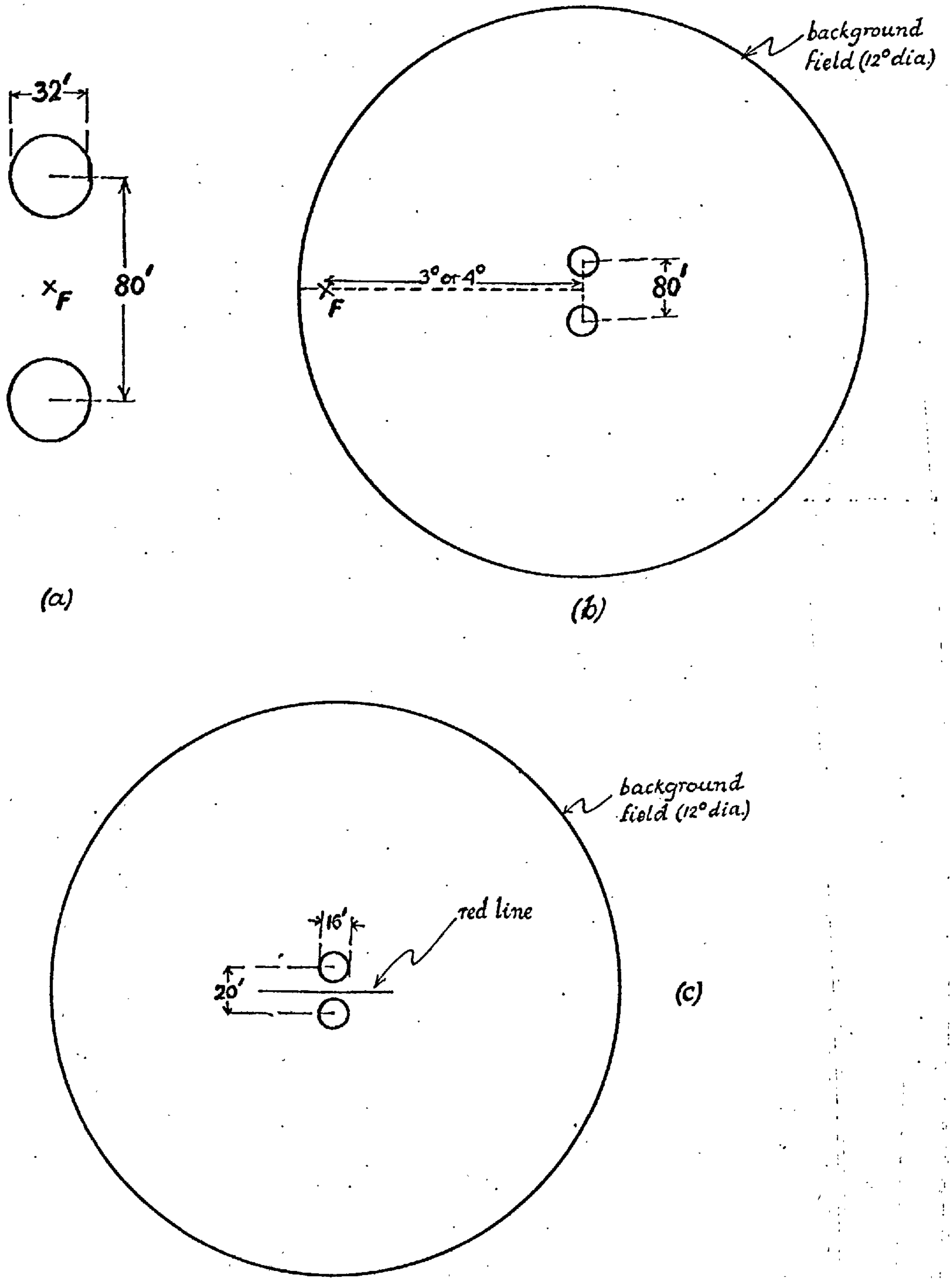


Fig. 122. Test fields as used for foveal observations (a and c) and peripheral observations (b) on the Broca-Sulzer effect. The upper field is steady and the lower one flashing. F is the point of fixation.

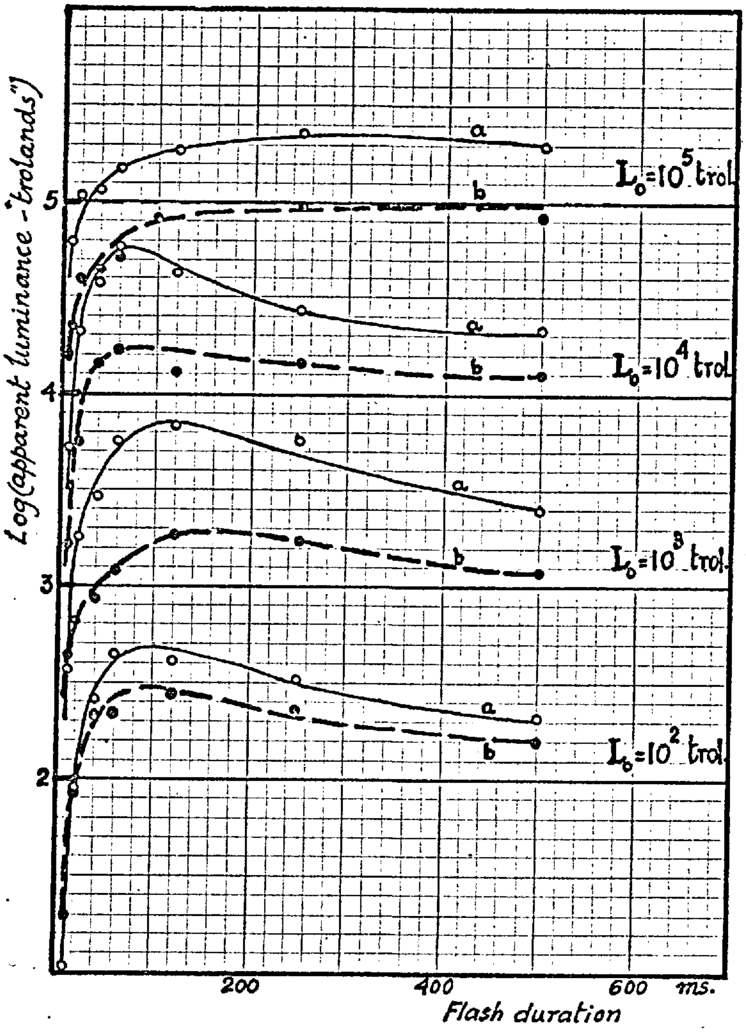


Fig. 123. Change of apparent luminance with flash duration for white test flashes viewed (a) foveally, (b) at 4° eccentricity (temporal retina) against a dark background. L_O is the actual luminance of the test flash as obtained in steady photometric comparison.
(α = 32', n = 1 c.p.s.)
Obs: BK.

compared either with a steady light in central fixation or with one in the periphery. The interest in practical applications is in the comparative performance of the two signals under the same conditions so that comparison with a steady light at a similar eccentricity was decided upon, the choice being partly biased by the fact that this seemed an easier judgment to make. One difficulty that immediately cropped up was the different rates of fading of the retinal images, this being more rapid for the steady light than for the flashing light, particularly at large eccentricities. It is not uncommon under certain circumstances for complete fading of the steady source to occur, when the experiment becomes rather pointless! Even in foveal observations the value of the fixed light equivalent was found to vary with the interval between the initial perception of the fields and the instant the match was established. The conditions of observation for the present experiments were selected on the basis of reproducibility from session to session, while the observer gained in experience, and some restraint must be exercised in generalising the results to other observing conditions. A fairly lengthy period of training seems necessary and it has not been possible to provide this for other observers so that the author's results have not been confirmed by independent observations. All the experiments have been carried out using white light.

In some observations with the earlier version of the apparatus (fig. 123) two 32' fields were used, centred 80' apart, and either a central fixation spot (fig. 122a) or one on the perpendicular bisector of the line of centres and at an angular distance of 4°

from this line (fig. 122b). In foveal observations the match was established between the sixth and the tenth flash and in peripheral observations at the second flash. The flash frequency n was 1 c.p.s. In later experiments with the present equipment (fig. 124-128) the field sizes were reduced to 16' so as to bring the spots closer together (20' centre to centre) within the central zone of the fovea. A thin red line of demarcation coinciding with the perpendicular bisector of the line of centres (fig. 122c) provided satisfactory fixation. For peripheral measurements the separation used was 80' but the field sizes were reduced to 16' and the eccentricity to 3°. Twenty determinations were made at each flash duration, alternately approaching the equality condition by increasing and by decreasing the luminance of the steady field. The flash frequency in these experiments was reduced to $\frac{1}{2}$ c.p.s. and the match established at the fourth or fifth flash in foveal observations and at the second flash in peripheral observations.

The curves in fig. 123 were obtained for a flashing light viewed against a dark background (a) foveally, (b) at 4° eccentricity (temporal retina). L_o is the troland value of the actual luminance of the flash as would have been obtained in photometric comparison using steady fields. The experimental points are far apart and inaccurate but indicate a fairly constant degree of overshooting over a wide range of luminances in foveal observation (curves a), as well as a more rapid rise to the maximum the higher the luminance, as found by other investigators. In the topmost curve however, $L_o = 10^5$ trolands, there is no well defined maximum; at this level of luminance there is an

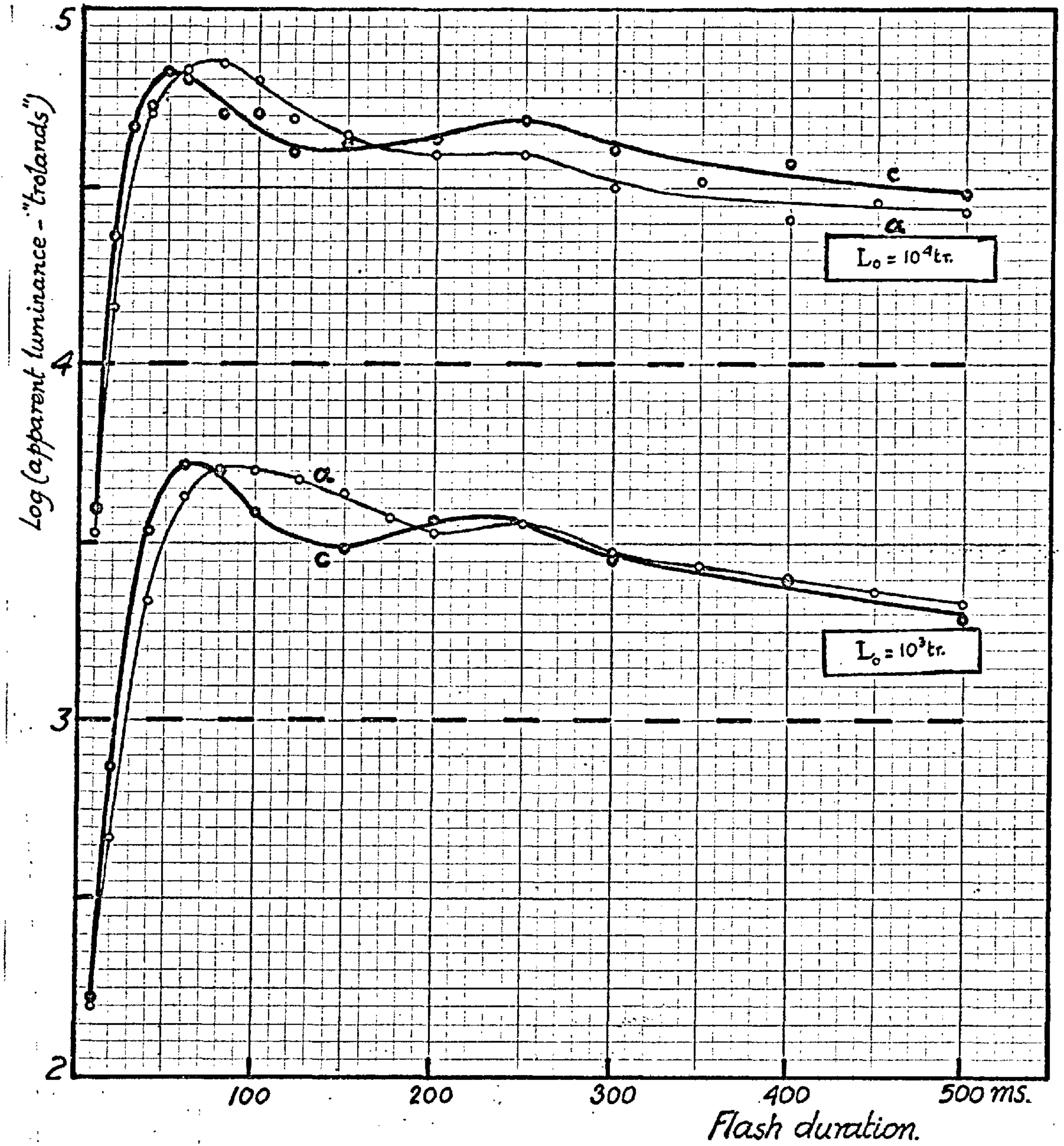


Fig. 124. Change of apparent luminance with flash duration for white test flashes viewed foveally against (a) a dark background and (c) a 12° field of luminance equal to one tenth of the actual luminance L_o of the test flash. (α = 16', n = $\frac{1}{2}$ c.p.s.)
Obs: BK.

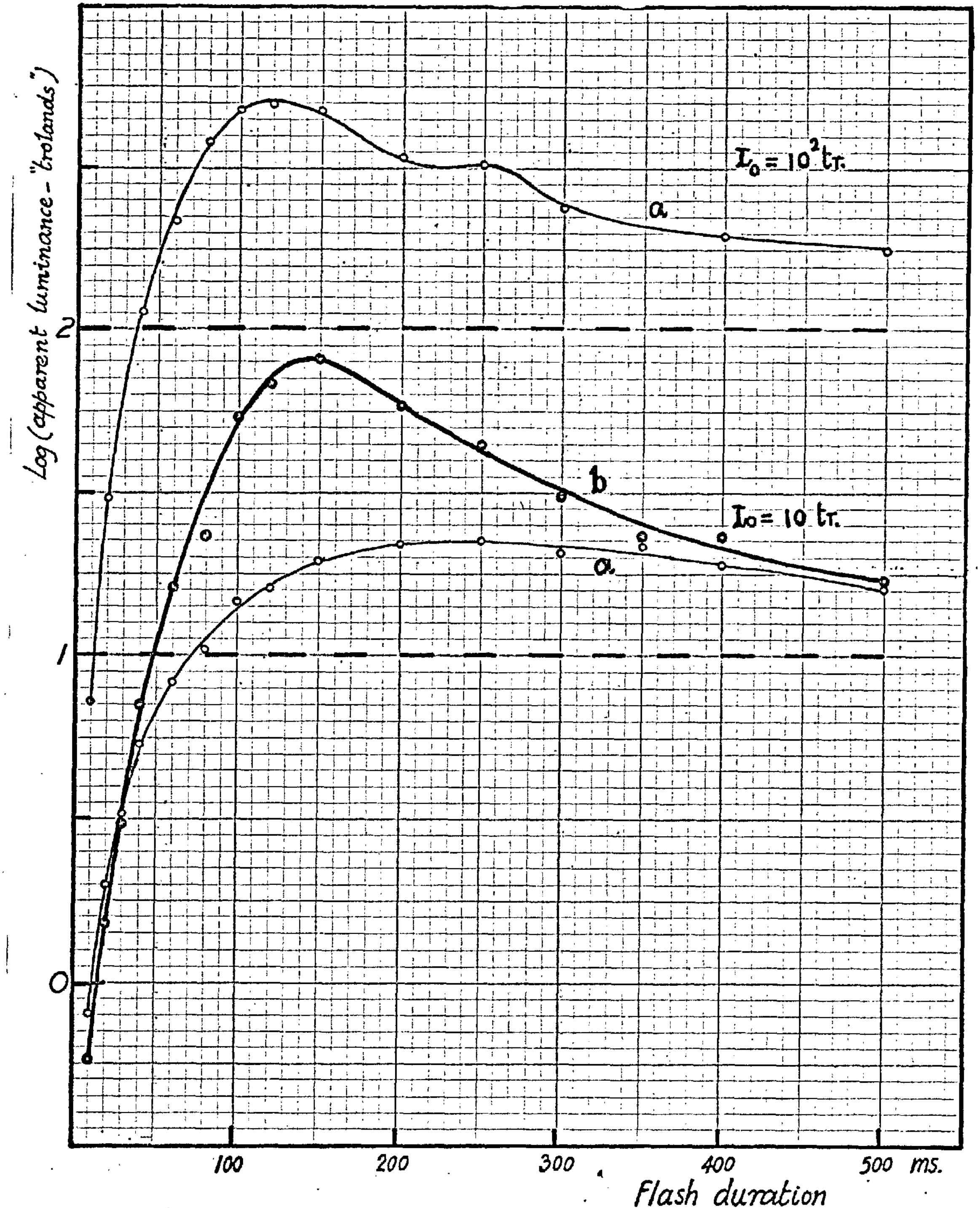


Fig. 125. Change of apparent luminance with flash duration for white test flashes viewed (a) foveally, (b) at 3° eccentricity (nasal retina) against a dark background (α = 16', n = $\frac{1}{2}$ c.p.s.)
Obs: BK.

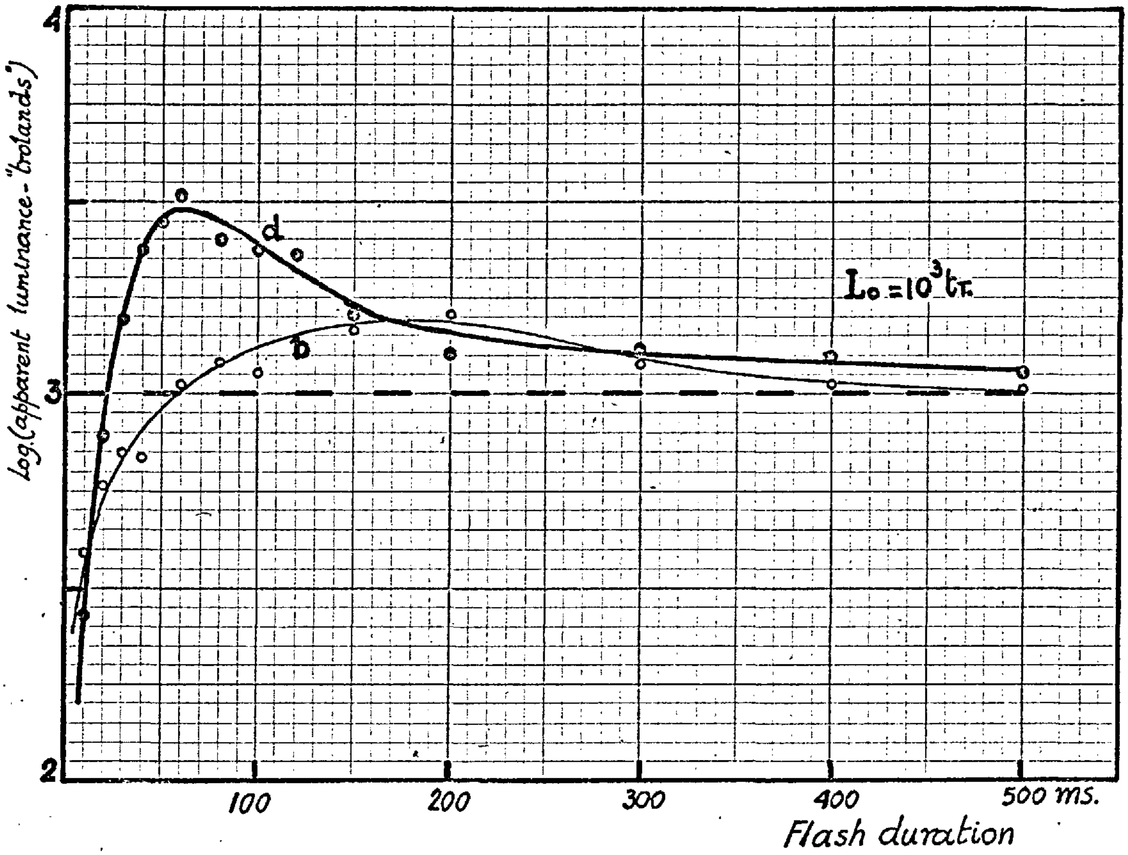


Fig. 126. Change of apparent luminance with flash duration for a white test flash at 4° eccentricity (nasal retina) viewed against (b) a dark background and (d) a background of luminance 100 trolands. L_o = 1000 trolands. (α = 16', n = $\frac{1}{2}$ c.p.s.)

Obs: BK.

