THE PERCEPTION OF LIGHT

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THE PERCEPTION OF LIGHT

An Analysis of Visual Phenomena in Relation to Technical Problems of Vision and Illumination

BY

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PREFACE

The following chapters are based on a course of six lectures given at the Imperial College in the autumn of 1937. They do not pretend to constitute an exhaustive treatise on vision; the book is more in the nature of an essay, in which I have tried to analyse the visual phenomena that seem to me to be of most importance to those concerned with lighting problems and with the technical manipulation of visual sensations. There is much activity in the realm of physiological optics at the present time, and I have endeavoured to reflect some of this activity in what follows. It may not be out of place to emphasize the importance of the purely physiological investigations now in progress; there is a very real danger that much of this work is liable to be overlooked by physicists and engineers.

I should like to acknowledge my indebtedness to Professor Ragnar Granit and Dr. R. J. Lythgoe for many valuable discussions during the past two or three years, the results of these discussions having inevitably found their way to some extent into this book. I also very much appreciated, and benefited from, the discussions which I had with some of those who attended the lectures to which I have referred.

W. D. WRIGHT.

IMPERIAL COLLEGE,
February, 1938.

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Many of the diagrams have been copied from original papers, and I am much indebted to the authors and publishers for permission to reproduce them. The original authorship is indicated under the diagrams; the publishers to whom acknowledgment is due are listed below:

The Royal Society for figs. 3, 4, 23, 38, 40.
The Proceedings of the National Academy of Sciences for fig. 12.
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Pflügers Archiv für d. gesamte Physiologie for fig. 19.
The Proceedings of the Physical Society for figs. 20, 37.
Revue d'Optique Théorique et Instrumentale for fig. 34.
Archives of Ophthalmology for fig. 43.
The Journal of Physiology for figs. 44, 45, 48, 49.
The Journal of Cellular and Comparative Physiology for figs. 46, 47.

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EXPLANATION OF UNITS USED IN THE TEXT

UNITS OF ILLUMINATION

Foot-candle: illumination of surface at distance of 1 foot from point source of intensity of 1 candle-power.

Micro-lux: 10^{-6} lux, where lux is illumination of surface at distance of 1 metre from point source of intensity of 1 candle-power.

UNITS OF BRIGHTNESS

Candle per square foot: brightness of surface which has an intensity in given direction of 1 candle-power per unit area of 1 square foot.

Equivalent Foot-candle: brightness of perfectly white, perfectly diffusing surface under illumination of 1 foot-candle.

Millilambert: brightness of perfectly white, perfectly diffusing surface under an illumination of 10 lux.

UNIT OF RETINAL ILLUMINATION

Photon: illumination of retina when an object which has a brightness of 1 candle per square metre is viewed through a pupil with an area of 1 square millimetre.

UNITS OF LENGTH

μ: 10^{-3} millimetres.
$m\mu$: 10^{-6} millimetres.

Bracketed figures in the text refer to papers listed on p. 97.

CHAPTER I

General Account of Visual Phenomena

Factors controlling Visual Sensations.

When light strikes the retina, we are conscious of a visual sensation which has two attributes—magnitude and quality. We are aware of a certain amount of light of some particular colour. The process of seeing, however, is concerned not merely with considering the light and colour qualities of each individual sensation; useful sight depends on relating a whole number of such sensations to each other and to preceding sensations.

The sensation at any instant is a function first of all of the physical stimulus—the light beam. The amount of energy in the beam will affect the intensity; the spectral energy distribution will affect the colour. It is also a function of the part of the retina on which the light falls, whether on the fovea or on some less central region, and is very much governed by the previous stimulation of the portion of the retina being used. Again, the sensation will be very much affected by the colour and intensity of the area surrounding the test patch.

These factors control the sensitivity of the retina and visual mechanism. In addition, the general physiological condition of the observer must play a part in controlling the perception mechanism, and in some problems this may be of considerable importance. Many visual experiments can only be repeated with consistency when care is taken to avoid fatigue, nervousness, and so on.

If we attempt to describe the variations of sensation with time, the problem becomes very complex. Thus the changing concentration of photochemical products in the retina, the varying diameter of the pupil, adjustments in the electrical condition of the retina, movements of the eye, all combine to introduce a fluidity and uncertainty into the visual response that are difficult to define. This will be true even for a simple test patch and uniform surround. When the problem is extended to considering the incredible complexity of the light pattern that normally enters the eye from almost any scene at which we may chance to look, we begin to appreciate the magnitude of the task with which we are faced. No wonder visual experts are full of "ifs" and "buts".

This complexity means that the investigation of any principle must be reduced to its simplest terms if a consistent, significant answer is to be obtained. On the other hand, it may also mean that, in practical problems in illuminating engineering which involve many factors and variables, it may be impossible to disentangle each variable and analyse it separately; the problem may have to be tackled as a whole.

Vision at High and Low Intensities.

The firmly established Duplicity Theory is based on the fact that there are two types of receptor in the retina, one, the photopic mechanism, being responsible for vision at high intensities, the other, the scotopic mechanism, for vision at low intensities. The photopic mechanism operates through some unknown photochemical substance secreted in light receptors (cones) situated at the back of the retina. The photochemical reaction initiates a nerve response by some process not yet understood, and this response passes from the cones through layers of cells and fibres to the front of the retina and travels along the appropriate nerve fibres to the optic nerve, and thence to the brain.

The scotopic mechanism operates through a photochemical substance known as visual purple which is secreted in another set of neurones (rods) situated in the same layer of the retina as the cones, but distinguished from them by their shape, a distinction not always very marked or characteristic. The response from the rods is also carried through to the front of the retina through layers of cells and travels to the brain via the optic nerve.

At high intensities the normal observer is conscious not only of a sensation of light but also of a sensation of colour. The photopic mechanism is thus the colour-perception mechanism. When we examine a spectrum, we see red at one end, violet at the other, with the familiar orange, yellow, green and blue at intermediate points. In addition to the change in colour through the spectrum, we can also see that the central portion is much brighter than the two extremes. If we make accurate observations of the relative intensity of the various colours and make corrections for the energy distribution through the spectrum, we obtain the photopic luminosity curve for an equal energy spectrum. This curve, curve A in fig. 1, has its maximum at $0{\cdot}555\mu$ for a normal observer, and the curve is obtained for brightness levels greater than about 10^{-1} candles per sq. foot.

When observations are made at a very much lower level, below about 10^{-4} candles per sq. foot, the scotopic luminosity curve, curve B in fig. 1, is obtained, and this has its maximum in the region of $0{\cdot}50\mu$. The difference between the two curves is one of the major facts, known as the Purkinje phenomenon, which distinguish photopic from scotopic vision. Another all-important fact is that scotopic vision is colourless or achromatic; that is to say, a spectrum, or any coloured object, illuminated to a brightness of less than 10^{-4} candles per sq. foot will appear of a uniform grey colour. One part of the object will be distinguished from another part only by a difference of intensity.

At brightnesses intermediate between 10^{-1} and 10^{-4} candles per sq. foot, a luminosity curve will be obtained which has its maximum somewhere between that of curve A and curve B, provided the curve is measured for a part of the retina which contains both rods and cones.

The identification of the rod, visual purple, system with scotopic vision is supported by the agreement of the spectral absorption curve of visual purple (1) with curve B, and from retinal potential records measured by Granit on a rod eye (2) (e.g. rat or dark-adapted frog), which also give a spectral response curve similar to curve B. The only direct physiological counterpart of the photopic luminosity curve so far available is that derived from retinal potential

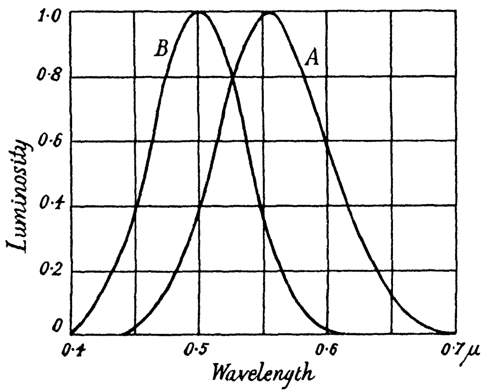

Fig. 1.—Luminosity curves for equal energy spectrum

Curve A.—High intensity, photopic, curve obtained with test object brighter than 10^{-1} candles per sq. foot.

Curve B.—Low intensity, scotopic, curve obtained with test object fainter than 10^{-4} candles per sq. foot.

records of a cone eye (3) (e.g. light-adapted frog), which yield a response curve similar to curve A.

Vision at the Centre and Periphery of the Retina.

Microscopical examination of the retina reveals that at the centre, the fovea, there is a small area subtending about ½°, which contains only cones. Moreover, each of these cones is connected to only one nerve fibre. Examination of a section taken at some distance from the fovea shows an intermingling of rods with cones; the greater the distance from the fovea the larger the number of rods, the fewer the cones. Another difference is that several neurones are now connected to the same nerve fibre; as many as 60–100 rods are sometimes found to converge to a common fibre. At the extreme periphery, all the neurones are rods.

There are a number of sensory phenomena associated with this structural variation across the retina. If the

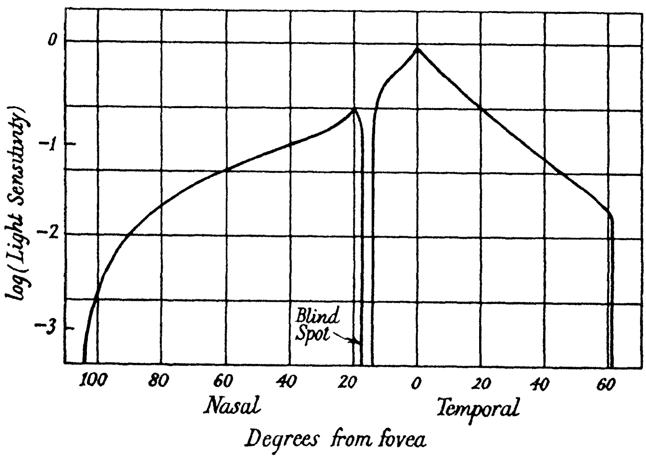

Fig. 2.—Variation of light sensitivity across the retina for photopic eye (Data only approximate)