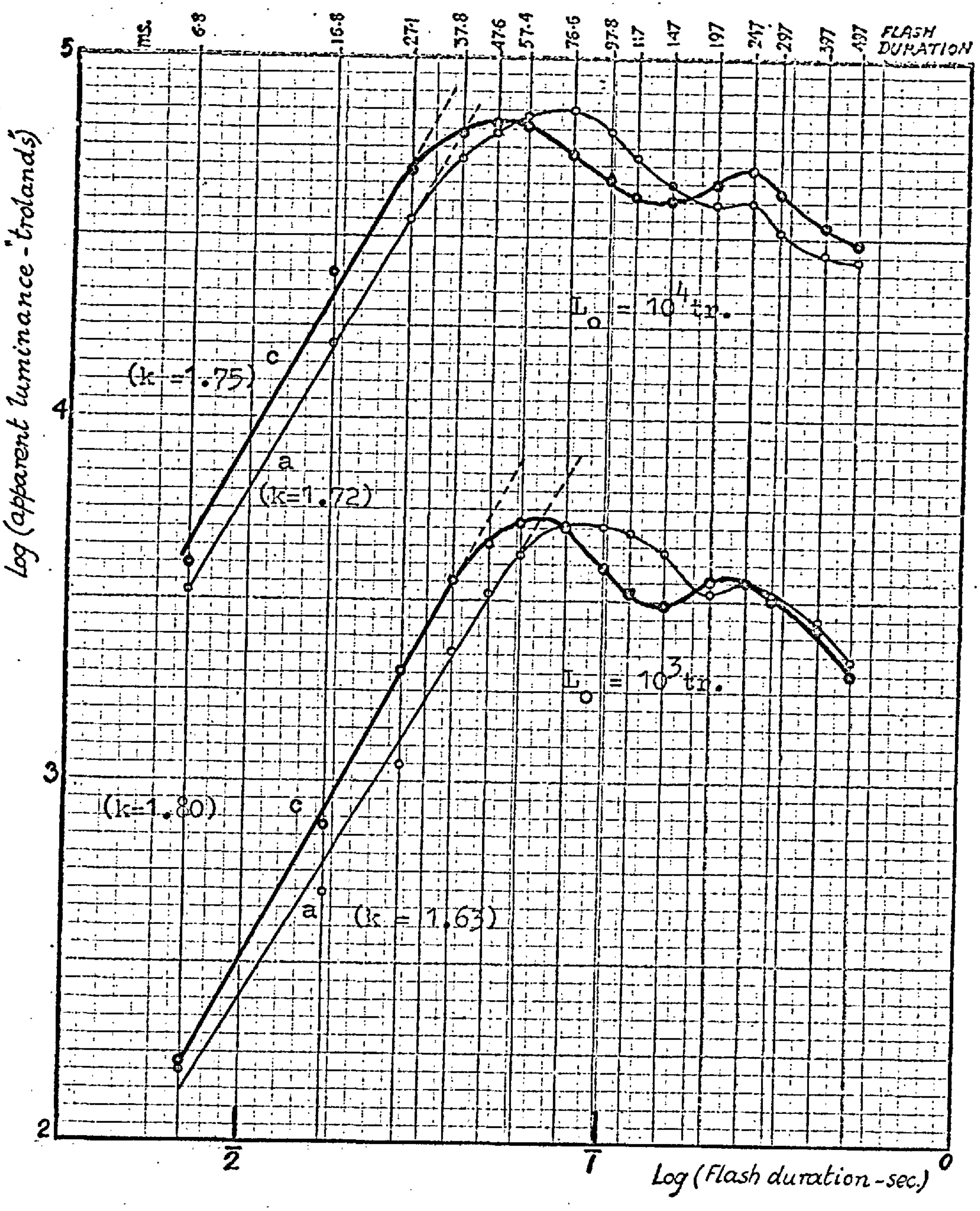


Fig. 127. Change of apparent luminance with flash duration for white test flashes viewed foveally against (a) a dark background and (c) a 12° field of luminance equal to one tenth of the actual luminance L_o of the test flash. (α = 16', n = $\frac{1}{2}$ c.p.s.)
Obs: BK.
(The data for the curves is the same as in fig. 124, but the time scale is logarithmic).

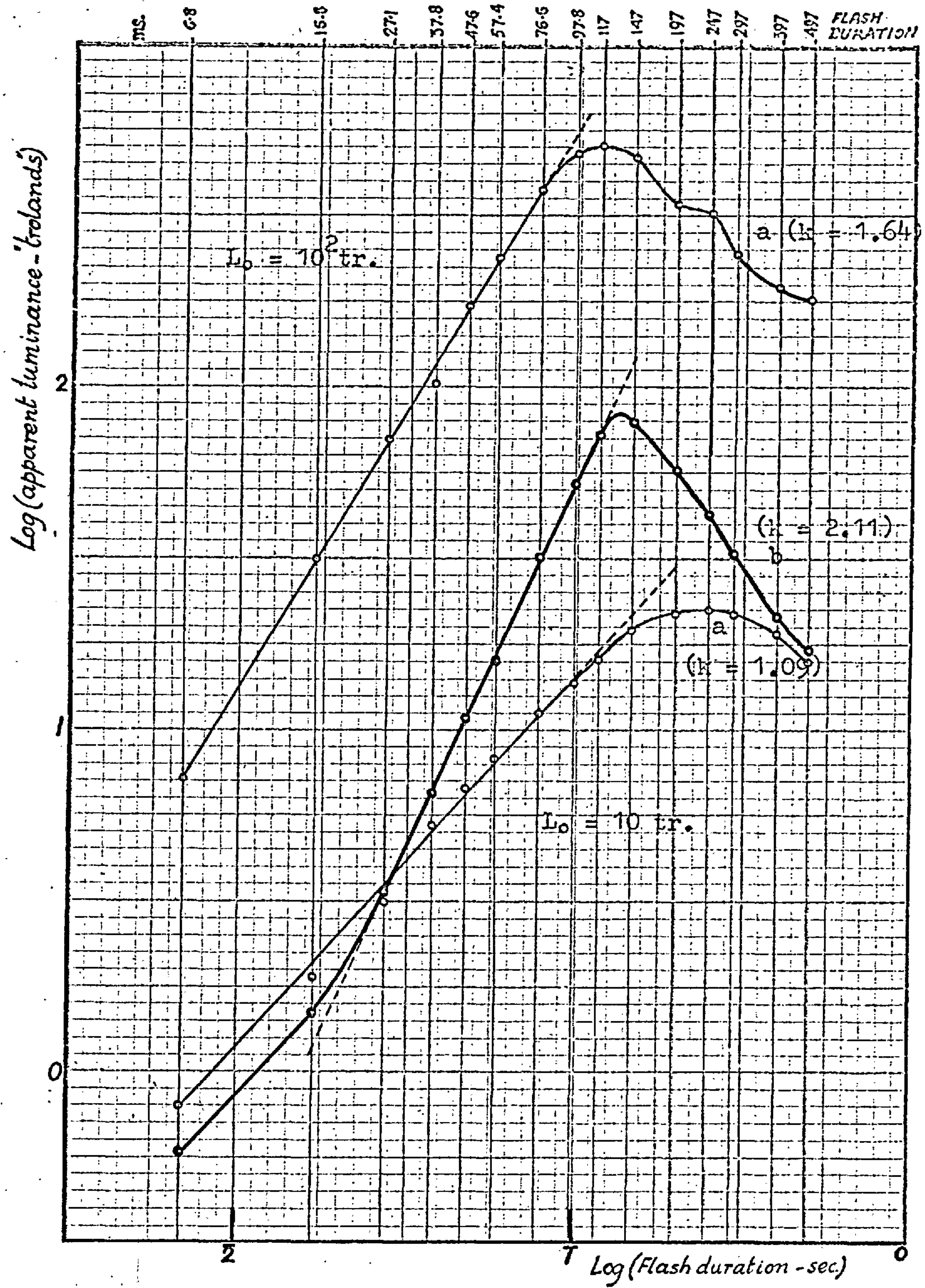


Fig. 128. Change of apparent luminance with flash duration for white test flashes viewed (a) foveally, (b) at 3° eccentricity (nasal retina) against a dark background ($\alpha = 16'$, $n = \frac{1}{2}$ c.p.s.)
Obs: BK.

(The data for the curves is the same as in fig. 125, but the time scale is logarithmic).

almost painful degree of glare and the photometric comparison becomes difficult to establish. The decrease in the overshoot with increase in luminance found in peripheral viewing (curves b) may also be ascribable to glare, which is still more pronounced for the rod mechanism. It is clearly difficult to define the exact state of adaptation of the eye under such circumstances.

The more precise later experiments (fig. 124, 125) generally confirm the previous observations. In foveal viewing against a dark background (curves a), there is a marked increase in the degree of overshooting as the luminance is raised from 10 to 100 trolands, after which the increase becomes more gradual. The equilibrium time t_e at which the apparent luminance L_a first attains the value L_o before going to the maximum and the time for attaining this maximum become shorter as the curves rise more steeply, and at luminances above 100 trolands a small secondary maximum appears at flash durations of about 250 ms., as has been previously reported by Buchner (1907) and Stainton (1928). On superimposing the flashes on backgrounds of luminance equal to one tenth of the actual flash luminance L_o (curves c, fig. 124) the rise to the maximum is sharper, as found by Stainton in moderate light adaptation, and the secondary maximum becomes more pronounced. The amount of overshooting however does not change within the limits of the experimental error.

In peripheral observation against a dark background, reducing the value of L_o to 10 trolands considerably reduces the glare effect and a pronounced overshooting is obtained (curve b, fig. 125), higher than observed in foveal vision under any observing conditions, though the time for attaining the maximum is relatively longer. It seemed desirable to find out what is the effect of reducing the glare in peripheral vision. The results graphed in fig. 126 were obtained by observation with a flash of actual luminance L_0 = 1000 tr. against a dark background (curve b) and a background of 100 trolands (curve d). In the first case, the maximum is very flat and reduced as compared to fig. 125, but in the second case, a rather higher and sharper maximum is obtained; at the level of background luminance used vision is photopic and this higher maximum may conceivably originate from the cone mechanism.

Plotting the data of fig. 125 and 126 with a logarithmic scale along the time axis (fig. 127, 128) brings out more clearly certain aspects of the phenomena. Comparison of the curves a in these two diagrams shows that as the luminance of the flashing field is raised the principal maximum shifts towards shorter flash durations whereas the secondary maximum occurs always at about 250 ms. The absence of the secondary maximum at L_0 = 10 trolands may be due to masking by the principal maximum, as the maxima would in this case be nearly coincident. Raising the overall level of adaptation of the eye by superimposing the flash on a bright background (curves c, fig. 127) shifts the principal maximum to still shorter durations but has no effect upon the position of the secondary maximum. This points to different origins for the two maxima. One suggestion is that the secondary maximum is associated with certain rhythmic processes going on within the visual system.

Another feature of fig. 127-128 is the linear rise almost right up to the principal maximum. This indicates that over an appreciable range of flash durations summation is occurring to a good approximation according to the law

$$L_a = \text{constant } t^k \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (35)$$

The range over which this equation is obeyed includes the equilibrium time t_e, so that writing $L_a = L_o$ at $t = t_e$ one obtains

$$L_a = L_o\left(\frac{t}{t_e}\right)^k \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (36)$$

The values of the exponent k for the linear portions of the curves are indicated in the diagrams. In foveal vision there is a fairly large change in k from 1.09 to 1.63 as L_o is increased from 10 to 100 trolands, after which its value remains relatively constant. The value of k for peripheral viewing (L_o = 10 tr.) is 2.11 and this would confirm Kleitman and Pieron's observation (p.30) that the rate of rise is higher for peripheral than for foveal vision. Close to the threshold Bloch summation (k = 1) might be expected to occur as is indicated by the lower part of curve b, fig. 128. The low value of k for curve a, L_o = 10 tr., may also be due to the measurements being carried out at a luminance not far removed from the cone threshold.

Whereas the results obtained from these experiments are of direct practical application in that they give a measure of the subjective impression caused by a flash under the stated conditions, it is difficult to say to what degree they represent the actual course of the visual response. This will depend upon the extent to which the judgment of equality is made in respect of an average sensation or the sensation at a particular instant during the course of the flash. Greater difficulty is generally experienced in establishing the photometric match at long flash durations, but decrease in the apparent luminance with increase in the flash length would indicate that the setting is biased towards the sensation near the end of the response. Raab and Osman (1962) and Naus (1967) have compared a brief flash with a longer standard flash using coincident onset and coincident termination and found that the Broca-Sulzer effect is absent in the first case. They have explained their results in terms of meta contrast as studied by Fry (1934) and Alpern (1957); the activity aroused by the earlier part of a flash being depressed by the later parts of the same flash or by a following flash on an adjacent position on the retina. In the author's opinion these findings may be more simply explained on the assumption that the initial course of the visual response is the same at a given luminance for all flash durations and that the result depends upon the instant at which the comparison is established. Crawford (1947) has traced the course of the visual response during a flash by determining the threshold for a very brief flash superimposed upon the main flash. It is interesting to compare the results of the experiments described here with his observations. (fig. 129). There is no evidence of a secondary maximum in Crawford's curves but a much sharper principal maximum is found, showing that in the present experiments an appreciable amount of averaging of the response must be taking place.

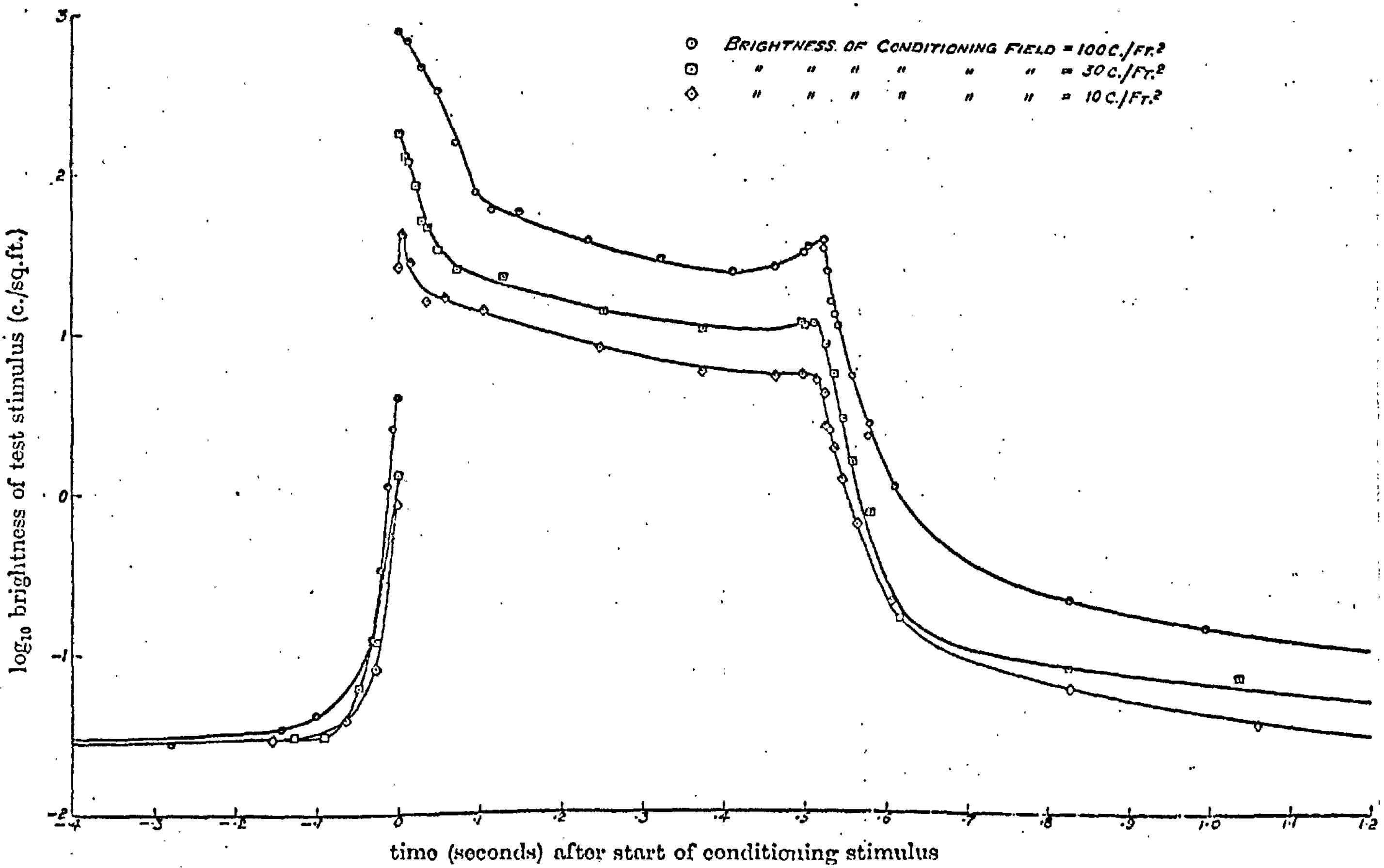


Fig. 129. Thresholds for a brief test stimulus (α = 30', t = 10 ms.) viewed against a longer conditioning stimulus (α = 12°, t = 524ms.) (Crawford.)

CHAPTER IX.

Sundry experiments and observations.

During the course of the investigations described so far, other experiments were performed from time to time with the aim of deciding upon the best conditions for certain observations or finding out some more promising line of research; often the excuse has been mere curiosity. The results of some such experiments have been included at the relevant places in the text, the results of some others as may possess a certain degree of general or practical interest are collected in this chapter. The data may be scanty and some of the experimental conditions lacking in rigour and accuracy, but nevertheless give an indication as to what may be expected under certain conditions.

Sudden changes in the frequency of a flash and the fading of the retinal image.

Near threshold a flashing light is more readily perceived than a steady light (pp. 51-52), the greater ease of detection being ascribed to the sequential variations in the train of nerve impulses. The fading of the image of a flashing light in the periphery is slower than for a similar steady light, but it is not difficult to obtain complete fading of a flashing light of about $\frac{1}{2}$° angular subtense and 1000-5000 troland value at 10°-20° eccentricity with moderately careful fixation at low levels of light adaptation. It is generally considered that blinking leads to a reappearance of the faded image but it was found that provided the blinking process did not seriously disturb the direction of fixation no reappearance of the flash occurred. Similar results were obtained by closing and reopening a shutter close to the observer's eye. This would indicate that a change in the sequence of nerve impulses does not lead to reappearance of the image and it seemed desirable to find out what would be the effect of a sudden change in the flash frequency. Light sector discs cut out of thin card were driven by a motor the speed of which could be adjusted by two series resistances over a range giving $\frac{1}{2}$ - 15 flashes per second. Short circuiting one of the resistances or introducing it into the circuit could bring about fairly rapid changes in the speed of the motor within one or two seconds. The observer fixated at about 10° - 20° from the source (angular diameter about 15') until there was complete disappearance of the flashing light when by pressing a switch an upward or downward change in frequency could be obtained. No reappearance of the image was generally observed unless fixation was disturbed during the operation of the switch.

The flashing light in a dark surround within a large background of high luminance.

Under conditions of high ambient illumination as met with in daylight it is conceivable that the conspicuity of a flashing signal may be increased by providing it with a dark surround and this practice is relatively common. Measurements were carried out to find the change in the threshold for a flashing light of 16'

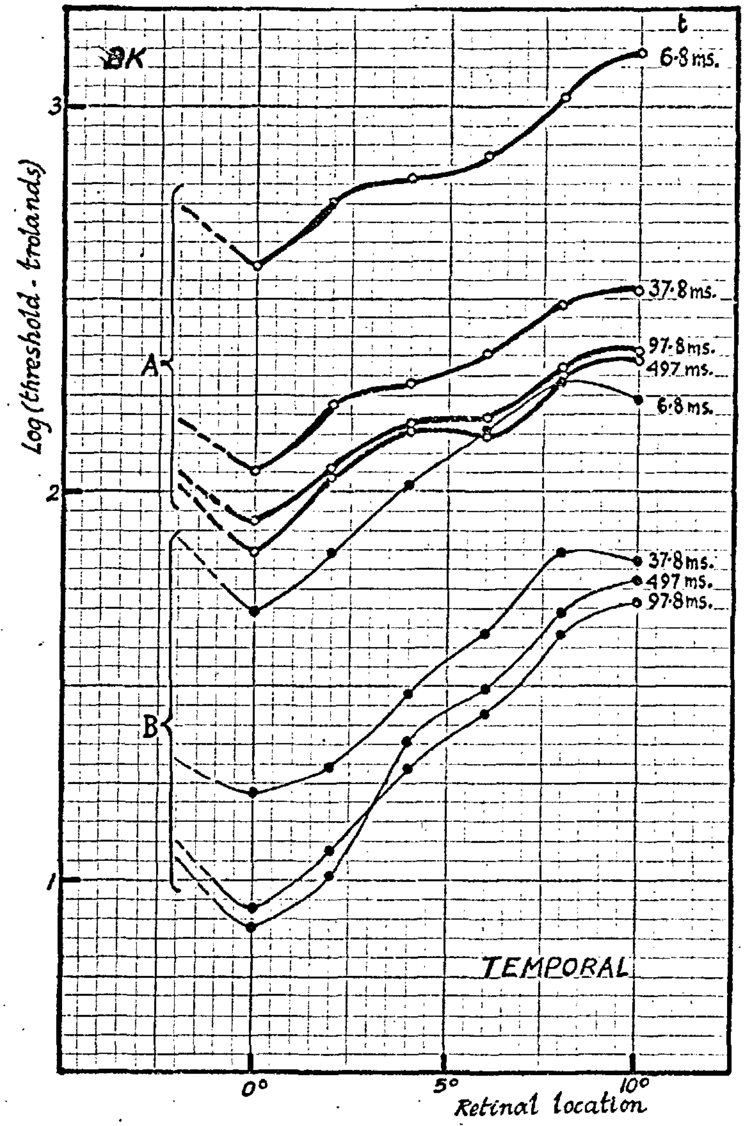


Fig. 130. Variation of threshold with retinal location for a white test flash ($\alpha = 16'$), (A) superimposed on a white 12° background of 1000 trolands and (B) viewed in a dark surround of angular subtense 35' within the same background (n = 1 c.p.s.)