apparent brightness of a high-intensity patch is measured for various positions of the patch on the retina, it is found that it is brightest when imaged on the fovea and of lowest intensity when focused on the periphery. The sensitivity for this condition, the photopic state, is illustrated in fig. 2. This curve is in general agreement with the cone distribution across the retina as their density is greatest at the fovea, least in the periphery, and in photopic vision it is the cones that are active and the rods inactive. If the same measurements are made for a patch of low intensity and with the eyes dark-adapted, the sensitivity is lowest, possibly zero, at the fovea, and increases to a maximum between the fovea and periphery. This is illustrated in fig. 3.

The sensitivity of the eye to colour also varies across the retina. If a small coloured object is moved across the field of view, with the eye fixated straight ahead, the colour of the object cannot be recognized until the object itself has entered well into the field of view. The point at which the colour is recognized depends on the size and brightness of the object, but a typical set of colour fields for various

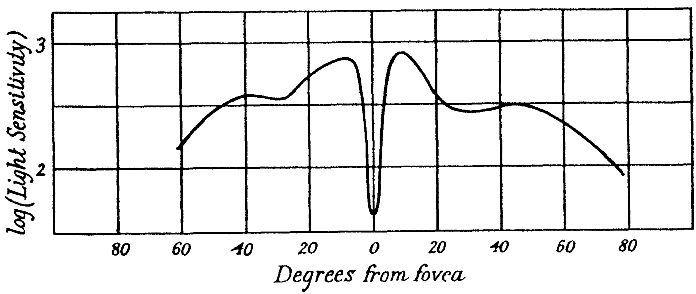

Fig. 3.—Variation of light sensitivity across the retina for scotopic eye. (Stiles)
(Curves appear to vary considerably from individual to individual)

colours is seen in fig. 4. The fovea can be regarded as the part of the retina most sensitive to colour, and this again is in accord with the known concentration of cones, the colour-perceiving mechanism, at the fovea.

The ability of the eye to resolve the fine detail of an object shows perhaps the most startling differences between centre and periphery. The fovea is essentially the seat of distinct vision; when we wish to see any object clearly, we automatically rotate the eyes to image the object on the fovea. The closely packed foveal cones and the 1 : 1 relation between cone and nerve fibre lead to a very high resolving power. In the outer parts of the retina the connexion of groups of neurones to one nerve fibre inevitably leads to a lowering of the visual acuity. The extent of the variation can be gathered from fig. 5.

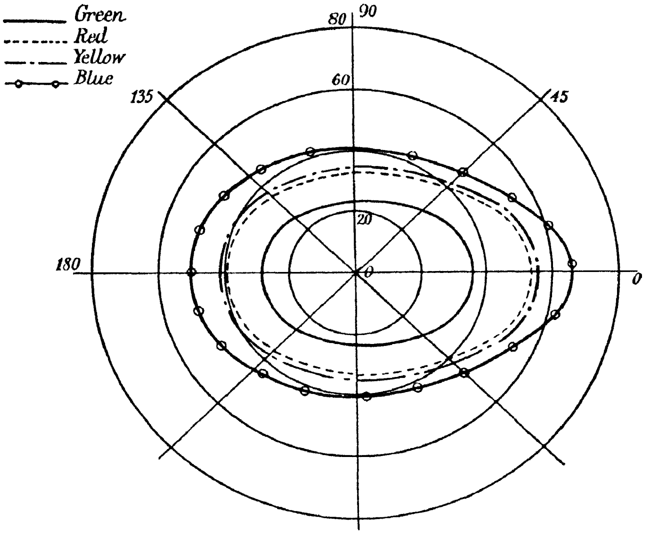

Fig. 4.—Field of vision for spectral colours of moderate illumination. (Abney)

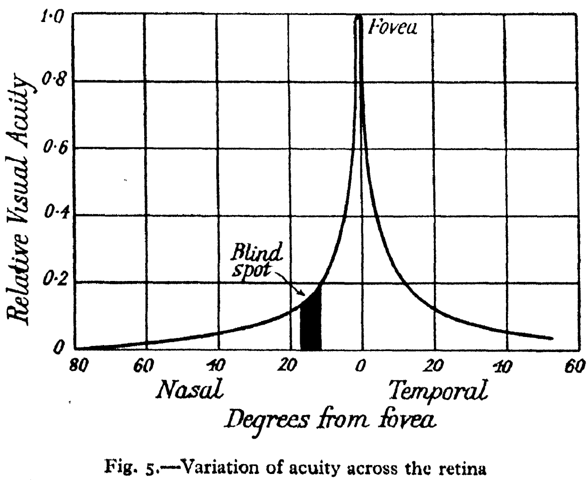

Fig. 5.—Variation of acuity across the retina

There also exists a difference between the fovea and periphery in the response to intermittent stimulation and to the detection of movement. The nature of these differences is so dependent on the particular conditions of observations that they cannot easily be summarized in a sentence or two; they will therefore be considered in detail in Chap. II.