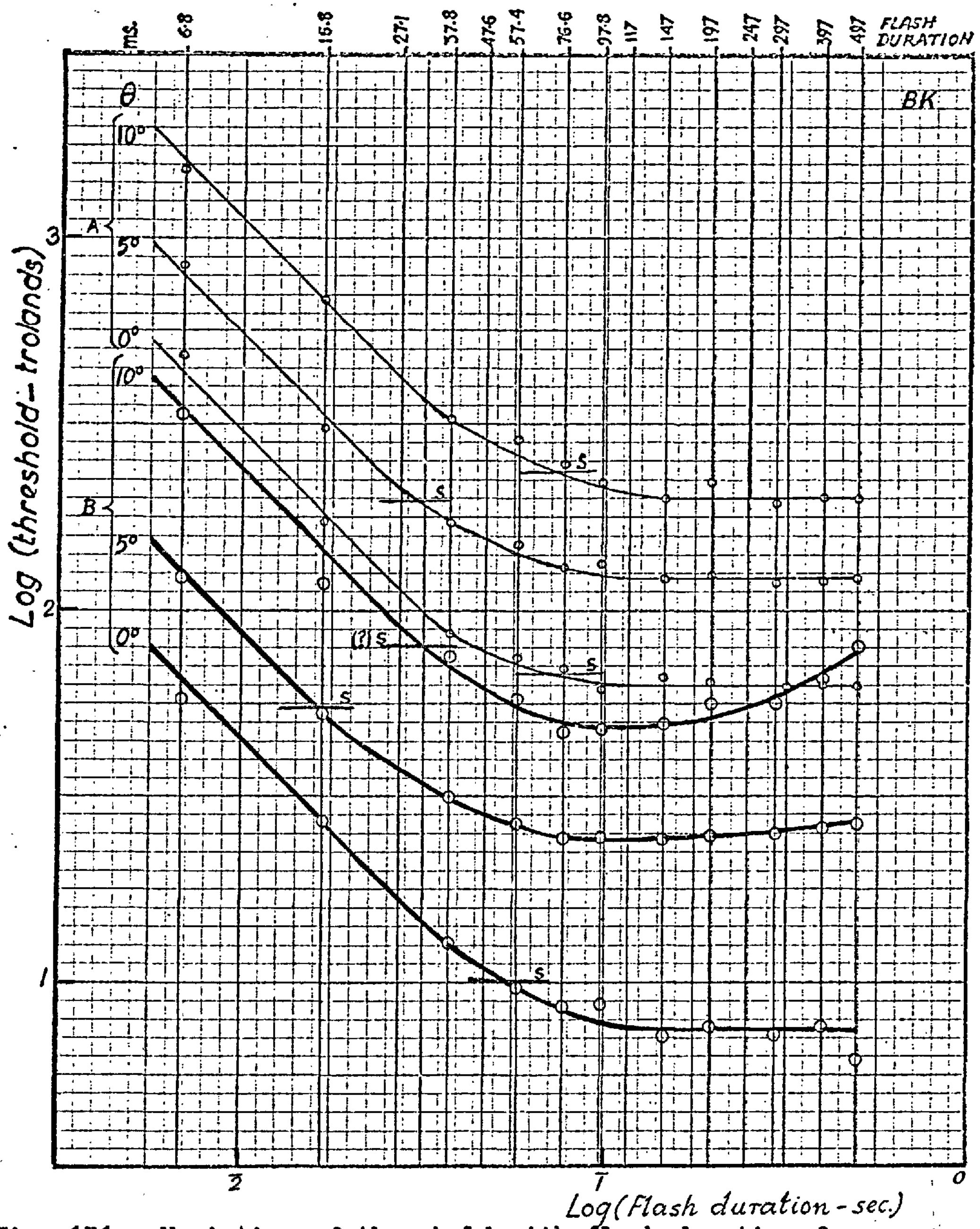


Fig. 131. Variation of threshold with flash duration for a white test flash (α = 16'), (A) superimposed on a white 12° background of 1000 trolands and (B) viewed in a dark surround of angular subtense 35' within the same background. θ is the eccentricity with the visual axis (temporal retina). n = 1 c.p.s.

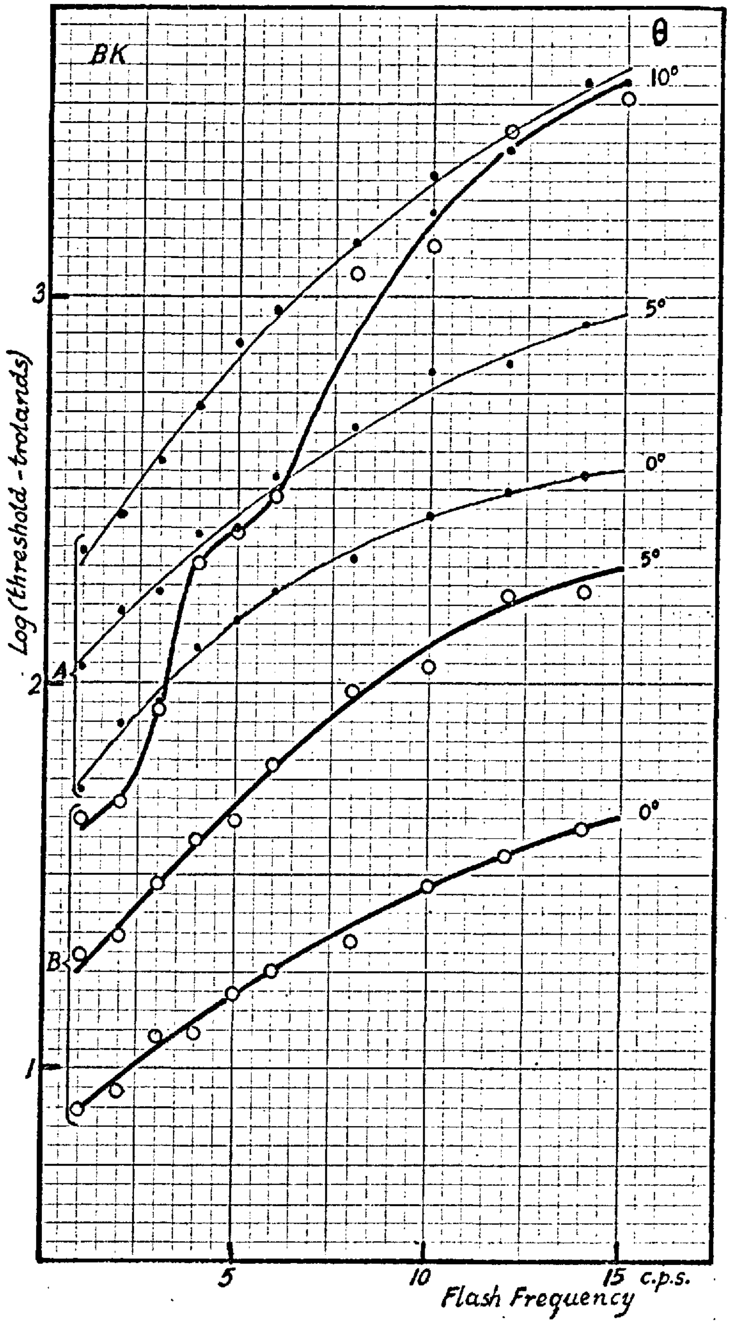


Fig. 132. Variation of threshold with flash frequency for a white test flash (α = 16') of constant light-dark ratio 1:9, (A) superimposed on a white 12° background of 1000 trolands and (B) viewed in a dark surround of angular subtense 35' within the same background. θ is the eccentricity with the visual axis (temporal retina). n = 1 c.p.s.

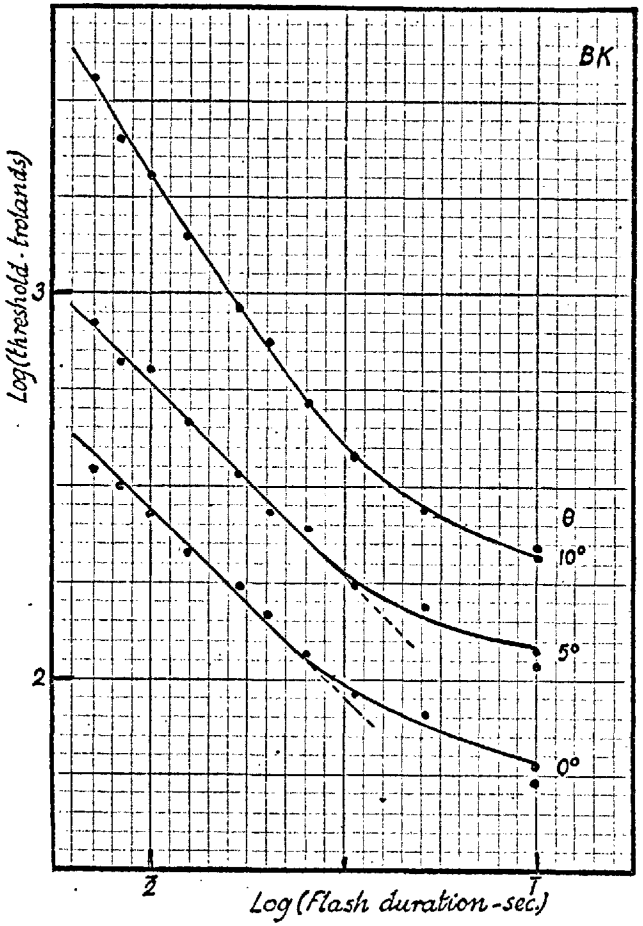


Fig. 133. Same data as in curves (A), fig. 132, but with log (threshold) plotted against flash duration.

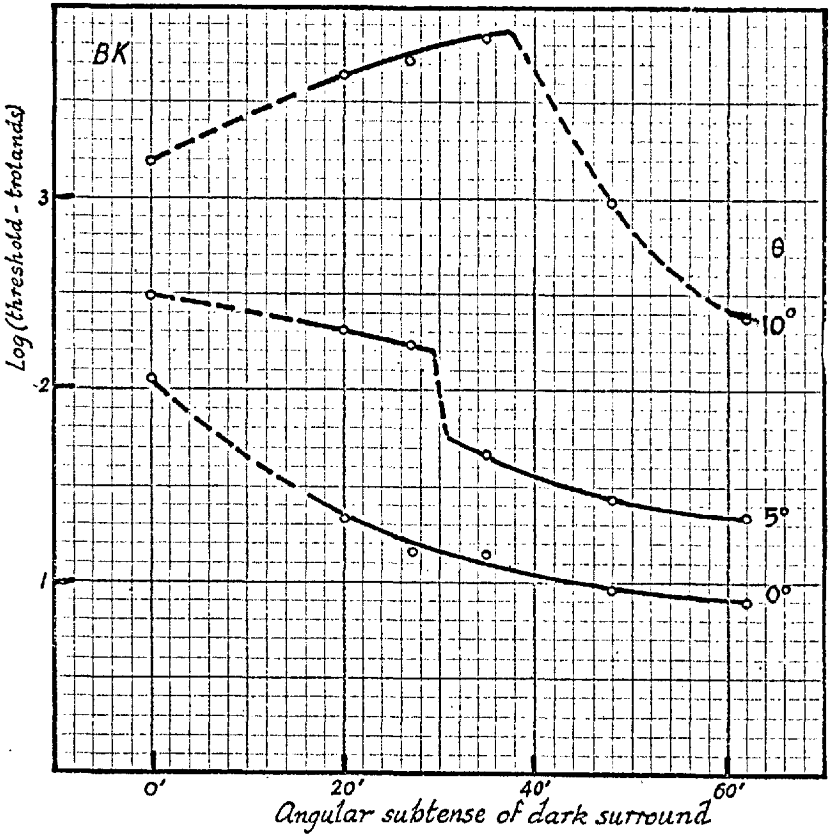


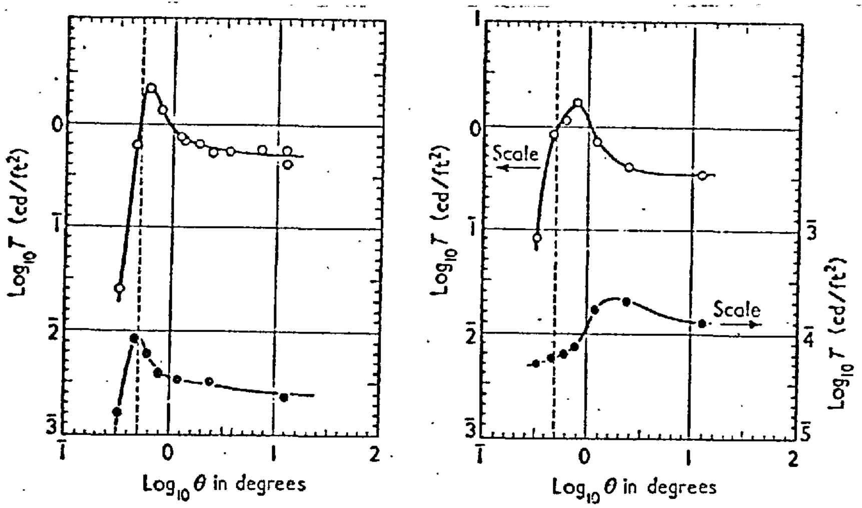
Fig. 134. Thresholds for a flashing light ($\alpha = 8'$, $t = 100$ ms., $n = 1$ c.p.s.), viewed in a dark surround against a 12° field of 1000 trolands for different sizes of the dark surround. θ is the eccentricity with the visual axis (temporal retina).

angular subtense produced when the flash was viewed within a dark surround (35' angular diameter) in the centre of a 12° conditioning field of 1000 trolands. The upper curves A (fig. 130) give the thresholds when the test flash is superimposed on the 1000 trolands background (cf. fig 61); the presence of the dark surround lowers the threshold by about 1 log unit (curves B). Similar results have been obtained by Stiles and Crawford (1932-1933). One unexpected feature was the crossing over of the two lowest curves, an increase in the flash duration leading to an increase in the threshold, with long flashes the threshold was more difficult to determine and the flashing character less distinct in presence of the dark surround. The effect of the change in the flash duration upon the threshold was therefore investigated and the results are shown in the next diagram (fig. 131). The upper curves are in fair agreement with fig. 104 and in central fixation the dark surround leads to a slightly greater degree of temporal summation. With increasing eccentricity there is however a marked tendency for the thresholds to rise at long flash durations confirming the previous observations. All the observations in these experiments were taken by approaching the threshold from below and the short line at S on the curves gives the corresponding threshold for a steady light under similar conditions. The threshold for the steady light is always higher than the lowest threshold attainable by using a flashing light (cf. p51-52).

Fig. 132 shows the effect of changing the frequency of the flashes, the flash duration t being kept at $^1/10$ of the flash period T (light-dark ratio 1:9). There is an increase in threshold at high frequencies. The data for the curves A are plotted differently in fig. 133 and the points at 5° and 0° eccentricity give initially a reasonably good fit to a line of slope -1, showing that it is primarily the flash duration and not the frequency that determines the threshold. At 10° eccentricity a steeper gradient is obtained indicating increased summation, though a more plausible explanation is that at large eccentricities the flash tends to appear at high frequencies more like a steady light with a consequent increase in the threshold. The introduction of the dark surround (curves B, fig. 132) led to a rather unexpected phenomenon. At low frequencies ($\theta = 10°$), the threshold occurs at around the expected value, but raising the frequency makes the flash character indistinct and the effect of the flash is to fill up the "hole" in the background. On further increasing the luminance the flash appears as flashing against a uniform background, and under certain circumstances two distinct thresholds can be obtained: one in which the flash appears within the dark surround and a higher one in which the background appears uniform. At high frequencies the threshold at 10° eccentricity is essentially the same whether the dark surround is present or not. The effect of the size of the dark surround on the threshold for a flash of angular subtense 8' is illustrated by fig. 134. As the size of dark surround is increased a point is reached at which there is a steep drop in the threshold in peripheral vision; this may also occur in central fixation with smaller angular subtenses than those employed but the change may be less marked. At 5° eccentricity the dark background is not perceived if its angular subtense is less than about 30' and at 10° eccentricity the presence of the dark background may actually raise the threshold above its value in absence of the background! Clearly, the injudicious use of a dark background may lead to a deterioration in the performance of a signal. These results should be compared with those of Crawford (1940, fig. 135) which show the changes in the incremental threshold for the eye in equilibrium with a steady conditioning field for various sizes and brightnesses of the latter.

Multiple flashes.

Group flashing is considered to lead to greater conspicuity and may make it easier to take a bearing in navigation (p.78). When the component flashes within a group are well separated in time, the threshold and suprathreshold apparent intensity of the signal as a whole are essentially the same as for one of the component flashes, but when the individual flashes follow each other in rapid succession it seems possible that the group may have different properties from a single flash. During the course of the experiments described in the preceding section it was found that at frequencies higher than about 8 c.p.s the impression of flicker is obtained even against high background luminances and it is certainly not possible to count the individual flashes when the frequency exceeds 4 or 5 c.p.s. For the dark adapted eye, the



(a) (b)

Fig. 135. (a) Variation of brightness threshold (T) with angular diameter of conditioning field (θ). Subject B.H.C. Fovea. Test field diameter, 0.50°; exposure, 1 sec. ○, conditioning field brightness = 39 cd./ft.^{2}; ●, conditioning field brightness = 0.19 cd./ft.^{2}

(b) Variation of brightness threshold (T) with angular diameter of conditioning field (θ). Subject B.H.C. Parafovea 8°. Test field diameter, 0.50°; exposure, 1 sec. ○, conditioning field brightness = 3.8 cd./ft.^{2}; ●, conditioning field brightness = 0.000123 cd./ft.^{2}
(From Crawford, 1940)

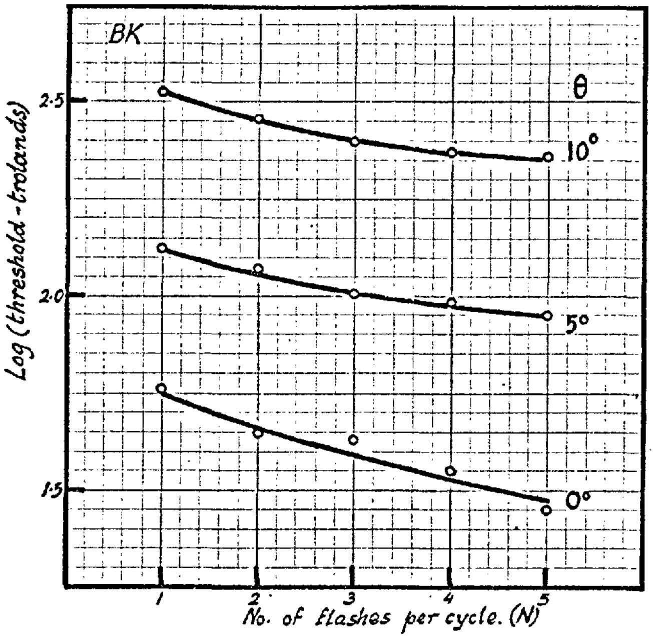


Fig. 136. Thresholds against a 12° background of 1000 trolands for a group of flashes (α = 16'), for different numbers N of component flashes in the group. The individual flashes are of 50 ms. duration at 100 ms. intervals and the last flash in the group is followed by a dark interval bringing the group period up to 1 second. θ is the eccentricity (temporal retina).

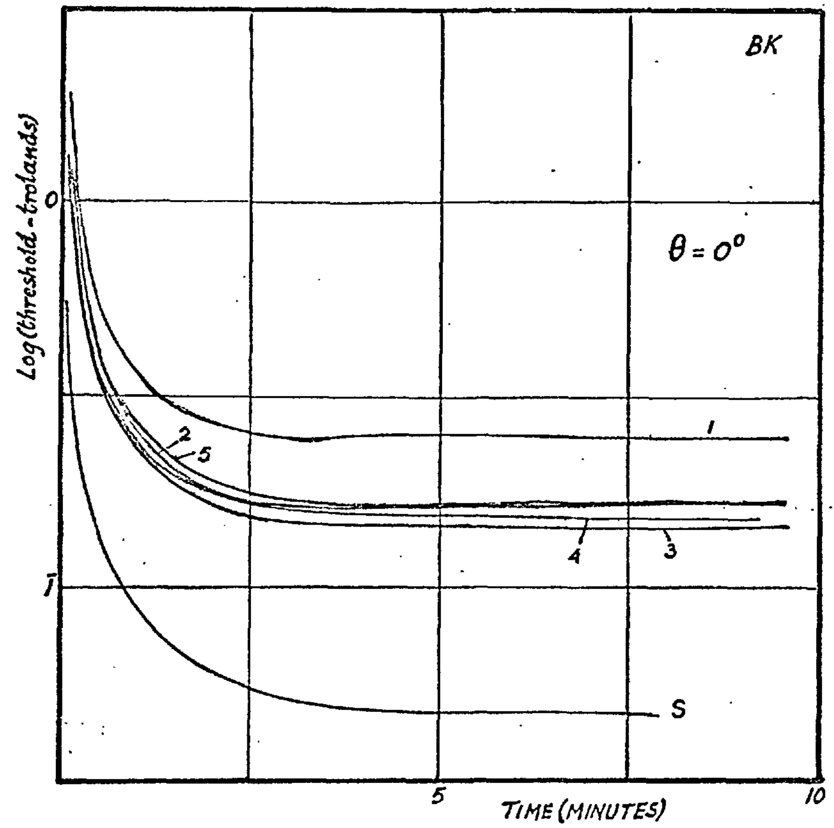


Fig. 137. Recovery curves in central fixation for multiple flashes after 3 min. pre-adaptation to a 12° field of 1000 trolands. Duration of each component flash = 50 ms; dark interval between component flashes = 50 ms, group frequency = 1 c.p.s., α = 32'. Figures indicate the number of components in the group. S is the corresponding curve for single flashes (α = 32', t = 2 sec., n = ¼ c.p.s.)

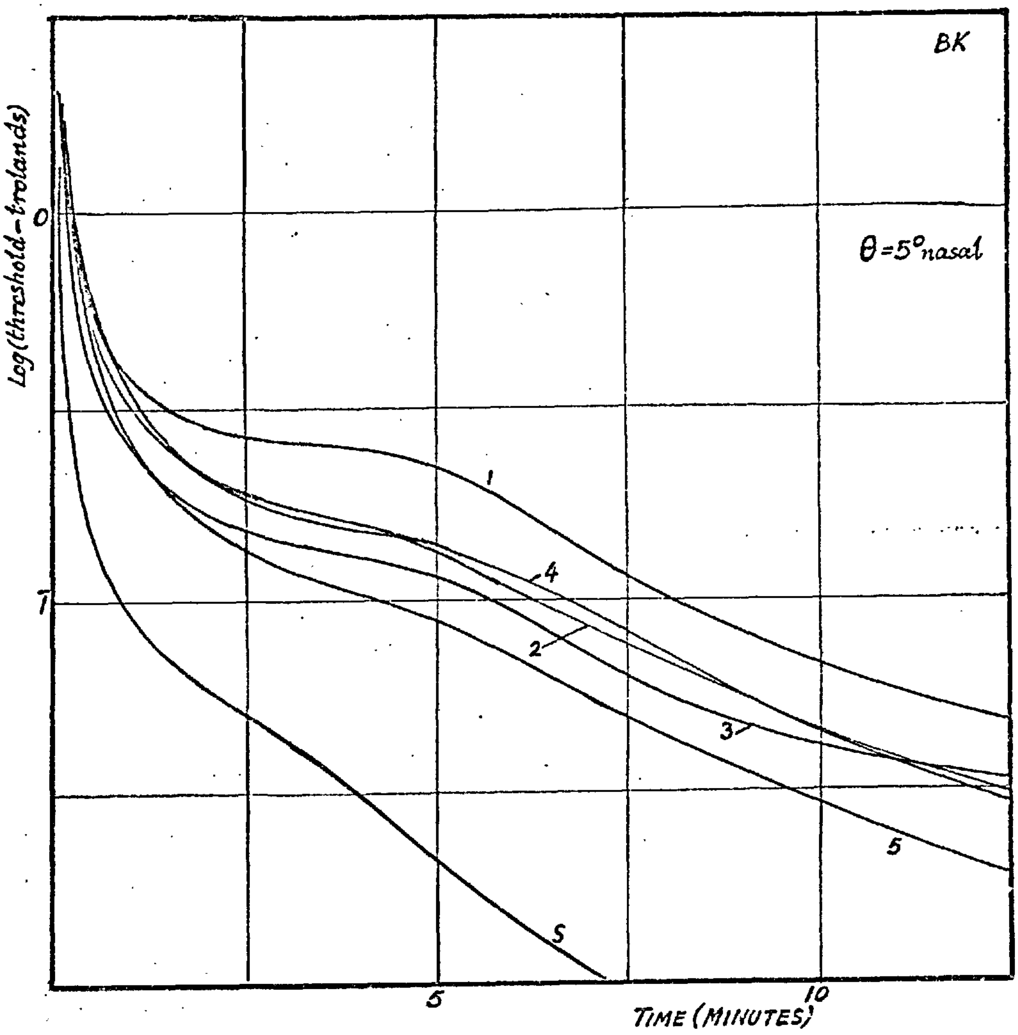


Fig. 138. Recovery curves at 5° (nasal retina) for multiple flashes after 3 min. pre-adaptation to a 12° field of 1000 trolands. Duration of each component flash = 50 ms; dark interval between component flashes = 50 ms, group frequency = 1 c.p.s., α = 32'. Figures indicate the number of components in the group. S is the corresponding curve for single flashes (α = 32', t = 2 sec., n = $\frac{1}{4}$ c.p.s.)