Adaptation.

The magnitude of the visual response is in no sense constant even for a given intensity of stimulus. There are three important ways in which this response is controlled. The first and the simplest is by means of the iris. This exercises a rapid control of limited range; when a high-intensity beam enters the eye, the iris automatically contracts. The maximum diameter in the dark-adapted eye is of the order of 8 mm.; the minimum diameter in the light-adapted eye is approximately 2 mm. When allowance is made for the directional sensitivity of the retina (see Chap. VI), this gives an intensity control of about 8 : 1.

The second control is through photochemical decomposition. When a reaction occurs in either the rods or the cones, the concentration of photochemical substance is reduced, and the same amount of light will initiate a smaller response. This reduction will continue until a balance is reached between decomposition and regeneration. Hence when we first enter a brightly lighted room we are conscious of this brightness and may even be dazzled by it. After a short time, the photochemical balance between decomposition and regeneration is reached, the response is considerably lower, and the room no longer appears abnormally bright. The eye is " light-adapted ". If we now pass out of the room into some dimly lighted passage, we are able to see very little. But with the removal of the light stimulus from the well-lit room, the photochemical substance in the retina is regenerated, its concentration can increase with practically no decomposition to retard the process, and soon there is sufficient light-sensitive material present for even the small amount of light from the dimly lit passage to produce a noticeable response; the observer can now see fairly well at the lower intensity. The improvement in visibility will increase until a balance is again reached between decomposition and regeneration, but the balance point will occur at a much higher concentration than before. The eye is now "dark-adapted".

It is quite certain that the actual photochemical reactions in the retina are very much more complex than is suggested by this simple account of decomposition and regeneration. Some further indications of this complexity are given in Chap. VI; for the present this simple scheme provides a useful working hypothesis from which to examine problems in illumination. Unfortunately this account is not sufficient to describe the phenomena that take place when both photopic and scotopic mechanisms are in operation. This question must be examined further.

Our direct knowledge of the photopic photochemical substance is negligible; but recent measurements of the light-adaptation process by the binocular matching method (4, 5) (see also Chap. III) suggest that the regeneration process is more rapid and more or less complete after 2 or 3 min. On the other hand, the scotopic regeneration process is slow (see Chap. II), and takes 30 min. before approaching completion. Hence when the eye is light-adapted, the photopic substance has to be decomposed only to a relatively small extent before a balance point is reached, while the slowly regenerated scotopic substance must be decomposed to a very large extent before a balance is obtained. Thus in the light-adapted eye we can consider that the rods are out of action and light is perceived only by way of the cones.

When the eye is dark-adapted, the photopic substance is regenerated rapidly, but the gain in sensitivity is small. The scotopic substance undergoes a slower regeneration, but the increase in sensitivity is very much greater. When both photopic and scotopic systems are fully dark-adapted, the actual sensitivity of the scotopic system greatly exceeds that of the photopic, presumably due to differences in the nature and amount of light-sensitive material secreted in the rods and cones respectively. Hence at very low intensities the cones cannot respond, and light is perceived only via the rods and visual purple.

The adaptation process can thus be separated into two general levels: the light-adapted state and the dark-adapted state; in the former, vision operates through the cones, in the latter through the rods. But although the distinction between these two states has received a great deal of attention from many workers, there has been little emphasis placed on the fact that in each of these states both light- and dark-adaptation can occur. Thus there is a wide range of high intensities in which only the cones are acting, and within this range they are capable of adapting either to a very high intensity or to a comparatively low intensity, the latter still being too high for the rods to come into operation. In the same way, there is a considerable range of very low intensities which are all below the cone threshold, but to the higher intensities of which the rod system will be light-adapted and to the lower intensities will be dark-adapted. The process of dark-adaptation cannot, therefore, be logically limited to the transition from cone to rod vision, nor can light-adaptation be limited to the transition from rod to cone vision. Four states have to be recognized.

When necessary we can distinguish the two general levels by the terms "photopic state" and "scotopic state", and describe the further subdivisions by the terms "dark- or light-adapted photopic eye" and "dark- or light-adapted scotopic eye". Intermediate between the photopic and scotopic levels there exists an overlap in which both states are in existence simultaneously.

In addition to the iris and the photochemical reaction, there is also evidence of a third control process, very rapid and probably electrical in origin. It appears that when light first strikes the retina the response rises rapidly to a maximum and then drops to a fairly steady value. An example of the development of the response is shown in fig. 6. The most striking evidence of this is obtained from measurements of retinal potentials, e.g. by Granit (6), and from nerve impulse records, e.g. by Hartline and Graham (7). The corresponding sensory phenomena have also been observed, recent measurements having been made by Schouten by the binocular method (8). Granit ascribes

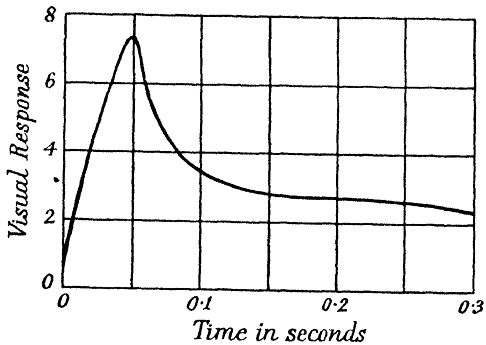

Fig. 6.—Development of the visual response

the fall in response to an inhibitory process, and Schouten associates it with the phenomena of simultaneous contrast.