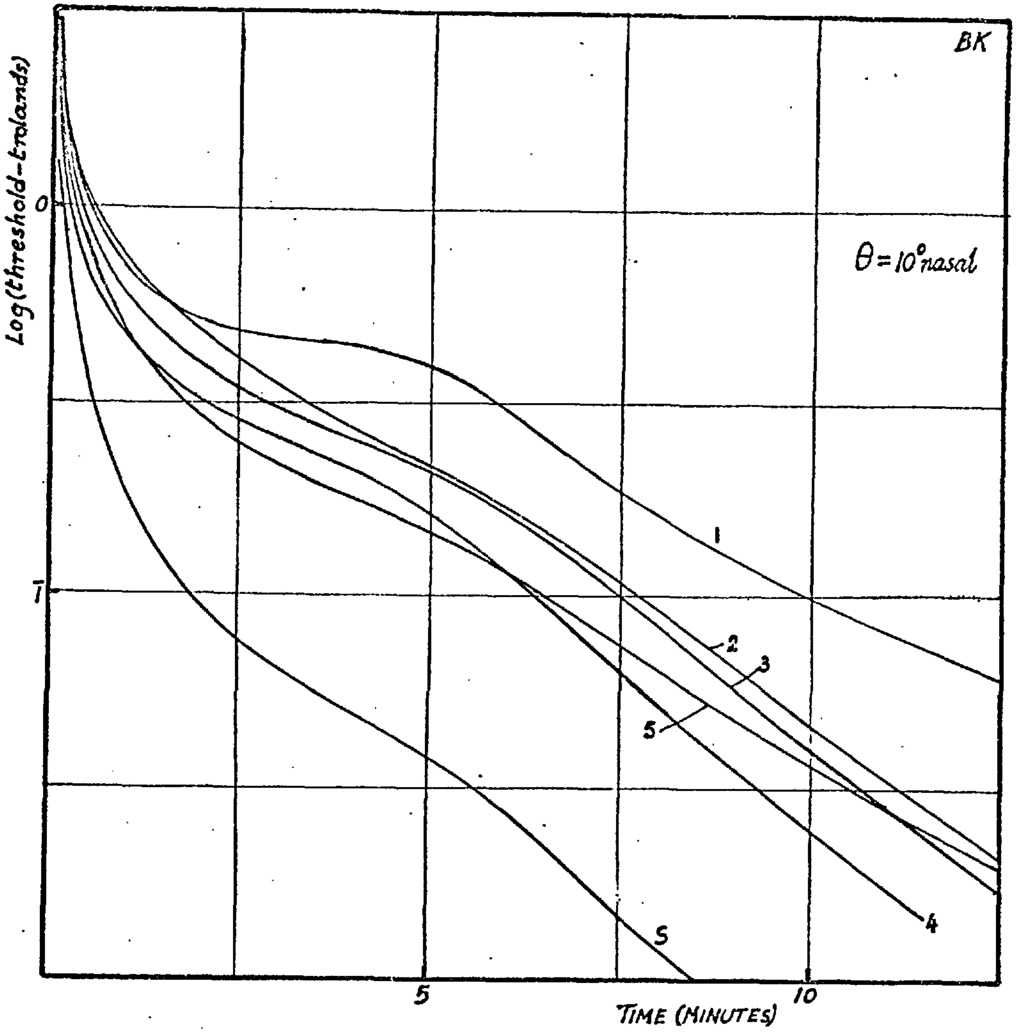


Fig. 139. Recovery curves at 10° (nasal retina) for multiple flashes after 3 min. pre-adaptation to a 12° field of 1000 trolands. Duration of each component flash = 50 ms; dark interval between component flashes = 50 ms, group frequency = 1 c.p.s., α = 32'. Figures indicate the number of components in the group. S is the corresponding curve for single flashes (α = 32', t = 2 sec., n = $\frac{1}{4}$ c.p.s.)

critical fusion frequency is very low and the flashing character may not be identifiable above 3 or 4 c.p.s. In rapid group flashing, conceivably the upper useful limit would be around 4 or 5 component flashes with a group frequency of about 1 c.p.s. The experiments described below were performed to find out to what extent the characteristics of a rapid "grouped flash" were different from those of a single flash.

Each group consisted of N individual flashes of duration t' and square waveform following one another at intervals of 0.1 second; a dark interval was inserted at the end of the last flash in the group to bring the total period of the group up to 1 second. It was relatively easy to distinguish between three cases: single flash, double flash, more than two flashes. When the group contained more than two flashes it was difficult to tell the exact number of components. The values of the threshold for flashes of angular subtense 16' viewed against a background of 1000 trolands are plotted against the number of components N in fig. 136 at three eccentricities. There is no appreciable gain to be obtained in practical applications with increase in N. The apparent luminance was measured for a single flash and a group of 5 flashes of angular subtense 10.9' and actual luminance 100 trolands at different values of the flash duration t' against a dark background (table 11). There seems again no advantage to be gained in this respect by using multiple flashes, the values in the two cases agreeing to within about 0.1 log unit.

TABLE 11.

The figures give the logarithm of the apparent troland value for a single flash at 1 c/s as compared with that of a group of 5 similar flashes spaced at 0.1 sec. intervals and followed by a dark interval to bring the group period up to 1 second. $\alpha = 10.9'$ and t' is the duration of the individual flashes. The actual flash luminance is of troland value 100.

t' (ms.)	Single flash.	5 component flashes.
10	1.99	1.89
20	2.15	2.06
30	2.18	2.14
40	2.18	2.22
50	2.28	2.19

Dark adaptation curves were next recorded with N = 1,2,3,4,5 after the eye had been pre-adapted for 3 minutes to a white 12° field of troland value 5000 (fig 137-139). S is the corresponding curve for a flash of duration 2 sec and frequency 1/4 c.p.s. Each curve is a single determination or the mean of two determinations. The course of recovery is much the same when two or more flashes are used and the curves for N = 2 to 5 tend to form a cluster separated from the curve for a single flash. This indicates some degree of summation occurring over successive flashes with dark adaptation. In case this summation extends to two flashes the curves for the multiple flashes will be displaced about 0.3 log unit below the curves for a single flash, which is roughly what is obtained in central fixation and at 5° eccentricity. On further dark adaptation there is some indication that summation may be

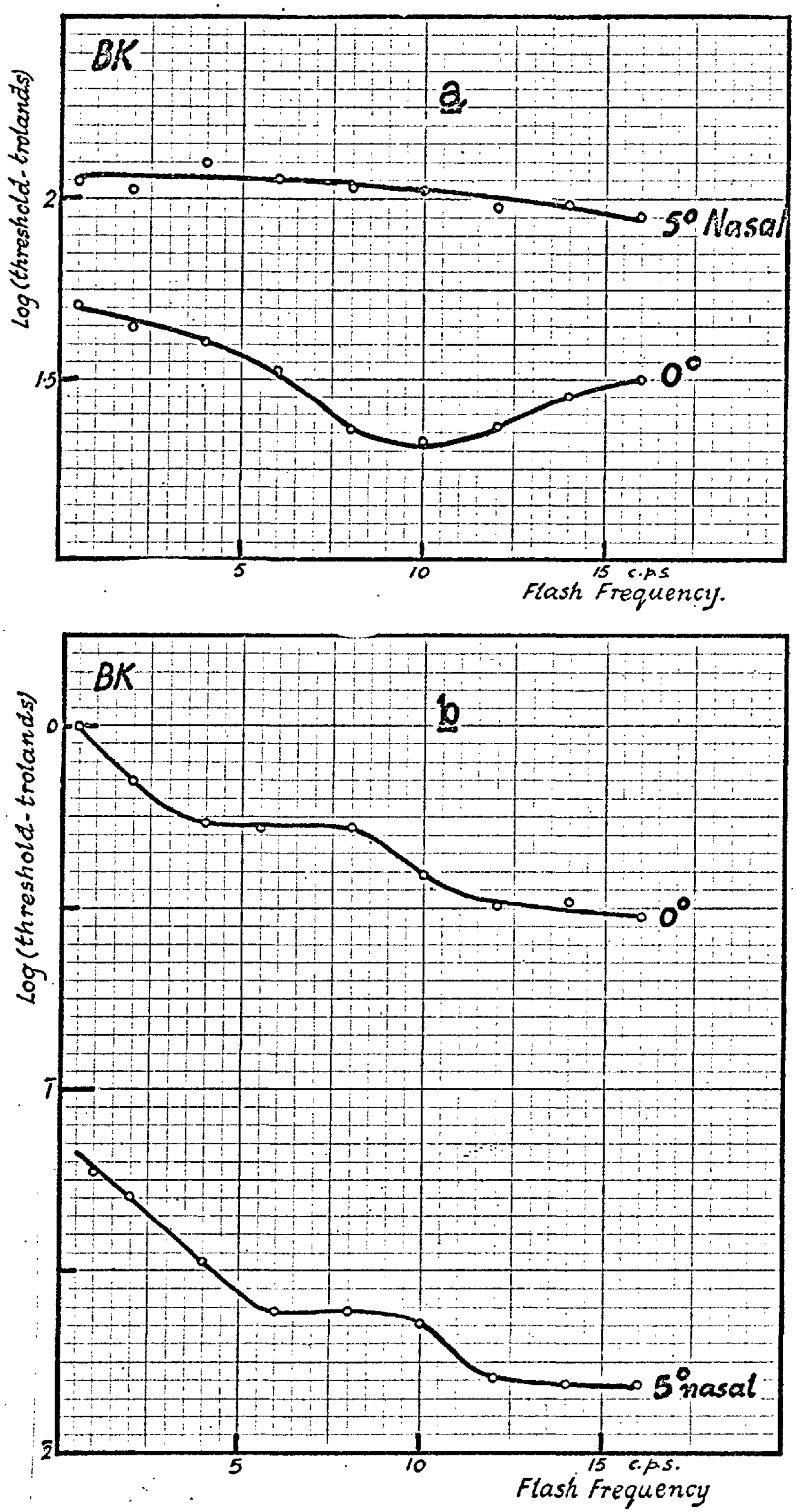


Fig. 140. Variation of threshold with flash frequency for flashes of constant duration t = 30 ms, viewed (a) against a 12° background of 1000 trolands and (b) a dark background.. (α = 32').

extending to 3 flashes at 10° eccentricity, but the evidence is not conclusive.

It appears therefore that apart from a slightly reduced threshold at low levels of light adaptation, the characteristics of a group of flashes are not markedly different from those of one of its components. Any gain in conspicuity achieved through grouping flashes must arise from the difference in appearance of the signal relative to other lights in the background - clearly a gain achieved through increase in metathetic contrast (p.10).

Changing the dark interval between flashes.

The effect of varying the dark interval between flashes of angular subtense 32' and duration 30 ms. was investigated by measuring the incremental threshold against a 1000 troland background and the absolute threshold in central fixation and at 5° eccentricity. The values of the threshold are shown plotted against the flash frequency in fig. 140 and indicate that different effects may be obtained under different conditions. Against a high background luminance and in peripheral vision the only noticeable change is the slow fall in the threshold at high frequencies as might be expected from Talbot's law. In central fixation however there is a well defined minimum at a frequency of about 10 c.p.s. Under similar conditions, de Lange Dzn (1961) found a greater sensitivity to flicker in his studies on the critical fusion frequency.

In dark adaptation there is an initial fall in threshold with increase in frequency, but once the flashing appearance is replaced by the sensation of flicker the threshold remains fairly constant. On further increase in the frequency the disappearance of flicker is accompanied by another drop in the threshold which is followed by a slow decrease as expected from Talbot's law. The data are meagre and insufficient and further confirmation is required before any conclusions can be derived from them, but they should be compared with those of Schmil who under similar conditions obtained a smooth transition with increase in the flash frequency (fig. 23, p.73).

CHAPTER X

SOME THEORETICAL CONSIDERATIONS.

Towards the end of the last century Cajal (1892-1893) used the light microscope to study the fine structure of the retina and this work was carried a large step forward through the extensive researches of Polyák (1941) some decades later. The type of structure revealed by such investigations has been illustrated in fig. 56 (p.142). Recently, Pedler (1965) has used the technique of electron microscopy to study the synaptic layers of the retina and the higher resolving power of the electron microscope has revealed interconnecting processes of such amazing complexity as have led him to regard these structures as operating like tiny computers and the retina as a data-processing device. Spatial perception is a complex phenomenon involving the perception of distance and orientation, form and colour, the detection of the movement of objects in the field of vision while compensating for the movement of the images of stationary objects across the retina, sharpening of the contours and improvement of the quality of the retinal image, etc., and these may depend on various processes of cybernetic feedback within the retina itself. On the other hand as different light patterns fall in rapid succession upon the retina, each must be perceived with complete obliteration of the impression created by the preceding pattern and the retina seems able to accomplish this over the whole of the visual field with near complete success. Because of the complexity of visual perception no simple theory is likely to account for the visual process, and unless and until the roles of the various retinal structures are more fully understood any theory must consist of some speculation.

The representation of the spatial and the temporal integrating ability of the visual system near threshold in the forms

$$L\omega^k = C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

and

$$It^n = c \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

is a convenient mathematical symbolism and the following interpretations may be given according to the value of the exponent. So long as the summation indices k and n are equal to unity, one may with some degree of confidence associate the maximum value of the solid angle ω and the exposure time t with the spatial and temporal resolving limits of the eye; zero index indicates absence of any further interaction. Fractional exponents on the other hand indicate varying degrees of interaction, though the experiment can seldom decide upon the exact nature of these interactions and occasionally such indices may arise from spurious effects introduced by the experimental technique. A negative exponent has been taken as indicating inhibition and one greater than unity some form of enhancement. Considering Pedler's discoveries, it does not seem surprising that widely different values have been obtained for the spatial summation index by different investigators under different conditions. It would seem to the author however that temporal summation may be a relatively simpler phenomenon, in spite of the dependence of the Bloch summation time upon the degree of spatial summation and the level of adaptation of the eye. The transition from complete summation (It = const.) to no summation (I = const.) is relatively sharp, irrespective of the retinal location, level of adaptation or spectral composition of the stimulus (chapter VI), and there is relatively little change in the degree of summation across the retina under any given condition of adaptation. In general the results of psychophysical experiments are in fair agreement with those of electrophysiological studies.

During the course of the present investigations it gradually dawned upon the author that the perception of a flashing light at or above the threshold may be largely determined by the degree of temporal summation and its relation to the rise and fall of the visual response during transient stimulation. An attempt has been made in what follows at explaining the results of certain experiments in these terms, and some of the ideas may be similar to those put forward by Luizov (1958). Very few data seem available in the literature on the perception of flashing lights well above the threshold and the agreement between such data is not very good, so that in view of the preceding paragraphs, the attempt may appear rather foolhardy. Nonetheless, without making any claims as to the correctness of the assumptions made, which can only be validated or disproved by future experiments, it is hoped that an indication is hereby given as to methods of approach to the problem which are different from those which have been so far conventionally used in the design and practical applications of flashing light signals.

Outline of a basic formula.

Let there be a source of light of variable intensity E (t) producing at the eye pupil an illumination E'(t). If the eye pupil be constant in diameter (Maxwellian field or artificial pupil), E' (t) will be proportional to E(t) and we can write

$$E'(t) = k.\ E(t) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (37)$$

The source will appear to an observer to have an apparent instantaneous intensity I (t) and in general

$$I(t) \neq E(t).$$

At any particular instant, we can visualise two processes going on simultaneously:

1.) the stimulation of the eye by the light tending to increase I (t),

2.) the decay of the visual sensation due to previous stimulation causing a decrease in the apparent intensity.

In general, over a short interval dt at an instant t, the increase dI in the apparent intensity due to additional stimulation will be proportional to E' (t) or E (t), but the constant of proportionality will be dependent upon the state of adaptation of the eye at the instant t. Let $\Phi(t)$ be this constant of proportionality, so that we can write

$$dI = \Phi(t).\ E(t).\ dt \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (38)$$

At a later instant τ, $(\tau > t)$, there will be left of this dI a fraction dI' defined by

$$dI' = dI.\ \Psi(\tau - t) \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (39)$$

where $\Psi(\tau - t)$ is some suitable function giving the decay of the apparent intensity with time.

The apparent intensity of the flashing light above that of an equal area of the background at time τ may now be obtained by performing the integration

$$I\ (\tau) = \int_0^{\tau} dI' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (40)$$

and substitution of the values of dI', dI from (39) and (38) yields

$$I\ (\tau) = \int_0^{\tau} \Psi(\tau - t).\ dI$$

or

$$I\ (\tau) = \int_0^{\tau} E(t).\ \Phi\ (t).\ \Psi\ (\tau - t)\ dt \quad . \quad . \quad . \qquad (41)$$

A knowledge of the decay function $\Psi(\tau-t)$ and the function $\Phi(t)$ characterising the state of adaptation of the eye should theoretically allow us to calculate I (τ). We shall refer to $\Phi(t)$ as the response function.

(Note: In the above formulae, assuming a constant source size, apparent intensity I may be replaced by apparent luminance L).

<u>The decay function $\Psi(\tau-t)$</u>

It seems reasonable to assume that this function must be such as to tend to 1 when $(\tau-t) \rightarrow 0$ and to tend to 0 when $(\tau-t) \rightarrow \infty$. Further if there is a steady light (E) and the eye is maintained at a constant level of adaptation, $\Phi(t) = c$, constant, and equation (41) may be written as

$$I\ (\tau) = cE\int_0^{\tau} \Psi(\tau - t).\ dt \quad . \quad . \quad . \quad . \quad . \qquad (42)$$

Further if we neglect the fading of the retinal image, for large τ, I (τ) attains a constant value; it is therefore essential that $\int_0^{\tau} \Psi(\tau-t)$ should be finite as $\tau \rightarrow \infty$.

Attempts have been made at various times to determine the nature of the decay function through studies of the visual after-image. Lasareff (1923) found an exponential type of decay while Pannevis (1948) found a power law type of decay. Craik and Vernon (1941) obtained an exponential decay for a white light stimulus with a time constant of about 30 sec. Rushton (1958, 1961) has quoted time constants of 130 and 360 sec. for the regeneration of the cone and the rod pigments respectively. Alpern and Barr (1962) deduced time constants of the order of 20 sec and 100 seconds for the decay of the cone and the rod photoproducts and concluded that the duration of the after-image is determined solely by the length of time it takes for the product of the photo-chemical reaction to deplete to some threshold value, casting doubt on Lassalle's photochemical explanation for the Broca Sulzer phenomenon (1947). The most recent and complete studies are possibly those of Padgham (1953, 1957, 1963); he has shown that whereas the after-images for monochromatic stimuli decay according to an exponential law, those formed by white light possibly obeyed a power law of the type

$$R = C.t^{-n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (43)$$

where $n \approx 3$. He has further shown that if the different types of receptors gave after-images decaying exponentially it could well happen that the overall effect might closely approximate to a power law. This author however quotes the rather short time constants of 6 sec. and 21 sec. for small and large field stimuli and thinks that these shorter time constants point to an electrical origin, suggesting that electrical models simulating nerve transmission are resistor and capacitor networks and the charges and potentials on such systems as well as the electrotonic potential on the axons of the ganglion cells would follow an exponential decay.

A different approach was that of Crawford (1947; fig. 129, p.255) who measured the changes in state of the visual adaptation by using a liminal test stimulus as the measure of the degree of adaptation. The decay part of Crawford's curves consist of two parts: an initial rapid fall over a period of about 0.1 second, followed by one of more gradual slope; there is also some evidence of an off-effect at the moment of cutting off the conditioning stimulus. Crawford's results may be explained on the basis that the apparent brightness is made up of two components: (i) a component with a fast decay rate possibly of "neural" (electrical) origin (time constant$\approx$0.02 secs.) and (ii) a "photo-chemical" component (time constant$\approx$0.5 sec.). The decay part of the curve can be represented by an equation of the type

$$I = ae^{-\phi_1 t} + be^{-\phi_2 t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

and assuming values 100 for a, $\phi_1 = 50$, and values between 1 and 3 for b, $\phi_2 = 2$, one can obtain fairly good approximations to these decay curves.

The faster component found by Crawford cannot be followed by methods based on study of the visual after-image, and even the decay rate for the photo-chemical decomposition products indicated by his experiments seems abnormally fast compared with results obtained by other workers; this should not however be too surprising when we consider the ease with which the eye adapts itself to rapidly varying

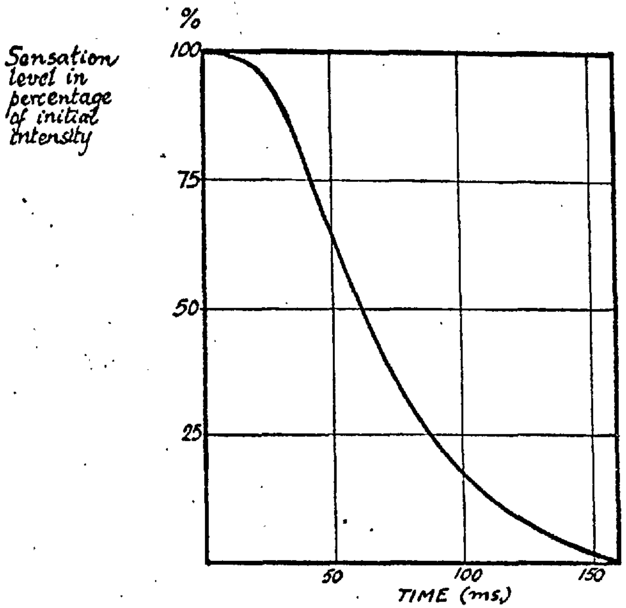


Fig. 141. Curve of the disappearance of the sensation of light (Piéron).

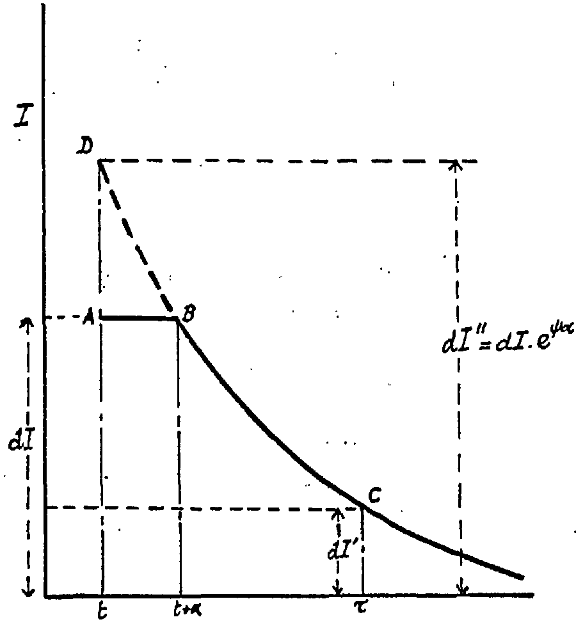


Fig. 142. Delayed exponential type of decay.

stimuli as we shift our gaze across a scene. In fact one cannot completely exclude the possibility that the faster decay rate may also be of "photo-chemical" origin. Following an earlier study by Crawford (1940) and using a monomolecular reaction as a qualitative illustration:

If n be the concentration of the photo-sensitive substance at time t, N the equilibrium concentration in the dark and I the intensity of light falling upon the retina, the equation representing the kinetics of the reaction during the exposure of the eye to light is

$$-\frac{dn}{dt} = KIn - L\,(N-n) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (45)$$

where K and L are constants of the forward and reverse reactions. Integrating and putting n = N at t = 0,

$$n = \frac{N}{KI+L} \cdot \left(KIe^{-(KI+L)t} + L\right) \quad . \quad . \quad . \quad . \quad . \qquad (46)$$

and it is clear from this that if K and L are large, the equilibrium concentration will be rapidly attained. In fact Crawford's results indicate that L may be smaller in value but quite comparable to K.

When the light is cut off the reverse reaction proceeds according to

$$\frac{dn}{dt} = L\,(N-n) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (47)$$

which on integration yields the exponential law

$$N-n = (N-n_0)e^{-Lt} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (48)$$

where n_0 is the value of n at the moment of cutting off the light.

It is quite possible that the primary photo-chemical decomposition is followed by secondary chemical decompositions of relatively slow speed and Crawford has produced evidence in favour of this. The changes in sensitivity which occur during upward adaptation consist of the fast α - adaptation of Schouten and Ornstein (1939) and the slower β - adaptation of Wright (1946, pp.126-128) and there is the possibility that both types of adaptation are photo-chemical in nature. Whatever be the origin of the decay process, it seems reasonable to assume that it is the faster decay rate as found by Crawford that will largely determine the visual response in transient or intermittent illumination, and that this may be of an exponential nature with a time constant of the order of 0.02 second.

One further notes that the duration of the visual impression for extremely short flashes, e.g. an electronic flash, may last for a significant fraction of a second - several times the actual flash duration. This is supported by physiological evidence as obtained by Adrian and Matthews (1927), Hartline (1934), Granit (1947). It seems therefore that the decay of the apparent brightness, which is small or negligible at first, is later accelerated. In fact, Piéron (1935) gives the curve of fig. 141 for the disappearance of the sensation of light.

In addition to the conditions laid down on p. 157, we shall assume therefore that the decay function for the apparent intensity must be such as to maintain the apparent intensity constant (or nearly so) over a certain interval (of the order of 0.1 second) followed by a fairly rapid decay of an exponential or possibly a power-law type. Some simple mathematical functions which satisfy these requirements are next considered.

The Inverse-Power Law type of decay.

One function which satisfies the necessary conditions and which is readily integrable is

$$\Psi(t) = \frac{\theta^n}{(\theta+t)^n}, \text{ where } n>1 \tag{49}$$

This function represents a decay curve similar to that in fig. 141; it diverges for $n \leqslant 1$, but converges for $n>1$. The simplest case arises when $n = 2$ and therefore taking $n = 2$, we write

$$\Psi(t) = \frac{\theta^2}{(\theta+t)^2} \tag{50}$$

For a square wave flash close to the threshold, against a dark or luminous background, we can assume to a first approximation that the state of adaptation of the eye is not changed by the flash so that putting $\Phi(t) = c$, equation (41) may be written as

$$I\ (\tau) = \int_0^\tau cE.\ \Psi(\tau-t)\ dt \tag{51}$$

Writing $x=\tau-t$, $dx = -dt$ and when $t = o,\tau$, $x = \tau,o$, so that

$$\begin{aligned} I\ (\tau) &= -\int_0^\tau cE\ \Psi(x)\ (-dx) = \int_0^\tau cE\,\Psi(x)\ dx \\ &= \int_0^\tau cE\,\Psi(t)\ dt \end{aligned} \tag{52}$$

Substitution of the value of $\Psi(t)$ from (50) yields

$$I\ (\tau) = \int_0^\tau cE.\frac{\theta^2}{(\theta+t)^2}\ dt$$

$$I\ (\tau) = c\theta\ \frac{E\tau}{\theta+\tau} \tag{53}$$

Bearing in mind that as $\tau \rightarrow \infty$, $I\ (\tau) \rightarrow E$ (p.157), the apparent intensity being equal to the steady light intensity, it follows that $c\theta = 1$, and we have

$$I\ (\tau) = \frac{E\tau}{\theta+\tau} \tag{54}$$

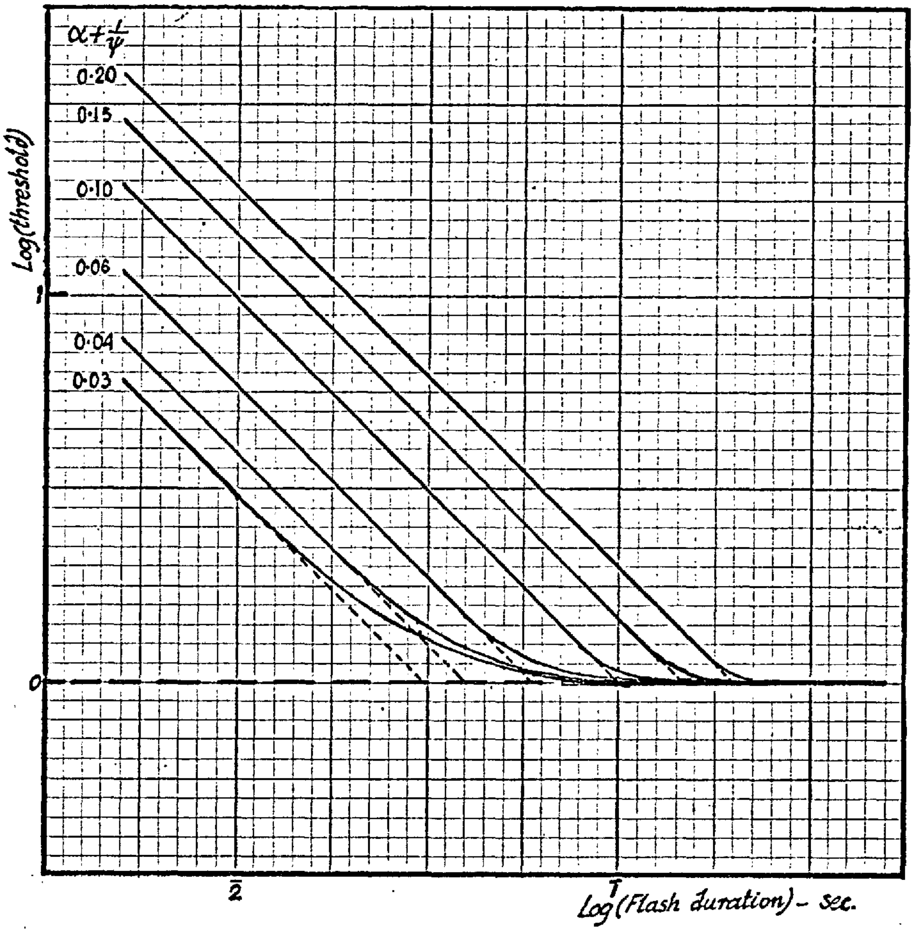


Fig. 143. Change of threshold with flash duration according to formula assuming delayed exponential decay. The dotted lines at a slope -1 would be expected on the basis of Bloch's law. The vertical scale is arbitrary and the horizontal line through the ordinate 0 is the threshold for a steady source, I = constant.

which is the Blondel-Rey equation. As τ becomes very small, $I(\tau) \rightarrow \frac{E\tau}{\theta}$, and for large τ, $I(\tau) \rightarrow E$.

The Exponential type of decay.

(a) Sigmoid type.

Assuming that the decay is of the sigmoid type (fig. 141), the decay function may be conveniently taken as

$$\Psi(t) = \frac{1+\theta}{\theta+e^{\psi t}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (55)$$

which satisfies the conditions $\Psi(t) \rightarrow 1$ as $t \rightarrow o$,

$\Psi(t) \rightarrow o$ as $t \rightarrow \infty$,

and has a finite integral as $t \rightarrow \infty$.

Following similar steps as in the preceding section, for a square wave flash close to the threshold and stable adaptation we write

$$\begin{aligned} I(\tau) &= \int_o^\tau cE\,\Psi(\tau-t)\,dt = \int_o^\tau cE\,\Psi(t)\,dt \\ &= cE\,(1+\theta)\int_o^\tau \frac{1}{\theta+e^{\psi t}}\,dt \quad . \quad . \quad . \quad . \quad . \quad . \quad (56) \end{aligned}$$

Writing $x = e^{\psi t}$ and performing the necessary substitutions and integration gives

$$I(\tau) = \frac{cE\,(1+\theta)}{\psi\theta}\ \log_e\left\{\frac{(1+\theta)e^{\psi t}}{\theta+e^{\psi t}}\right\} \quad . \quad . \quad . \quad . \quad . \quad (57)$$

As $\tau \rightarrow \infty$, $e^{-\psi\tau} \rightarrow o$ and $I(\infty) = \frac{c\,(1+\theta)E}{\psi\theta}\log_e(1+\theta) = E$

so that

$$\frac{1}{c} = \frac{1+\theta}{\psi\theta} \cdot \log_e(1+\theta) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (58)$$

For small τ, writing $e^{\psi\tau} = 1$ in the denominator of the bracketed expression of eq. 57, we have

$$I(\tau) = \frac{E\tau}{\frac{1}{\psi}\log_e(1+\theta)}$$

and writing $\alpha = \frac{1}{\psi} \log_e (1+\theta)$,

$$I(\tau) = \frac{E\tau}{c}.$$

In general, substitution of the value of c in eq. 57 gives

$$I(\tau) = \frac{E}{\log_e (1+\theta)} \log_e \frac{(1+\theta)}{(1+e^{-\psi\tau})} \quad . \quad . \quad . \quad . \quad . \qquad (59)$$

which is the equation corresponding to the Blondel-Rey equation in this case.

With suitable values for the constants θ, ψ, this equation can give a better fit to the Toulmin-Smith and Green data (fig.1, p.9) than the Blondel-Rey law (fig. 9, p.39), particularly over the initial portions of the curve.

(b) Delayed type of exponential decay.

In this case we assume that the apparent intensity remains at a constant value for a period of time α, after which an exponential decay sets in. This may very well happen if we imagine an off-effect triggering off the decay process and the decay curve would be as ABC in fig. 142. Assuming near threshold conditions of stable adaptation and a square-wave flash, we have

(1) for $\tau \leqslant \alpha$,

$$I = \int_0^\tau c\,E\,dt = cE\tau \, . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (60)$$

(2) for $\tau > \alpha$,

the integral may be broken up into two parts:

(i) a part $o < t < \tau - \alpha$ for which decay has already started,

(ii) a part corresponding to $\tau - \alpha \leqslant t \leqslant \tau$ for which there has been no decay.

For the mathematical treatment of the decay process, we may use the following artefact (fig. 142):

Let there at time t be an increment dI in the apparent intensity of which there is a fraction dI' left at time τ. The decay has proceeded exponentially only for time $\tau - (t+\alpha)$, but for calculations we can assume that the decay started at time t at the point D, obtained by producing the exponential part of the curve backwards, and that the initial increment was $dI'' = dI.\, e^{\psi\alpha}$ instead of dI. Thus for $\tau > \alpha$,

$$I\ (\tau) = \int_0^{\tau-\alpha} c.Ee^{\psi\alpha}.e^{-\psi(\tau-t)}dt + \int_{\tau-\alpha}^{\tau} cE.dt$$

$$= \frac{cE}{\psi}\ (1 - e^{-\psi(\tau-\alpha)}) + cE\alpha \quad . \quad . \quad . \quad . \quad . \quad . \quad (61)$$

As $\tau \rightarrow \infty$, $I\ (\infty) = cE\ (\frac{1}{\psi} + \alpha) = E$

so that

$$c = \frac{1}{\alpha + \frac{1}{\psi}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (62)$$

For small τ, $(\tau \leq \alpha)$,

$$I\ (\tau) = cE\tau = \frac{E\tau}{\alpha + \frac{1}{\psi}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (63)$$

and in general,

$$I\ (\tau) = \frac{E}{\alpha + \frac{1}{\psi}}.(\frac{1}{\psi}\ (1 - e^{-\psi(\tau-\alpha)}) + \alpha) \quad . \quad . \quad . \quad . \quad . \quad (64)$$

This equation gives about as good a fit to the Toulmin-Smith and Green data as equation 59 and lends itself more easily to mathematical manipulation.

Equivalent integration time.

Threshold experiments all indicate that for very brief flashes the visual response is dependent on the total energy content of the flash and not upon the temporal distribution of this energy or the duration of the flash (chapter VI). The various types of decay function considered all aim at satisfying this temporal summation condition for brief flashes - in fact the delayed exponential decay exactly satisfies it; for brief flashes we have derived

$$I(\tau) = \frac{E\tau}{\theta}, \quad \text{(inverse power law);}$$

$$I(\tau) = \frac{E\tau}{\alpha} \text{ where } \alpha = \frac{1}{\psi}\log_e(1+\theta), \quad \text{(sigmoid exponential decay);}$$

$$I(\tau) = \frac{E\tau}{\alpha+\frac{1}{\psi}}, \quad \text{(delayed exponential decay).}$$

It will be noted that the factors $\frac{1}{\theta}$, $\frac{1}{\alpha}$, $\frac{1}{\alpha+\frac{1}{\psi}}$ by which $E\tau$ has been multiplied to give $I(\tau)$ were introduced into the calculations to make $I(\infty) = E$ for very long flashes or steady lights. Extending the idea of temporal summation to include flashes of all durations, it follows that under steady illumination conditions, the visual response at an instant t is the same as if the eye were summating over an interval terminating at t and equal to the denominators of these fractions (θ, α, $\alpha+\frac{1}{\psi}$), ignoring all previous stimulation. In fact all these quantities have the dimensions of time and we shall define them as the "equivalent integration time under steady illumination conditions" or simply the "integration time Θ".

Assuming a time constant of 0.02 sec, $\psi = 50$, as indicated by Crawford's experiment for rapid decay (p.280) equation 64 has been used to calculate the threshold for various values of the integration time (fig. 143) - the intersection of the sloping and horizontal parts of the curve give the integration time $\Theta = \alpha+\frac{1}{\psi}$. The corresponding curves for the same values of Θ in the case of the Blondel-Rey equation have been given in fig. 84. Comparison of fig. 143, 84

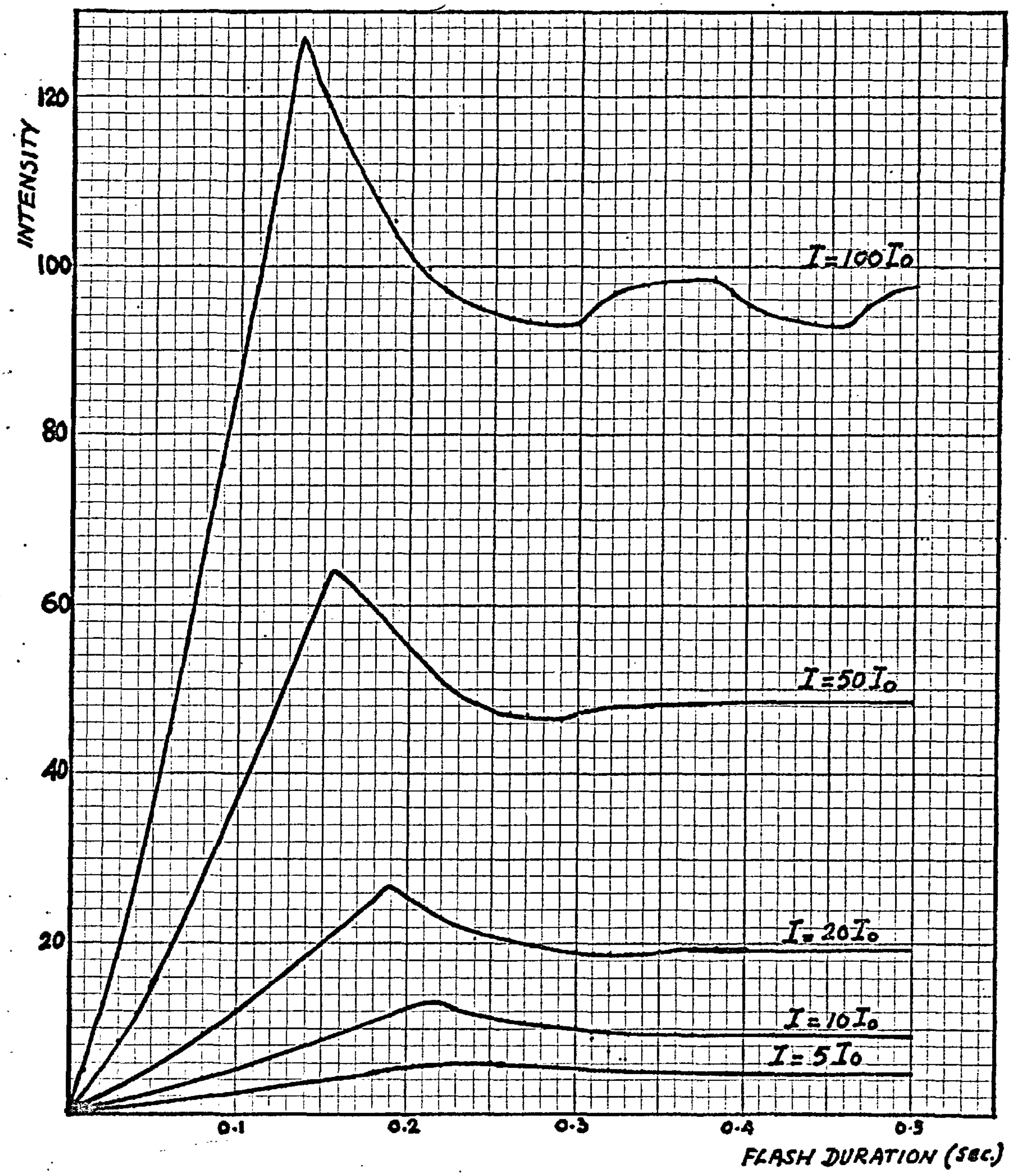


Fig. 144. Change of apparent intensity with flash duration on the assumption of delayed type of exponential decay. I_o is the threshold intensity.