Acuity, Discrimination and Contrast.

The acuity of vision depends largely on the presence of the individual receptors in the retina. As we always use the fovea for obtaining anything in the nature of sharp vision, we need only consider the density of the cones in that region. There are estimated to be some 150,000 cones per sq. mm. at the fovea, and each cone subtends approximately 40 sec. of arc at the nodal point of the eye. When a sharp edge bounding two levels of intensity falls on the fovea, the cones on one side will initiate larger responses than those on the other side. When the light pattern of some intricate shape, e.g. a letter, is focused on the fovea, we can imagine that we have the corresponding pattern in the receptors and nerve fibres.

It is frequently assumed that the limit of resolution is set by the size of the cones and by the sharpness of the image formed by the optical system of the eye. These must be the chief factors, but they cannot be taken to give the limit directly. Any theory based on the idea of an image lying in a steady position on a mosaic of cones is inadequate. A very high mechanical precision would be required

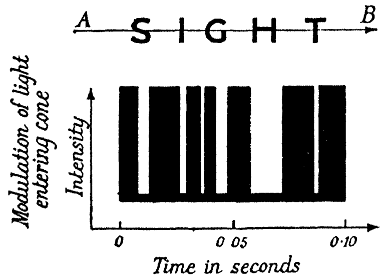

Fig. 7.—Approximate modulation of light falling on cone as it scans the word "sight" along the line AB

to keep the retina in a fixed position to an accuracy of, say, half the diameter of a cone, and in any case the eye is known to suffer from small twittering movements of the order of 1 or 2 min. of arc. The fact is that the retina has to respond to changes of stimulation with remarkable rapidity, and its ability to do so will be an additional measure of its efficiency in resolving fine detail. This can be appreciated by considering the stimulation of a single fibre when, say, reading a line of print. Assuming the eye swept across the print at a uniform speed,* the wave form of the light modulation acting on a single cone while reading one word would be of the type shown in fig. 7. Even

* Actually the eye reads a line of print in a series of jerks. This does not affect the mean time taken for each cone to scan the line, and does not appreciably modify the need for a wide range of frequencies for good resolution.

if we assume that the moderate time of $\frac{1}{10}$ sec. is required to read a five-lettered word, the print of one branch of a letter is only impressed on the receptor for something of the order of $\frac{1}{250}$ sec. The range of frequencies that the receptor-fibre system would have to handle in order to reproduce such a wave-form with any accuracy is very considerable. This is an aspect of the problem into which we cannot enter here. But it is easy to see that good visual acuity is dependent not only on the size of receptor and the optical definition, but also on the time constants of the transmission of the nerve impulses under various conditions of stimulation. To explain visual acuity phenomena we need to know how the trains of impulses (see Hartline, Chap. VI) vary for a light- or dark-adapted eye, for large and small amounts of light, for the presence or absence of light surrounds or glare spots, and so on. Quite recently, for example, Granit (9) has reported an amplifier effect which he has found in his retinal potential experiments; he finds that the difference between the responses from two stimuli is amplified when the eye is sensitized, as it were, by previous stimulation to a somewhat more intense beam. The effect is most marked when the sensitizing stimulus is applied just before the two test stimuli. As Granit suggests, such an effect may be of great importance in relating visual acuity and discrimination with eye movements.

Visual acuity is very closely allied to the ability to discriminate intensities. It is much harder to read black print on grey paper than black print on white paper. If the grey is made darker, the print eventually becomes illegible. We should expect that a change in the conditions of observation which tended to improve the power of intensity discrimination would also improve visual acuity. Measurements made on the just noticeable intensity difference, ΔI, between two fields of intensities I and $(I + \Delta I)$ for various values of I, give the curve in fig. 8. In this diagram $\Delta I/I$ is plotted against $\log I$; at low intensities ΔI is large relative to I, but at higher intensities it is reduced to a nearly constant level. This means that if we had two intensities, I_1 and I_2, such that the ratio I_1/I_2 was always constant, the contrast between I_1 and I_2 would be very much greater for high values of the two intensities than for low values. At very low values, I_1/I_2 might become comparable with or smaller than $\Delta I/I$, in