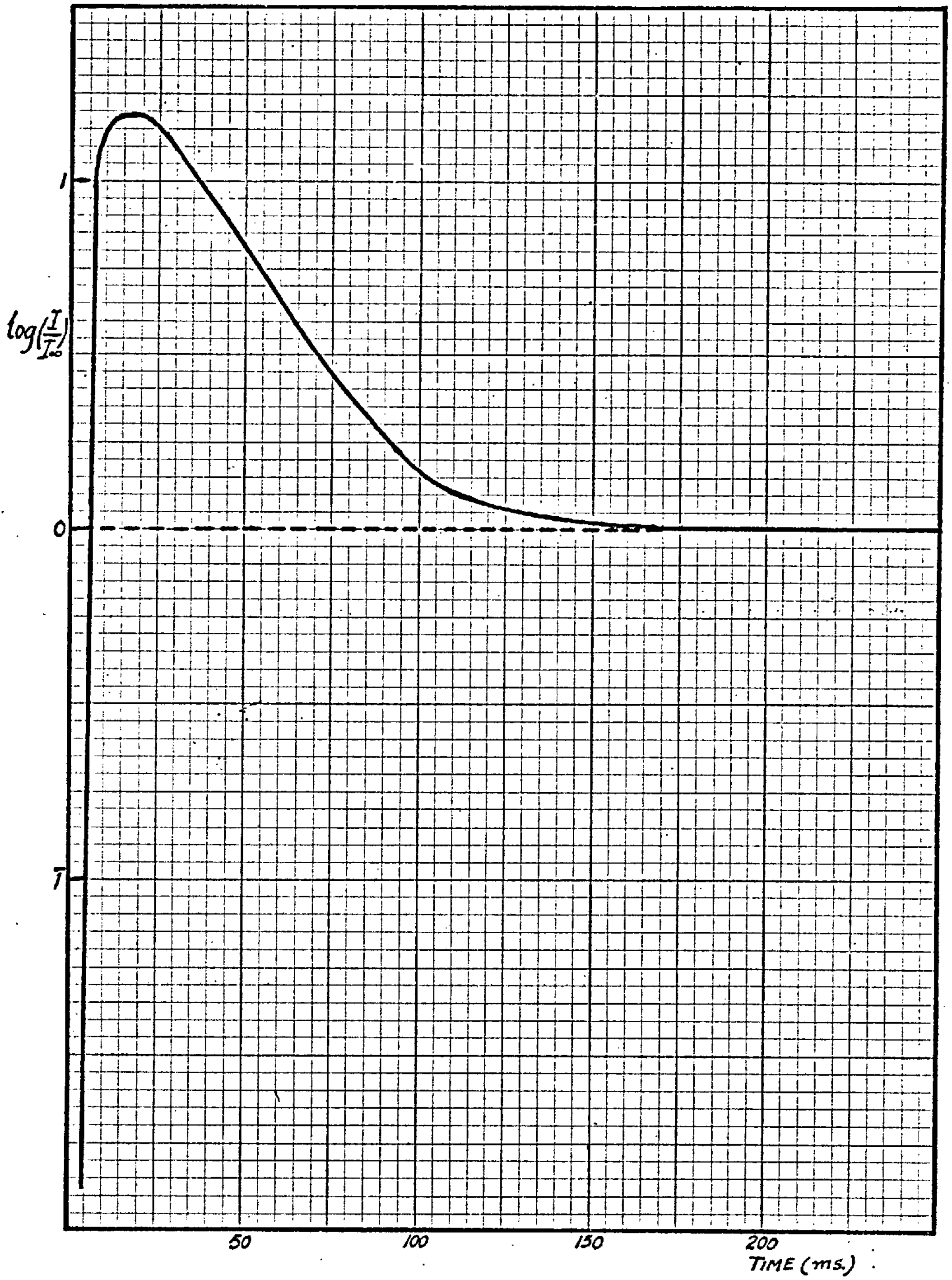


Fig. 145. Change of apparent intensity with flash duration. See text.

and fig. 100-110 in chapter VI shows that equation 64 fits the experimental observations much better than the Blondel-Rey equation. The curves of fig. 143 show that as θ is increased the sharper is the transition from It = const. to I = const. and this may well be reflected in the measurements by the author (fig. 104-106).

The Response Function $\Phi(t)$.

So far we have considered only flashes not far above the threshold so that the state of adaptation of the eye is not appreciably disturbed by the flash and we have treated the response function $\Phi(t)$ as being a constant. If these flashes be brief enough there is complete temporal summation (p.288); E is then proportional to the additional light energy falling upon the visual system in time τ and $(E\tau/\theta)$ the increment in the apparent intensity. In fact we could write

$$dI = \frac{E.\,dt}{\theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (65)$$

θ being a function characterising the state of adaptation of the visual system.

Let us now consider the dark-adapted eye looking at a flash of intensity E well above the threshold. The state of adaptation of the eye is continually changing during the observation of the flash and we no longer expect our equations to apply; $\Phi(t)$ can no longer be treated as a constant. For long flash durations however (or steady illumination), the function $\Phi(t)$ will approach a constant value and the equations we have derived for $I(\infty)$ should still remain valid. Hence, even when the apparent intensity is well above the threshold, we can still consider the integration time as given by Θ (which is originally derived from the expression for $I(\infty)$, and we can therefore write, by analogy with equation 65,

$$I(\infty) = \frac{E\,\Theta}{\Theta} = E \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (66)$$

Let us further consider a light source of intensity variation given by $E(t) = E_o(1+\cos\omega t)$, of frequency close to the critical fusion frequency N_c, such that the variation of the apparent intensity does not sensibly affect the state of adaptation of the eye - Θ may be treated as constant. Provided the time constant for the decay function is small compared to Θ, we may treat the system to a first approximation as similar to a steady light (eq. 66) and write

$$I(t) = \frac{1}{\Theta}\int_{t-\Theta}^{t} E_o(1+\cos\omega t)\,dt = \frac{1}{\Theta}E_o\Theta + \frac{2E_o}{\Theta\omega}\sin\frac{\omega\Theta}{2}\cos\omega(t+\frac{\Theta}{2}) \quad . \quad (67)$$

This represents a steady intensity E_o on which is superimposed a ripple of frequency ν, $(\omega = 2\pi\nu)$ and amplitude $\frac{2\,E_o}{\Theta\,\omega}\sin\frac{\omega\Theta}{2}$. This ripple will disappear when $\frac{\omega\Theta}{2} = \pi$

or $\frac{2\pi\nu\Theta}{2} = \pi$

or $$\Theta = \frac{1}{\nu} = \frac{1}{N_c} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (68)$$

as ν must be equal to the critical fusion frequency when the ripple disappears. Equation (68) has been derived by making what are at best only crude approximations, (see p.298) but indicates that the function Θ is closely related to the reciprocal of the critical fusion frequency, which may not be too surprising a result. It seems fairly reasonable to assume in the absence of other evidence that $\frac{1}{\Theta}$ and N_c are similar functions of intensity.

Now, according to Le Grand (1957) the critical fusion frequency N_c increases with the mean luminance L_m according to the Ferry-Porter law:

$$N_c = a \log L_m + b \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (69)$$

Piéron, however, has proposed a formula of the type

$$N_c = a\,(L_m)^n \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (70)$$

It is not possible to say which of the two formulae more closely represents in form the variation of $\frac{1}{\theta}$ with intensity. θ however is identical with the constant a of the Blondel-Rey equation (p.35) and Hampton and Luizov both found that a varies as an inverse power function of the intensity (eq. 10a, 10b, p.40), which might be expected from Piéron's equation. We shall assume therefore that θ is a function of I given by an inverse power law of the type

$$\theta\,(I) = \frac{a}{I^n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (71)$$

where n is a fractional power.

It must be emphasized that it is not claimed that equation (71) is the correct law for the function θ (I), but has been merely selected to illustrate the method of calculation described below, though it seems probable that an equation of this type may hold over certain ranges.

We may now generalise equation (65) by writing

$$dI = \frac{E.\ dt}{\theta\,(I)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (72)$$

θ being treated as a function of the apparent intensity and not the actual intensity of the flash, as it characterises the state of adaptation of the visual system. Comparison of equations (72) and (38) identifies $\frac{1}{\theta(I)}$ with the response function $\Phi(t)$, I being a function of t, and we can now rewrite equation 41 as

$$I\ (\tau) = \int_0^{\tau} \frac{E(t)}{\Phi(I)}\ \psi(\tau - t).dt \quad . \quad . \quad . \quad . \quad . \quad (73)$$

In general, equation 73 is not directly integrable, but keeping dt small in comparison with Φ, a step by step calculation becomes possible, each successive value of $I\ (\tau)$ being used to change Φ. Such a calculation has been attempted using the delayed exponential type of decay (p.287). In this case

$$\Phi = \alpha + \frac{1}{\psi}$$

where α is the delay time and $\frac{1}{\psi}$ the time constant for the exponential decay. It seemed more natural to suppose in this case that it is α only which varies with the apparent intensity I, as this determines the state of adaptation of the eye and the delay before the decay process is triggered off. This would be in agreement with the fact that as $\alpha \rightarrow o$ at high levels of adaptation, $\Phi \rightarrow \frac{1}{\psi}$; the critical fusion frequency should approach a constant value as found by Hecht and Shlaer (1936). In the calculations α has been arbitarily given the value 0.20 sec. at the absolute threshold I_o and at a higher intensity I, α has been calculated from the formula

$$\alpha(I) = 0.20\ \left(\frac{Io}{I}\right)^{0.23}$$

The choice of the value 0.23 for the exponent is also arbitrary and rests upon the fact that Piéron and Luizov give values of 0.25 and 0.23 for this exponent, whereas Hampton gives the much higher value 0.81. The results from the calculations are shown plotted in fig. 144, page 290, where the steady level intensity is indicated as a multiple of the threshold intensity, and should be compared with fig. 4, p 29.

The curves of fig. 144 indicate that the Broca-Sulzer type of effect should follow as a necessary consequence of the decrease in the integration time with increasing level of light adaptation, and that the maximum is more quickly attained at high intensity levels. Using a logarithmic scale for the intensity however shows relatively little change in the degree of overshooting, which would appear to be in line with some of the results described in chapter VIII. On the assumption that θ (I) varies as an inverse power of I (eq.71), equation (72) may be written as

$$dI = \frac{E\ dt}{(a/I^{n})}$$

or

$$\frac{dI}{I^n} = \frac{E}{a}.\ dt$$

Integration yields

$$\frac{I^{1-n}}{1-n} = \frac{E}{a}\ .\ t$$

or

$$I^{1-n} = kt$$

where k = E (1-n)/a = constant.

Taking logarithms,

$$(1-n) \log I = \text{const.} + \log t \quad . \quad . \quad . \quad . \quad . \quad . \quad (74)$$

From equation 74, it follows that a graph of log I against log t should give a straight line of slope $\frac{1}{1-n}$. It is interesting to observe that over the portions of the curves where equation 72 may be expected to hold in fig. 127-128, the graph gives a good straight line fit. In fact the slopes of the curves indicate a value of around 0.4 for the exponent n.

A Different Method of Calculation.

In the preceding argument the integration time or delay time has been used as a measure of the state of adaptation of the eye, and this has been taken as being a measure of the fast or α - process of adaptation. The slower β - adaptation has been neglected as it is not likely to affect the apparent intensity of a flash of relatively short duration. A different approach to the problem would seem possible if one knew exactly how the sensitivity of the eye varies with time at the onset of a stimulus well above threshold. The only measurements of this type seem to be those of Schouten and Ornstein and of Wright (pp. 126-128). An attempt has been made to approximate to Schouten's results by a function of the type

$$\Phi(t) = a + be^{-\phi t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (75)$$

and one obtains $\Phi(t) = 0.12 + 0.88\ e^{-75t}$ approximately. It seems significant that the exponent is of the same order of magnitude as in Crawford's decay curves; however, it is quite likely that the relative values of a and b are determined by the level of the conditioning stimulus. Neglecting the delay time for the onset of the decay as this will necessarily be very small at high intensities we can take $\Psi(\tau - t)$ as being given by

$$\Psi(\tau - t) = e^{-\psi(\tau - t)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (76)$$

and equation (41) becomes

$$I\ (\tau) = \int_0^\tau cE\ (a + be^{-\phi t})\ e^{-\psi(\tau - t)}dt \quad . \quad . \quad . \quad . \quad (77)$$

where c is a suitable normalising constant.

On integration (77) gives

$$I\ (\tau) = cE \left\{ \frac{a}{\psi} - \left(\frac{a}{\psi} - \frac{b}{\phi-\psi} \right) e^{-\psi\tau} - \frac{b}{\phi-\psi}\ e^{-\psi\tau} \right\}. \quad . \quad . \quad (78)$$

Taking $\emptyset = 75$, $\psi = 50$, $a = 0.02$, $b = 0.98$, this function is shown plotted on a logarithmic intensity scale in fig. 145 (p.291) and the curve is found to be rather similar to the initial part of Crawford's curves.

Calculation of the Critical Fusion Frequency.

In the case when a light has an intensity variation given by E (1 + cos ωt), the critical fusion frequency may be more appropriately calculated as outlined below, assuming a delayed exponential decay.

The eye being in a quasi-stable state of adaptation, the delay time α may be treated as being constant, and equation 61 may be written as

$$\begin{aligned}
I(\tau) &= \int_0^{\tau-\alpha} cE(1+\cos\omega t)\, e^{\psi\alpha} e^{-\psi(\tau-t)} dt + \int_{\tau-\alpha}^{\tau} cE(1+\cos\omega t)\, dt \\
&= \int_0^{\tau-\alpha} cE\, e^{\psi\alpha} e^{-\psi(\tau-t)} dt + Re\left\{ \int_0^{\tau-\alpha} cE\, e^{\psi\alpha} e^{i\omega t} e^{-\psi(\tau-t)} dt \right\} \\
&\qquad + \int_{\tau-\alpha}^{\tau} cE\, dt + Re\left\{ \int_{\tau-\alpha}^{\tau} cE\, e^{i\omega t} dt \right\} \\
&= \frac{cE\, e^{\psi\alpha}}{\psi}\left(e^{-\psi\alpha} - e^{-\psi\tau}\right) + cE\alpha \\
&\qquad + Re\left[\frac{cE}{\psi+i\omega} \cdot e^{\psi\alpha} e^{-\psi\tau} e^{(\psi t+i\omega t)} \right]_0^{\tau-\alpha} \\
&\qquad + Re\left[\frac{cE}{i\omega}\left(e^{i\omega\tau} - e^{i\omega(\tau-\alpha)}\right) \right]
\end{aligned}$$

$$I(\tau) = cE\alpha + \frac{cE}{\psi} - \frac{cE}{\psi} e^{\psi(\alpha-\tau)} + Re\left[\frac{cE}{\psi+i\omega}\cdot\left(e^{i\omega(\tau-\alpha)} - e^{-\psi(\tau-\alpha)}\right)\right]$$
$$+ Re\left[\frac{cE}{i\omega}\left(e^{i\omega\tau} - e^{i\omega(\tau-\alpha)}\right)\right]$$

As $\tau \rightarrow \infty$, we have

$$I(\infty) = cE\alpha + \frac{cE}{\psi} + Re\left[\frac{cE}{\psi+i\omega}\cdot e^{i\omega(\tau-\alpha)}\right] + Re\left[\frac{cE}{i\omega} e^{i\omega(\tau-\alpha)}\left(e^{i\omega\alpha}-1\right)\right]$$

$$= cE\left[\alpha + \frac{1}{\psi} + \frac{\psi}{\psi^2+\omega^2}\cos(\omega\tau-\omega\alpha) + \frac{\omega}{\psi^2+\omega^2}\sin\omega(\tau-\alpha)\right.$$
$$\left. + \frac{1}{\omega}\sin\omega(\tau-\alpha).(\cos\omega\alpha-1) + \frac{1}{\omega}\sin\omega\alpha\cos\omega(\tau-\alpha)\right]$$

$$\doteq cE\left[\alpha + \frac{1}{\psi} + \sin\omega(\tau-\alpha)\left\{\frac{\omega}{\psi^2+\omega^2} + \frac{1}{\omega}(\cos\omega\alpha-1)\right\}\right.$$
$$\left. + \cos\omega(\tau-\alpha)\left\{\frac{\psi^2}{\psi^2+\omega^2} + \frac{1}{\omega}\sin\omega\alpha\right\}\right] \quad . \quad . \quad .(79)$$

This is equivalent to a steady intensity $cE\,(\alpha + \frac{1}{\psi}) = E$, since $c\,(\alpha + \frac{1}{\psi}) = 1$, eq. 62, upon which is superimposed an oscillation of amplitude $(A^2+B^2)^{\frac{1}{2}}$ where A and B are the coefficients of $\sin\omega(\tau-\alpha)$ and $\cos\omega(\tau-\alpha)$ respectively. As we increase the frequency of the flashing light, critical fusion frequency will be attained when the amplitude of the ripple becomes too small to allow detection.

The above illustrates how the critical fusion frequency could be calculated in the simple case when the intensity varies sinusoidally. More complicated wave shapes can be similarly treated using methods of Fourier analysis as employed in the analysis of electrical network response functions.

The discussion in the present chapter has aimed at stressing certain relations which, in the opinion of the author, may exist between the following factors:

(a) the threshold,
(b) the fixed light equivalent of flashing lights,
(c) the critical fusion frequency,
(d) the rise and fall of the visual response during transient stimulation.

The lines along which such relationships may be sought for and the quantitative checks carried out to test the assumptions made in any theory have been indicated. At the present stage a more detailed analysis does not seem possible, but one can readily think of experiments which should lead to a more exact quantitative formulation. A clearer understanding of such relationships should allow a more efficient use of the large body of information available in the literature on vision in the design of flashing signals and also yield useful information about the mechanism of the visual process.

APPENDIX.

Symbols used in chapters IV-IX.

The following symbols have been used in the presentation of the experimental data in chapters IV to IX:

α = angular subtense of test field (minutes of arc)

t = flash duration (sec. or ms.)

B = Troland value of luminance of background conditioning field (trolands).

n = Flash frequency (c.p.s.)

θ = eccentricity with visual axis (degrees and minutes of arc)

(Note: θ has been used instead of Θ in typing).

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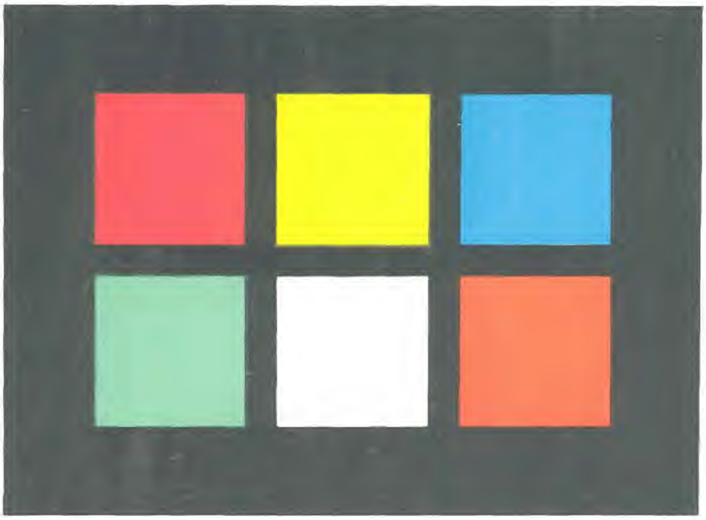

FIG. 1. The colour stereo effect may be seen by looking at this pattern through prisms or de-centred pupils, and a lateral shift of the patches is observed as the eye is moved relative to a pupil.

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THE COLOUR STEREOSCOPIC EFFECT

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INTRODUCTION

COLOUR Stereoscopy refers to an apparent depth difference which is at times observed between coloured objects lying in the same plane. This is not to be confused with the brightness produced by atmospheric haze and associated with distance, and which has led redness to be regarded by artists as an advancing colour and blueness as a receding colour. The colour stereoscopic effect may readily be seen by sticking small squares of coloured paper on a black background (Fig. 1), and viewing the arrangement from a distance of a metre or so through a pair of prisms (even a single prism will do) of about 5 dioptres each,[1] with their vertices facing each other as in Fig. 2. The dispersion caused by the prisms leads to a relative displacement of the images of different colours within the eye, and the disparity will tend to make the blue patches appear closer than the red, other colours taking up positions according to their order in the spectrum. The above arrangement of prisms causes the eyes to converge, and is hereinafter referred to as a "converging arrangement". With the sense of the prisms reversed, or a "diverging arrangement", the order of occurrence of the colours in depth is reversed, though discomfort may be caused by the strain imposed upon the eyes in the effort to maintain divergence.

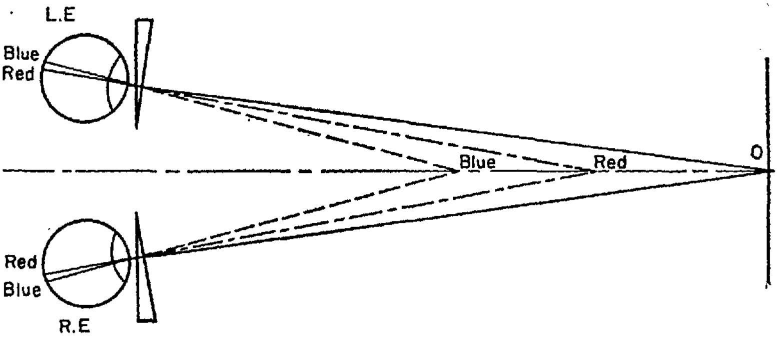

FIG. 2. A converging arrangement of prisms making blue appear an advancing colour.

The colour stereo effect may also be seen by exploiting the chromatic aberration of the eye. With the outer half of each eye pupil covered by a visiting card, the inner halves simulate the effect of looking through converging prisms (Fig. 3), and blue appears as an advancing colour,[1] with the inner halves of the pupils covered, the effect is reversed in depth. With

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[1] These experiments have been described by I. KOHLER (1962).

holes of about 2-mm diam. punched in the cards and placed in front of the eyes so as to be suitably decentred with respect to the eye pupils, the effect may show up even more markedly than with prisms.

In general, observations through prisms are more satisfactory when the overall level of illumination is high and the eye pupils contracted, whereas observations through de-centred artificial pupils show up to advantage at low levels of illumination, with the eye pupils fully dilated and allowing a considerable degree of de-centration of the artificial pupils both inwards and outwards.

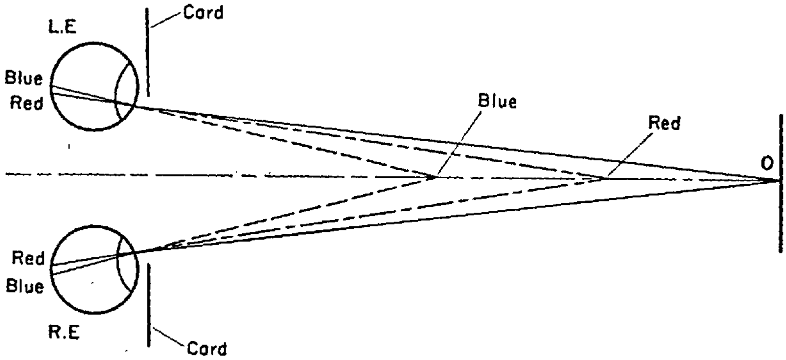


FIG. 3. With the outer halves of the eye pupils covered, the inner halves act as converging prisms and show the colour stereoscopic effect.

De-centred pupils show the dispersive power of the optical system of the eye in a striking manner in certain monocular observations. Thus, when viewed against a dark background through a decentred pupil a white patch shows a marked fringing effect (Fig. 4a). Again, if two adjacent red and blue patches be viewed through an artificial pupil which is given a to-and-fro motion relative to the eye, the patches appear to come together and separate laterally (Fig. 4b).

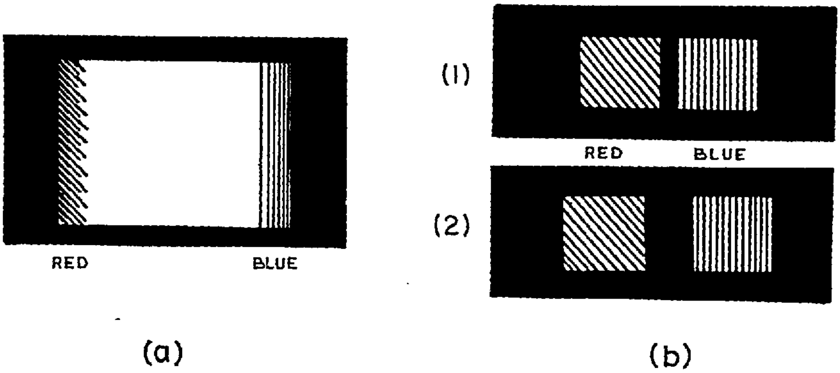


FIG. 4. (a) Fringing effect with a white patch viewed through a pupil de-centred to the temporal side of the right eye.

(b) Relative shift of red and blue patches viewed through a pupil de-centred (1) to nasal side, (2) to temporal side of the right eye.

The above effects can be readily demonstrated, and the following experiments aim rather at finding how far can similar effects be observed with the unaided eyes, and how the colour stereoscopic effect compares with certain other monocular clues in influencing our judgment in depth perception.

APPARATUS

The colour patches used were cut from stiff paper or thin card printed in highly saturated colours and having as fine a surface texture as possible without being unduly glossy, only those surfaces which gave reflection in one well-defined region of the spectrum being selected. Surface texture appeared to have a marked influence on the apparent positions of the patches in depth, and lighting had to be carefully arranged so as to avoid any shine leading to a spurious effect of texture.

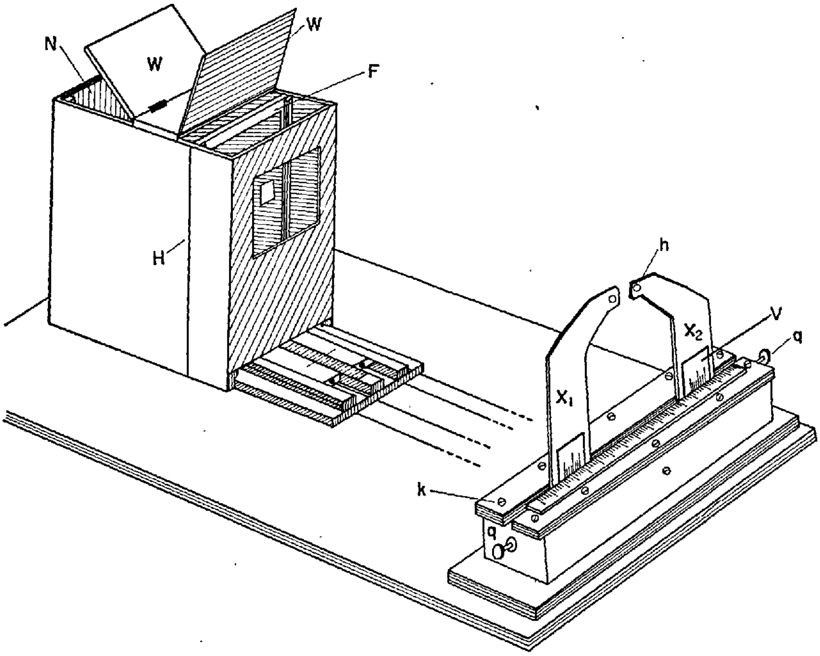


FIG. 5. Viewing box and pupil de-centring arrangement.

A viewing box for observation of the patches against suitable backgrounds in the absence of other depth clues, and an arrangement for producing controlled de-centration of artificial pupils of different types and sizes are illustrated in Fig. 5, and certain details of the internal construction of the viewing box in Fig. 6.

The viewing box

Square colour patches Q_1, Q_2, . . . of 2-cm side (Fig. 6) were mounted on a pair of fine black threads stretched across an inverted U-shaped frame F and viewed against the background N set about 35 cm further behind. A distance of 115 cm, at which the width of the patches subtended an angle of 1°, was chosen for the observations; at distances of this order, the binocular acuity of most observers is about ½ mm or better and slight degrees of myopia or hypermetropia do not affect the sharpness of the visual image. The windows W (Fig. 5) allowed different sets of frames and background panels to be inserted in the viewing box, and with these windows open the illumination of the patches and the background could be controlled by lamps suitably disposed above them and shielded from the observer's eyes.

The apparent positions of the patches were located by the pointers P_1, P_2 fixed in the wooden mounts M_1, M_2 of the slides S_1, S_2, which could be adjusted by the observer pulling on the cords K, L. Provision was made for a zero check on the alignment of the pointers before each set of observations, and the depth separation could be read against the scale R with an error not exceeding 0·2 mm.

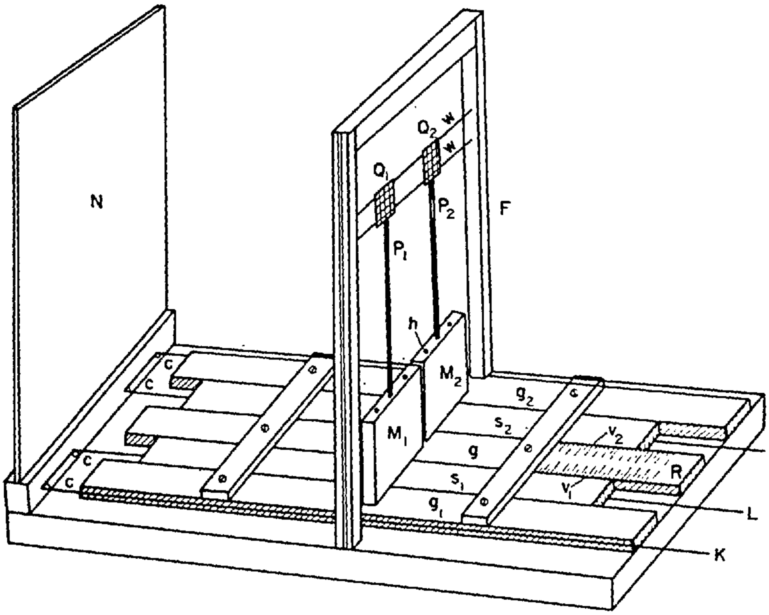


FIG. 6. Details of viewing box.

The box was painted inside a dull black, and was so set up in relation to the subject that only the white pointer tips and the colour patches were visible through the square aperture of about 20-cm side in its front wall. All details of internal construction which could influence judgment of depth were carefully screened from the observer. The pointers (Fig. 7) were made by filing flat the tops of stout knitting needles, and the flat spring S allowed a small piece of coloured card to be fixed against the pointer face when required.

The pupil de-centring arrangement

The arms X_1, X_2 of this could be given a lateral displacement by the screws **q**, and had a hole **h** of about 1-cm diam. at the top and at the same level as the colour patches in the viewing box. Small recesses on the reverse side and immediately behind these holes could take pupils of different diameters, slits, etc., and the displacement of the arms could be read by the verniers **v** to 0·1 mm. As it was found that small lateral movements of the observer's head did not cause any measurable change in the depth effect—an increase in disparity between the coloured images in one eye being apparently offset by a corresponding decrease in the other eye—no particular provision was made for fixing the observer's head, apart from providing a chin-rest if necessary. The subject was generally asked to position his head so as to see the two fields through the artificial pupils as symmetrical as possible about the point of fixation, the de-centration measured being the combined de-centration for both eyes.

Patch illumination and adapting illumination

Daylight was used for the experiments at high illumination levels, and subdued daylight or artificial light from incandescent filament lamps at low levels of illumination; the differences in the spectral composition of the light from these two sources did not appear to cause any measurable change in the effects observed. The observations were carried out under three different conditions, governed by the intensity of illumination of the surround.

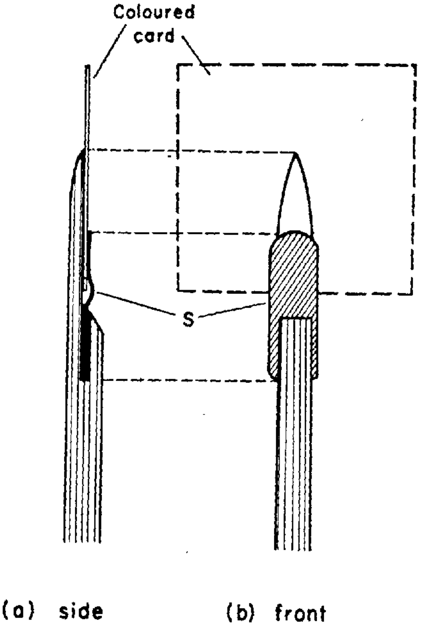


FIG. 7. Details of pointer tips.

No absolute meter being available, comparative measurements of the adapting illumination E_a, and the patch illumination E_p were made by placing a photographic exposure meter at the position of the observer's eyes and at the position of the test patches respectively. The values of E_a and E_p given below for the observing conditions are best estimates from the rated values of commercial incandescent lamps, after making due allowance for the reflection factor of the surround, etc.

Observation condition	*Adapting illumination* E_a (lumens ft^{-2})	*Patch illumination* E_p (lumens ft^{-2})
(1) Low illumination	¼–1	½–20
(2) High illumination	30–40	5–50
(3) Very high illumination*	about 200	200–1000

* These experiments were performed outdoors.

Most of the experiments were carried out with the viewing box and the colour patterns described below set against a white screen.

QUALITATIVE OBSERVATIONS

Preliminary observations showed that subjects wearing glasses gave slightly inconsistent observations on readjustment of their spectacles, and it was therefore decided to rely on the observations of those whose unaided vision was quite good. Every volunteer was given a routine test for far and near sight with Snellen's test chart and test types, and a test for colour blindness with the Ishihara plates. Only those whose unaided vision in each eye was 12/9 for far sight and N5 for near sight were called upon to observe.

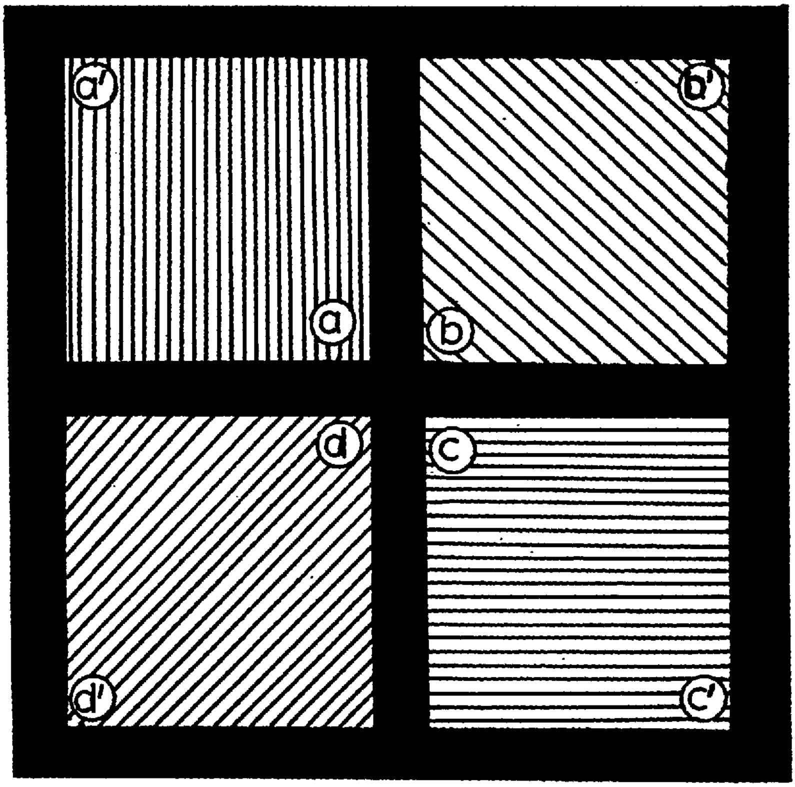


Fig. 8. Pattern as used for determining the most suitable angular subtense for observing the colour stereo effect.

As far as possible, observers were led on to discover the colour stereoscopic effect for themselves when it was presented to them in an exaggerated form with the help of prisms or de-centred pupils before they were asked to make unaided eye observations. This was rather easy with a set of eight or ten patches mounted in the viewing box; in fact, even with the unaided eyes many found it difficult to believe that the patches were in the same plane and had to convince themselves by a close examination of the frame. The observers were next shown the effect with prisms and with the patches stuck on a sheet of black paper pinned to a drawing-board, after which most could easily overcome knowledge of the fact that the patches were in the same plane, and even with this arrangement could see the depth effect with the unaided eyes. As the memory of a previous observation seemed occasionally to influence the judgment of an observer in subsequent observations, steps were taken after each observation to eliminate the memory of it from the subject's mind, e.g. by presenting a series of rapid and confusing observations of exaggerated effects, or diverting the subject's attention for a sufficient time from the experiment. The observations were arranged in increasing order of difficulty and some typical ones are described below in the order they were presented.

Observations

A series of patterns was made with pieces of coloured paper stuck on a black background, and the purpose of each type of pattern and the observation for which it was used are now described.

(a) Coloured squares were arranged as in Fig. 8, varying either the width or the separation of the patches for any one set of patterns at a time. The observer fixated the centre of the pattern through converging prisms and decided which patterns showed the colour stereo effect most clearly. Most observers favoured the patterns in which the patches subtended an angle of 1° at the eye with an angular separation of ¼–½°. With the largest patches used, the corners a, b, c, d appeared turned up or digging into the background whilst a′, b′, c′, d′ appeared to be in the same plane. The colour stereoscopic effect seems to be negligible at angles of more than 2½–3° with the visual axis. Irregularly orientated patches often tend to show the depth effect more readily at first glance, but make the estimation of the apparent positions of the colours in depth more difficult, as irregular orientation appears to give a spurious tilt to the patches.

(b) Subjects were asked to look through converging or diverging prisms, or de-centred pupils, at sets of patches of angular subtense 1° and separation ¼° mounted in the viewing box against a dark background, and to arrange the patches in their order of appearance in depth. One set consisted of patches of highly saturated colours, and also included a white, greys, and a purple which showed red and blue fringing of almost equal intensity when viewed through a prism; other sets consisted of patches of only two or three hues, but with different degrees of desaturation, etc.

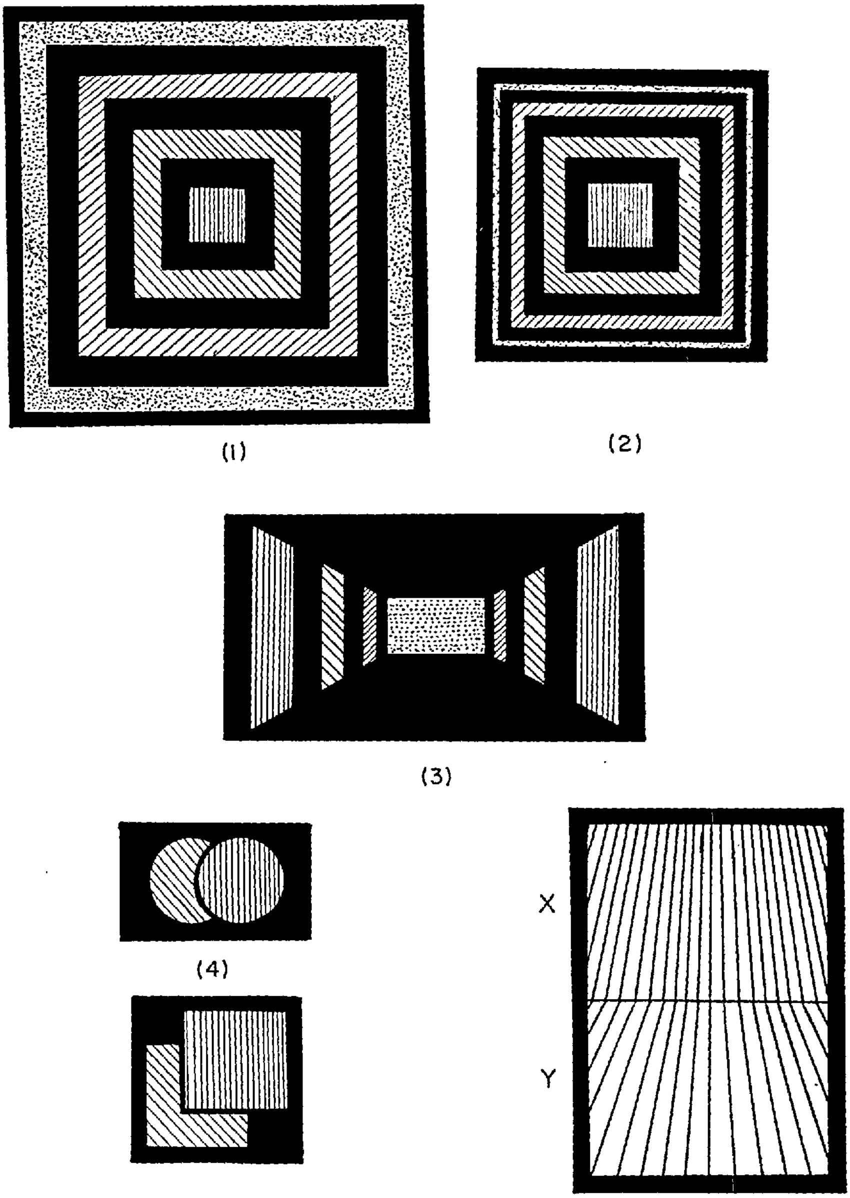
The saturated colours were arranged in their order of occurrence in the spectrum, blues appearing as an advancing colour with converging prisms or with artificial pupils de-centred inwards, and reds appearing as an advancing colour with diverging prisms or with artificial pupils de-centred outwards. White and greys were placed in a plane between yellow and green at a position corresponding to an estimated wavelength of 5600 Å; purple was also seen close to white, though it must be mentioned that the purple used was rather more desaturated than the other colours and some observers believed that they could detect a small change in its position with the nature of the source. There was general agreement that the depth effect diminished with desaturation, the colours approaching the position occupied by white, as might be expected.

It was noted that whereas monocular observations showed a marked fringing effect, especially with white and desaturated colours, binocular viewing gave a much sharper appearance to the edges.

(c) Subjects were next asked to view the arrangements used in (b) with the unaided eyes and to arrange the colours in their order of appearance in depth, and to judge how the depth effect changed with the distance of observation. Increase in the observation distance led to an increase in the depth effect, as might be expected if the angular dispersion of the rays within the eye were more or less constant.

It was at this stage of the experiments that certain discrepancies were observed between the unaided eye observations at high and at low levels of surround illumination. All observations were henceforth repeated at both levels of adaptation.

Though in many cases observers had some difficulty in seeing a depth difference between close spectrum colours, they generally arranged the colours in their order of occurrence in



(1) (2)

(3)

(4)

(5) (6)

FIG. 9. Some of the patterns as used for detecting the reversal in the colour stereoscopic effect with change in the overall state of adaptation of the eye.

the spectrum, and had little difficulty in judging the positions of well-separated colours like red and green or blue. Many appeared to see blue as an advancing colour at low illumination, and red at high illumination, and it was therefore decided to carry out further tests to find out whether such a "reversal effect" really existed. Some of the observations now attempted would also show how the colour stereoscopic effect compares with certain other monocular clues to depth in influencing our judgment of distance, and others aimed at finding whether any possible reversal of the depth effect would be accompanied by a corresponding relative shift in the images of the colour patches on the retina.

(d) Patterns as illustrated in Fig. 9 were made with coloured paper on a black background, and after the subject had observed them through prisms to familiarize himself with the type of observation, he proceeded to examine them with the naked eye.

In (1) the central square subtended an angle of 1° at the eye, and the width of each of the strips forming the hollow squares $\frac{1}{2}°$. If the colours of the successive squares as we move away from the centre are from red to blue in their order of occurrence in the spectrum, such a pattern when viewed through converging prisms or pupils de-centred inward will look hollow in the centre. If the order of the colours, or the sense of the prisms, or again the direction of de-centration of the pupils be reversed, the pattern looks convex, like "camera bellows". In this, as well as in the following cases, it was found suitable to have the patterns in pairs with colours arranged in opposite orders so that the subject might easily establish a comparison. Some patterns were also included with the order of the colours bearing no relation to their order in the spectrum. Patterns of types (2) and (3) were made on similar principles, except that width gradient and converging lines were here introduced to create an impression of perspective, which could be made to enhance or oppose the idea of depth conveyed by the colour stereoscopic effect. Similarly, patterns (4) and (5) give the impression of overlay, and in (6), where the rectangles X and Y were in different colours, the change in the patterns of lines drawn on them could be made to give the impression of a corner or a step-edge. By careful consideration of the observations made by any subject with these various patterns, and under conditions of low and high adapting illumination, it would be possible to tell with greater certainty whether he was really seeing a depth effect and a reversal with the state of adaptation of the eye.

In (1) and (2) the colour stereo effect dominated the other depth clues, but with a pair of patterns of type (2), with the colours in opposite order, one pattern would appear to be more hollow than, say, the other appeared to be bulging. The impression of a corridor conveyed by (3) was usually too strong to be overcome by the colour stereoscopic effect, but, of a pair of patterns, one usually gave a greater depth impression than the other. In (4) and (5) the impression of overlay was much too strong, and in (6), out of a pair of patterns, one was generally described by the observers as conveying a "more natural impression" than the other.

(e) These observations aimed at finding whether there was any difference in the lateral displacements of the images on the retinae inside the eyes, and if so, whether it was in such sense as to produce the observed depth effects.