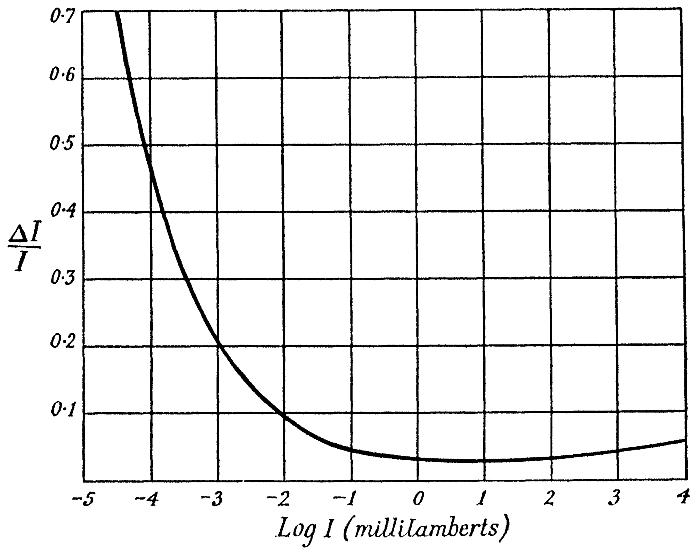

Fig. 8.—Intensity discrimination curve. $\Delta I/I$ in relation to log I, where ΔI is just noticeable intensity difference observed at different values of the intensity, I.

which case no contrast at all would be visible. This reduced contrast is an important contributory factor to the decrease in visual acuity with reduced illumination.

Measurements of just noticeable intensity differences correspond to measurements of the smallest perceptible degree of contrast between two fields, but in practice we are often concerned with quite large contrasts between two or more intensities. The phenomena of contrast are many and varied. In general, the presence of a bright surface near a test object will make that object look darker; a dark surface will make that object look lighter. There is also a reciprocal effect of the test object on the appearance of the neighbouring surface. Corresponding effects are produced between fields of different colour.

For many technical problems of illumination, a knowledge of the contrast present between an object and its surround is the all-important factor. The determination of the contrast value involves two major problems, (*a*) the measurement of the contrasting sensations, and (*b*) the definition of the contrast when the sensation magnitudes have been measured. These problems are discussed in detail in Chap. V.

CHAPTER II

Vision at Low Intensities

Dark-adaptation.

The course of dark-adaptation can be determined by first light-adapting the eye to a given intensity and then, on being confined to the dark, measuring the intensity required to make a test patch just visible at given times from the commencement of the dark-adaptation. These observations can be varied according to the size and shape of the test object, the intensity of the pre-adaptation, and the part of the retina used in making the observations, but the principle of the method is the same in all cases and may be regarded as the standard method of observation. Other methods have been proposed, such as the measurement of visual acuity or the observation of the latent period between stimulus and sensation during adaptation, but while such experiments may provide interesting data, they are not a direct measure of the adaptation process. Adaptation is essentially the process through which the magnitude of the response is controlled. It governs the apparent brightness of a given stimulus; that is its fundamental purpose, and it is that characteristic which must be measured if the true course of adaptation is to be recorded. (For a review of dark-adaptation investigations, up to 1929, see Adams (10).)

The interpretation of the dark-adaptation curve depends very largely on the way in which the results are plotted. In fig. 9 the threshold intensity itself is plotted against the time from the commencement of dark-adaptation. A very rapid drop occurs in the first few minutes, and this is followed by a much slower fall to a steady value reached after 30 min. On the other hand, if we regard the sensitivity as inversely proportional to the threshold intensity and accordingly plot 1/threshold against the time in the dark, we obtain the curve in fig. 10. This curve shows little increase in sensitivity during the first few minutes, but a

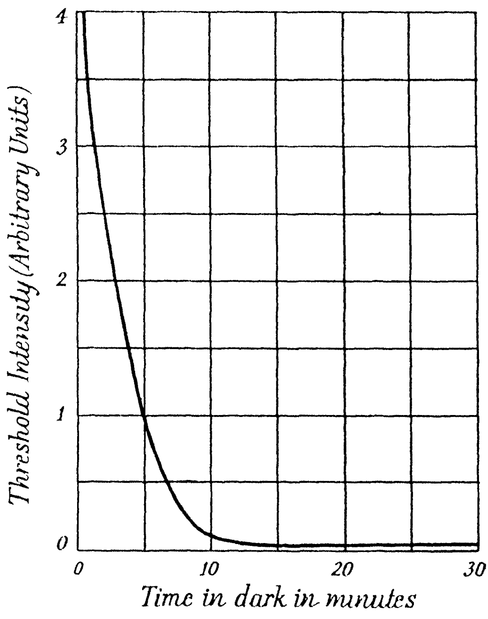

Fig. 9.—Dark-adaptation curve. Threshold intensity

very rapid rise between 10 and 20 min. Finally, we have the curve of log(1/threshold) against the time in the dark (fig. 11). In this case the gain in sensitivity occurs at a steadily decreasing rate, being most rapid at the start and slowing down almost to zero after 30 min.

Which of these curves correctly represents the course of adaptation? The answer depends on the nature of the assumptions we are prepared to make and the point of view from which the question is asked. If we assume that dark-adaptation is due to the regeneration of a photochemical substance, that in the photochemical reactions the response initiated is directly proportional to the concentration of the light-sensitive substance, and that for a given test patch to be just visible, a constant photo-

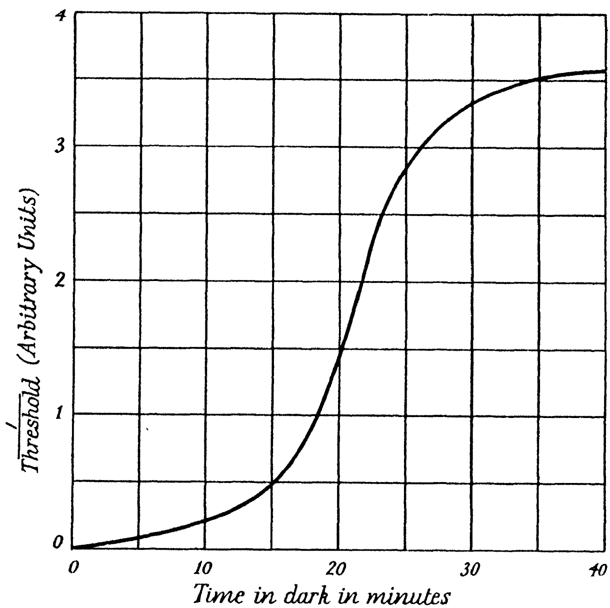

Fig. 10.—Dark-adaptation curve. Reciprocal of threshold intensity

chemical decomposition must occur, then it follows that the 1/threshold curve of fig. 10 records the change in photochemical concentration.

If, on the other hand, we want a record of the apparent brightness of a test object of constant physical intensity during the course of dark-adaptation, then we have to make some assumption regarding the relation between stimulus and sensation. If we assume that the sensation is proportional to the logarithm of the intensity, then the log

(1/threshold) curve in fig. 11 shows the growth of the sensation of a given test patch during dark-adaptation. This assumption is not legitimate, but in the absence of any alternative relation we may regard the curve as giving an approximate representation of the apparent changes in sensation that are actually observed (see Chap. V). Personally I suspect that the true sensation changes follow a markedly different curve.

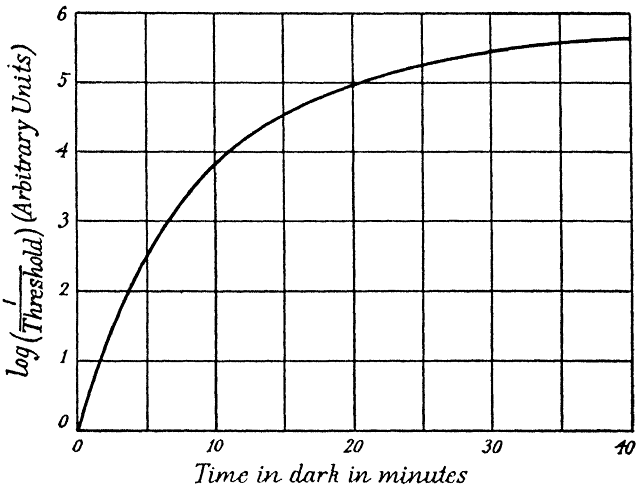

Fig. 11.—Dark-adaptation curve. Log of reciprocal of threshold intensity

We have so far paid no attention to the part played by both the rods and cones in the adaptation process. The experiment represented by fig. 9 corresponds only to rod dark-adaptation. This can be measured either by using a part of the retina where there are few cones, or by employing a previous light-adaptation of too low an intensity to cause any appreciable cone reaction. When the pre-adaptation is relatively high and an area of the retina is used that contains both rods and cones, it has been shown by several workers that the threshold curve is in two parts.

Curves obtained by Winsor and Clark (11) for three pre-adaptation intensities are shown in fig. 12. The double nature of the curve is clearly marked in the case of the highest intensity adaptation; the first portion is due to the combined recovery of both the rods and cones, while the later part is due to the more prolonged rod process alone.

As might be expected, the shape of the curves varies

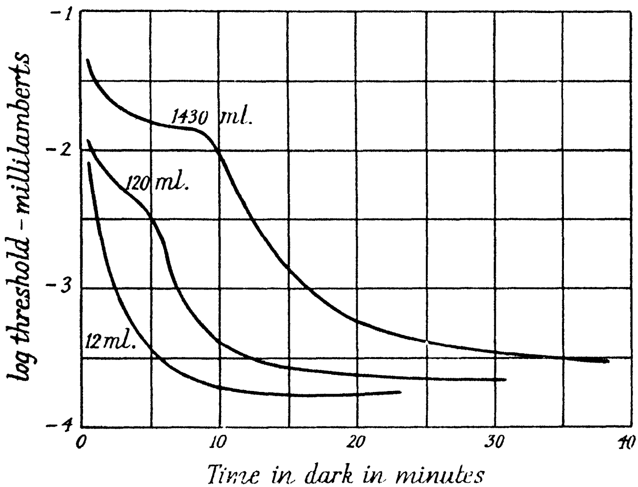

Fig. 12.—Variation of dark-adaptation with intensity of previous stimulation (Winsor and Clark)
Initial intensity of light adaptation shown in diagram

considerably from one part of the retina to another, since this will change the relative importance of the rod and cone processes. It is also found that different types of curve are obtained for varying times of stimulation (12). For a review of these results, Hecht may be consulted (13).