If a fine line PQ be drawn or a hair be stretched or a black edge XY be placed over adjacent coloured strips as at (1) in Fig. 10, and be viewed through a prism with its base towards the right, say, the greater deviation of the blue rays will make the part of the line over the blue strip appear broken and displaced to the left. Again, if strips of red and green or blue paper about $\frac{1}{2}$ cm by 10 cm be stuck on a black background as at (2) so as to enclose two narrow gaps w, on looking at the arrangement through a prism the unequal displacements of the red and the blue images will make one gap appear to close down and the other to open up—this is particularly noticeable with thin wedge-shaped gaps of angle about ½° or even less. In (3), A and B are two patterns made up of two colours which are complementary or nearly so: a red and a blue-green. On looking at the arrangement through a prism as at p, the patches tend to overlap in A and separate in B, so that a white line of demarcation appears in A and a dark line in B; reversing the sense of the prism will make the white line appear in B and the dark line in A.

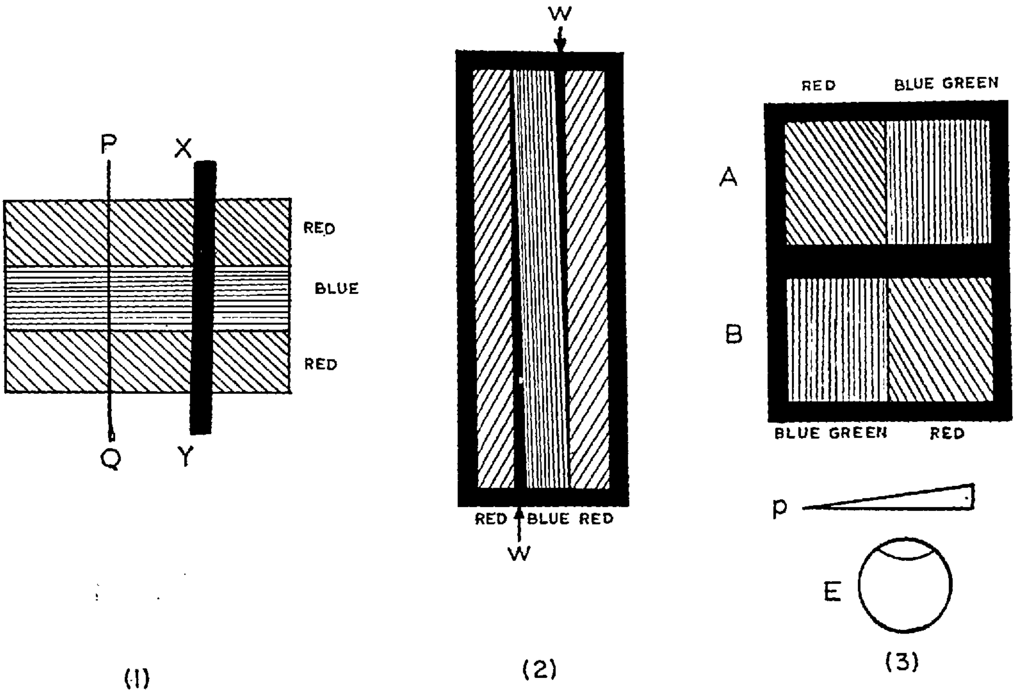


FIG. 10. Patterns as used for determining the relative shift of the images of the colour patches on the retina.

After having been shown the above effects with prisms, observers were asked to see if they could detect similar effects with the unaided eyes, and whether there were any differences in the observations with the right eye and the left eye. Patterns of type (1) proved most satisfactory, perhaps because they made use of the vernier acuity of the eye; patterns of type (3) gave doubtful results with some observers. Many of the observers found that at low levels of adaptation blues appear to be displaced towards the right relative to red as seen by the left eye, and in the opposite direction as seen by the right eye. The sense of the displacement reversed at high levels of adaptation.

(f) Some of the observations described in section (c) were repeated, keeping the level of the adapting illumination of the surround constant and varying the illumination of the patches over the ranges indicated on p. 317. It was found that for a given adapting illumination, the illumination of the patches could be varied over a considerable range without changing the nature of the observations. The value of the adapting illumination for which the depth effect seemed to be nil was noted.

(g) The observers were asked to look at a set of patches in the viewing box, and attempts were made to neutralize the depth effect by placing suitable prisms in front of their eyes. Although this method did not prove very accurate—another method is described below—the observers could easily tell when the depth effect was enhanced and when it was reduced or reversed, giving a clue to the original sense in which it was seen.

Conclusions from the qualitative experiments

It was only when over 80 per cent of the observations of a subject tallied, and in particular when the observations (e) and (g) corroborated the other observations, that it was assumed that the subject was really seeing the colour stereoscopic effect, and that he had observed a reversal of the effect only when the nature of almost all the relevant observations reversed with change in the level of the adapting illumination.

Out of a group of twenty-five observers, all could observe the colour stereoscopic effect with the unaided eyes, and seventeen observed a reversal of the effect. Three of these twenty-five observers had defective colour vision: one was a mild deuteranope, one a strong protanope, and the third had such poor colour discrimination that he was hardly able to read any of the Ishihara plates. Whereas the strong protanope always saw red as an advancing colour, the others observed the reversal effect. On the assumption that the colour stereoscopic effect is due solely to an aberration caused by the optical system of the eye, it would be expected that colour-blind people should also see it.

It was noted that all the seventeen subjects who saw the reversal effect found red to be an advancing colour at high levels of the surround illumination, and blue to be advancing at low illumination. Of the other observers, three always saw red as an advancing colour, and one always saw blue; the observations of the other four were not judged trustworthy, though two believed they had seen a reversal.

With most of the subjects who saw the reversal effect, this seemed to take place at an adapting illumination between 3–8 lm/ft^2; at "low illumination" and "high illumination", prisms of 1–2 dioptres, diverging and converging respectively, would neutralize the effect. Three observers, however, could only see a reversal at over 100 lm/ft^2, and one at less than 1 lm/ft^2—these, as well as the observers who could not see any reversal, required prisms of 4–6 dioptres to cancel the effect.

The above seems to indicate that the mechanism of the eye would tend to give good "colour correction" for average states of adaptation, and that the colour stereo effect observed under other conditions is inherent in this mechanism.

OTHER EXPERIMENTS

These aimed at establishing whether there was exact correlation between the angular shift of the images of the colour patches within the eye and the observed depth difference, measuring more exactly the prism power required to cancel the depth effect as seen with the unaided eyes, and searching for some explanation for the reversal effect.

(a) *Measurements of depth difference in the apparent positions of the colour patches*

With the arrangement of Fig. 5, two methods were tried for measuring the depth differences in the apparent positions of the colour patches for various degrees of de-centration of artificial pupils and with prisms of various powers in front of the eyes:

(1) Alignment of pointers. Two suitable colour patches were mounted in the viewing box, Fig. 6, and, observing through de-centred pupils or prisms, the pointers P_1, P_2 were aligned with them;

(2) Alignment of colour patches. Two suitable colour patches were mounted on the pointers, Fig. 7, and the observer aligned them to appear in the same plane; the actual separation between them was then taken as being the depth difference observable had they been in the same plane.

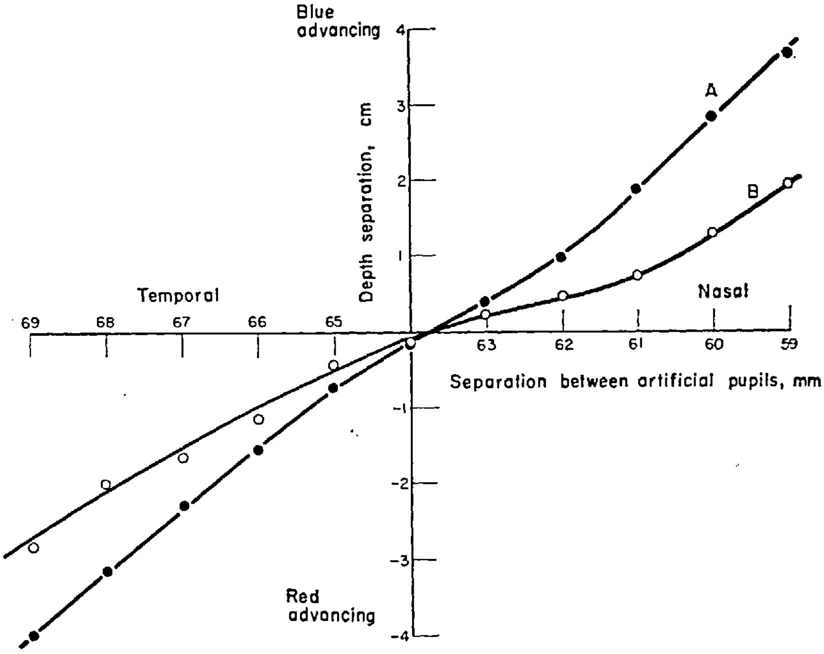


FIG. 11. Depth differences between red and blue patches as seen through de-centred pupils and as measured by alignment of (A) colour patches, (B) pointers.

With either method, it was essential to adjust the observer's head so that his eyes were symmetrically situated with respect to a line passing midway between the objects being aligned and perpendicular to the plane of observation, so as to avoid spurious effects due to other depth clues like overlay and parallax. Though method (1) would appear to give a more direct measurement of the depth difference observed with colour patches lying in the same plane, it involves comparison through an intermediate colour; method (2) compares directly the two colour patches and was preferred by most observers, as it was more rapid and gave more consistent results, probably because of the higher binocular acuity for objects lying in a horizontal plane.

Typical results for one observer are shown in Fig. 11 as obtained with de-centred pupils of 1·65 mm diameter by either method, lighting conditions being so arranged that there was no perceptible depth difference as seen by the unaided eyes. Figure 12 shows the variation in depth difference as measured by alignment of the colour patches with the total prism power in front of both eyes, under conditions of low illumination for the same observer.

Using either de-centred pupils or prisms, it was generally found that measurements by alignment of pointers gave consistently lower values for the depth difference than measurements by the alignment of the colour patches. As the latter method gave results in better agreement with values calculated from the angular displacement of the images of the colour patches on the retina, the discrepancy would seem to be inherent in the method.

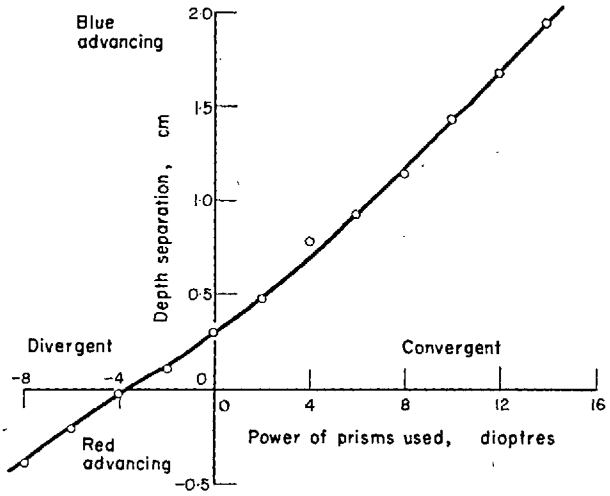


FIG. 12. Apparent depth difference in positions of red and blue patches seen through prisms and as measured by alignment of the patches.

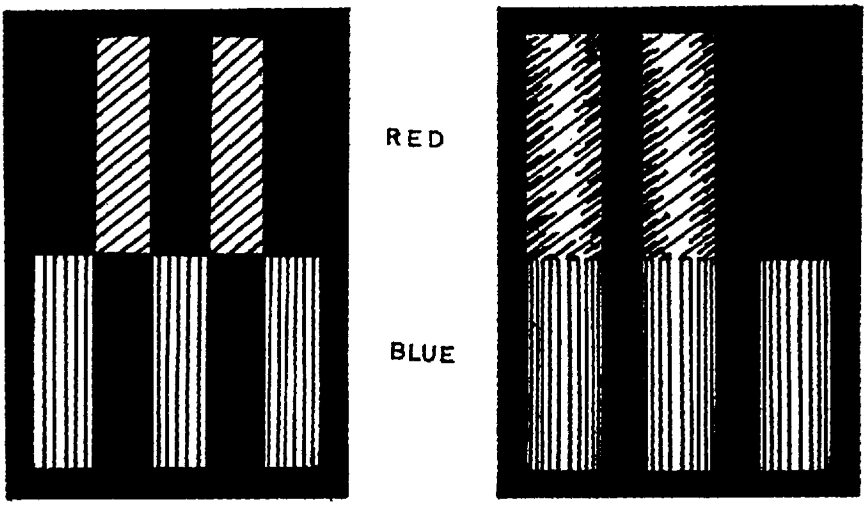
(b) *Determination of the prism power required for neutralization of the depth effect*

The observer measured first the depth difference between two colour patches as seen by the unaided eyes by either of the methods described above, and next by viewing through prisms sufficiently powerful to reverse the effect first observed. The prism power required for cancellation was then calculated by proportion and a check made by fitting prisms of the calculated power in front of the observer's eyes. Either method of determining the depth difference gave the same value for the neutralizing prism power, and for most observers this varied over a range of about 4 dioptres from conditions of "low illumination" to conditions of "high illumination". Even when a reversal of the effect could not be seen, this order of variation was generally observed.

(c) *Measurement of the relative angular shift of the centres of mean position of the images of the colour patches within the eye*

Calculations based on the optical constants of the material of the prisms used indicated apparent depth differences far in excess of the values observed. This would be expected from the desaturation of the colour patches used. Other observations, however, seeming to indicate that the "eyes" appear to locate the colour patches in depth by judging their centres of mean position, attempts were made at measuring the angular shift between these within the eye. Of the various methods tried, the following seemed to give the most consistent and reliable results.

Patterns as in Fig. 13a were made of coloured strips stuck on a black background. With a prism of about 10–12 dioptres in front of one eye, and the other eye shielded by an opaque disc, the observer was asked to recede from the pattern until the relative lateral displacement of the colours was one strip width, and the appearance as in Fig. 13b. From the distance of observation and the strip width (about 4 mm), the angular shift could be calculated. Colour-fringing with the strips used made the observations rather difficult, and allowance had to be made for the dispersion within the eye itself. This was achieved by using the prism in diverging and converging positions, when the mean of the two determinations would give the angular shift produced by the prism alone, and the difference twice the angular shift produced by the eye. The angular shift produced by the eye, being obtained by a difference method, would not be very accurate, but the values obtained were of the same order of magnitude as calculated from the depth difference measured by the observer under the same conditions of illumination. The following are typical results for one observer:



(a) (b)

FIG. 13. Pattern used for determining the angular shift of the images within the eye.

L.E. Angular shift with 12D con. prism: $2.6_9'$.
Angular shift with 12D div. prism: $3.3_2'$.
Angular shift caused by prism: $3.0_0'$.
Angular shift caused by eye: $0.3_2'$.

R.E. Angular shift caused by prism: $2.7_5'$.
Angular shift caused by eye: $0.3_3'$.
Mean angular shift caused by prism: $2.8_8'$.

The observer was next asked to measure the depth difference seen with the unaided eyes, and with the same prism power as above. From the known value of his interocular separation, the angular shift caused by the prism could be calculated, and the results obtained by the two methods compared. For the same observer,

Angular shift required from 12D prism to produce observed change in depth effect as determined by

(1) alignment of pointers: $2.1_0'$.
(2) alignment of colour patches: $2.4_6'$.

Angular shift required to produce depth effect as seen by unaided eyes as determined by alignment of colour patches: $0.4_0'$.

Sources of error which could possibly account for the discrepancies observed are curvature of field and change in apparent width of the strips as seen through the prisms, change in convergence and accommodation, etc.

The above experiments would seem to indicate that the colour stereo effect is due solely to a relative shift of the images of the colour patches on the retina, as produced by a pupil de-centred with respect to the eye lens. The effect would disappear at certain levels of adaptation if the position of the de-centred pupil were such as to oppose the dispersion caused by the cornea to that caused by the eye lens, the fovea being an off-axis point with respect to the optical system of the eye. The following were considered as possible causes for the reversal of the effect:

(1) opening of the eye pupil, bringing into use parts of the cornea of different curvature or regions of the lens of different optical properties,

(2) shift in the centre of mean position of the image due to aberrations, the Stiles–Crawford effect, etc.

(3) an eccentric opening of the pupil of the eye, leading to a de-centring effect,

(4) changes in the retina and its spectral sensitivity as the relative activities of rods and cones change.

Since a slight shift in the position of the head did not produce any measurable change in the depth effect when observing through de-centred pupils, it was considered that (1) and (2) were not likely to be responsible for the reversal effect. Some of the measurements described earlier would seem to indicate that if the reversal of the colour stereo effect were due to an eccentric opening of the eye pupil, this would be of the order of only 0·2 mm, and therefore not detectable with the pupil de-centring arrangement. One would moreover expect that if a symmetrical opening of the pupil does not produce a change in the depth effect, the introduction of artificial pupils of different diameters, but at the same separation in front of the eyes adapted to low levels of illumination, would not produce any change in the depth effect. An observer was therefore asked to adjust the pupils in the pupil de-centring arrangement so that the depth effect was nil. A travelling microscope was next mounted in front of the apparatus, and the original pupils were replaced by others of different diameter but at the same separation—this could be done to within about 1/25 mm. The microscope was then removed and the observer tried to see whether he could now detect any depth difference. Though pupils varying from 1·5 to 4.5 mm were used, no depth difference could be detected on changing the pupils. One would expect therefore that measurements of the distance between the pupils of the de-centring arrangement for zero depth effect with pupils of different diameters would give the same separation; these, however, gave erratic results, most probably owing to difficulty in re-setting the microscope after each observation.

The above experiment, though not very conclusive, would seem to indicate that the pupils of the eyes open eccentrically. This could very well be due to a distortion of the image of the iris as seen through the cornea in the direction of the visual axis. The pupil of the human eye appeared asymmetrically situated with respect to the iris with several subjects examined. Attempts at detecting an asymmetrical opening of the eye pupil using a corneal reflex method have so far proved unsuccessful. The part played by changes in the spectral sensitivity of the retina in the reversal of the colour stereo effect have not yet been studied.

The colour stereoscopic effect with other than dark backgrounds

With other than dark backgrounds, it would be expected that different degrees of colour fringing at the line of demarcation between the background and the colour patches would lead to different apparent shifts of the centres of mean position of the images of the colour patches, depending upon the relative brightnesses of the patches and the background, the degree of saturation of the colours, etc. Thus, if one looks at a pair of red and blue–green patches, as in Fig. 14b, through a converging prism in front of the right eye, both patches will appear displaced to the left as in (a), the blue showing slightly greater displacement than the red. But the white background will give a red fringe to the right and a blue fringe to the left, overlapping the patches as shown by the dotted lines. The colours being fairly complementary, this would lead to a possible apparent broadening of the white gap, so that the centre of mean position of the red gap would appear displaced to the left with respect to the blue. It is fairly clear that another converging prism now placed in front of the left eye would make red appear an advancing colour with respect to blue, though the reverse is observed against a dark background. It has been observed that if one views the patches in the viewing box against a white background, and the intensity of illumination on this be increased whilst that on the patches be kept constant, a point is reached when the effect reverses, whether the observer be looking through de-centred pupils or prisms. Similarly it is found that desaturated colours at times tend to show a greater depth separation than highly saturated colours when viewed against a white background.

FIG. 14. Displacement of red and blue patches as seen against a white background.

SUMMARY

Given suitable viewing conditions, all people with normal binocular vision seem capable of observing with the unaided eyes an apparent difference in depth between coloured objects lying in the same plane.

The colour stereoscopic effect is most readily seen when patches of highly-saturated colours lying within an angle of about 2–2½° on either side of the visual axis are viewed against a dark background in the absence of other clues to depth perception. The order of appearance of the colours in depth is the same as their order in the visible spectrum, provided the colours are of the same degree of saturation—white tends to take up the same position in relation to other colours as the colours near the region of maximum sensitivity of the eye. The depth effect increases with viewing distance and decreases with desaturation of the colours, and can be exaggerated, neutralized or reversed with the help of de-centred artificial pupils or suitable prisms in front of the observer's eyes.

In unaided eye observations, with a large number of people there appears to be a reversal of the order of the colours in depth as the overall state of adaptation of the eye is changed by varying the brightness of the surround. Whereas at low levels of illumination blue is an advancing colour, at high levels red appears closer to the observer. Though with some people this reversal occurs only at very low or very high levels of adaptation, and in some cases could not be attained, with many the depth effect is zero at average levels of illumination of the surround.

People suffering from defective colour vision, but whose eyesight is otherwise normal, seem capable of seeing the colour stereo effect in much the same way as ordinary trichromats.

When the colours are viewed against an other than dark background, the apparent distribution of the colour patches in depth varies in a complex manner with the colour of the background, the degree of saturation of the colour patches, the brightness of the patches relative to the background, etc.

Qualitative observations as well as quantitative measurements seem to indicate that the effect is due solely to a relative lateral displacement of the images of the colour patches on the retina. The reversal of the effect might be due to an eccentric opening of the eye pupils or changes in the spectral sensitivity of the retina at different levels of adaptation.

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Abstract—An attempt has been made to study the apparent depth difference observed under certain conditions between coloured objects lying in the same plane. It has been found that with many people there occurs a reversal of this colour stereoscopic effect with change in the overall state of adaptation of the eye. Some measurements have been made to find out whether, in the absence of other clues to depth perception, the depth differences observed are solely due to the relative displacement of the images of the colour patches on the retina.

Résumé—On tente d'étudier les différences apparentes de profondeur que l'on observe sous certaines conditions entre des objets colorés situés dans un même plan. On trouve chez beaucoup de sujets un renversement de cet effet stéréoscopique coloré en fonction de l'état général d'adaptation de l'œil. On a fait des mesures pour savoir si en l'absence d'autres facteurs de la perception de profondeur, les différences observées provenaient seulement du déplacement relatif sur la rétine des images des surfaces colorées.

Zusammenfassung—Es wurde ein Versuch gemacht, den unter gewissen Bedingungen beobachteten scheinbaren Tiefenunterschied zwischen farbigen Objekten, die in der gleichen Ebene liegen zu messen. Wir fanden, dass sich dieser stereoskopische Farbeffekt bei vielen Menschen mit einem Wechsel im Adaptationszustand umkehren kann. Es wurden einige Messungen gemacht um herauszufinden, ob beim Fehlen anderer Möglichkeiten zur Tiefenwahrnehmung die beobachteten Tiefenunterschiede nur auf die relative Verschiebung der Bilder der Farbflecke auf der Netzhaut zurückzuführen sind.