Foveal Dark-adaptation.

The difficulty of applying the results of theoretical investigations on dark-adaptation to practical problems is made much harder because it is so often impossible to specify the part of the retina that will be used in practice. But it is particularly important to know the extent of any dark-adaptation that can occur at the fovea.

There has been considerable controversy as to whether the fovea is capable of any dark-adaptation at all. This may have been due in part to a failure to distinguish between the dark-adaptation of the photopic and scotopic mechanisms referred to in the previous chapter. There is no doubt whatever that the photopic process at the fovea is capable of very considerable dark-adaptation. Thus binocular experiments (see Chap. III) show that after fairly intense light-adaptation, the subsequent dark-adaptation may result in a 50 : 1 or 100 : 1 increase in sensitivity. This is small compared to the 10,000 : 1 gain that can occur with the rod mechanism, but it is in no sense a negligible factor. The photopic dark-adaptation is generally complete after 2 or 3 min., and for my own eye, I have rarely found a gain in sensitivity by more than a factor of 2 or 3 during a further 30 min. dark-adaptation. There is always the likelihood that some observers may be capable of greater foveal adaptation than others, but it is safe to conclude that any scotopic adaptation that may occur at the fovea is of no practical importance.

Relation between Area, Intensity and Time of Exposure.

If experiments are made to determine the threshold brightness of a patch of light for a given state of adaptation, it is found that the larger the area of the patch the lower the brightness required for visibility. For the fovea, the product of the threshold intensity and the area is approximately constant, so that the eye is sensitive to the total amount of light received and not to the light per unit area of the retina. This is valid up to an angular size of field of about 2·5°. For peripheral vision, between 1° and 10° from the fovea, Piper (14) found that (threshold intensity $\times \sqrt{\text{area}}$) = constant. It is to be expected that a difference would be found between the fovea and the periphery because of the difference in the distribution of the cones in the two cases. It is also to be expected that, in the periphery, considerable differences would be found in the relation with different levels of adaptation, as this would change the relative importance of the rods and cones.

Wald has examined this problem afresh in a recent paper (64), and shows that the simple relations just quoted are at best only approximations from a more complex law, and claims that they have only survived because of their simplicity. But they may still be used as a general guide to illuminating engineers, even though their validity for theoretical purposes is in question.

When the threshold is measured for varying times of exposure, it is again found that, within limits, the eye is sensitive to the total amount of light received. Thus Charpentier (15) derived the law:

$$\text{Threshold intensity} \times \text{time of exposure} = \text{constant}$$

for exposures not exceeding $\frac{1}{8}$ sec. For very short exposures, below 0·005 sec., the intensity has to be greater than that indicated by this equation.

Some very beautiful experiments by Hartline (16) (see Chap. VI) on nerve impulses from single fibres confirm the constancy of the intensity-time product for short exposures, and this work should be consulted in order to visualize the basic phenomena underlying the problem.

Limits of Vision.

It will be fairly obvious that sensory observations on thresholds are very difficult to make with any great reproducibility. They are very liable to vary from day to day for the same observer, and are certain to vary from observer to observer. For this reason considerable differences are encountered in the literature of the subject even for thresholds determined under the same conditions. But it is important to have some idea of the range over which the eye can operate, and it is particularly interesting to know the relation between the limits for rod and cone vision. This information is tabulated below, but it must be emphasized that the figures can only be approximate; they have been derived from a general estimate based on the results of various workers.

Total intensity range over which the eye can operate:
10^{-8} candles per sq. foot to 10^{4} candles per sq. foot.

Range of operation of cone mechanism:
10^{-4} candles per sq. foot to 10^{4} candles per sq. foot.

Range of operation for rod mechanism:
10^{-8} candles per sq. foot to 10^{-1} candles per sq. foot.

Observation of Movement.

Movement of an object is detected because of the change in distribution of the light striking the retina. It is safe to assume that, if certain parts of the retina are more sensitive than other parts to changes of stimulation, then they will more easily detect movement, and if certain conditions of illumination are more favourable to the observation of changes of stimulation, then those conditions will also facilitate the observation of movement. We can therefore discuss the problem of motion in terms of the sensitivity to flicker, and will confine this brief discussion to references to some exhaustive work by Lythgoe and Tansley (17).

For an illumination of 6·8 foot-candles and previous light-adaptation to 7·2 foot-candles, dark-adaptation produces a lowering of the critical frequency, an effect least noticeable at the fovea but most prominent at the periphery. With a test patch illumination of only 0·25 foot-candles, the fovea still shows a decrease, but the extreme periphery shows a marked increase. During light-adaptation, the critical frequency rises rapidly for all parts of the retina for a well-illuminated test-object (6–8 foot-candles). The area of the retina most sensitive to flicker varies according to the intensity of the field and the state of adaptation, and also from observer to observer. Figs. 13 and 14 show that in the dark-adapted eye the fovea is more sensitive at high intensities, the periphery at low intensities; and in the light-adapted eye, a region of the retina some 50° from the fovea is most sensitive at high intensities, the fovea becoming slightly the more sensitive region at low intensities. The intensity of the surround

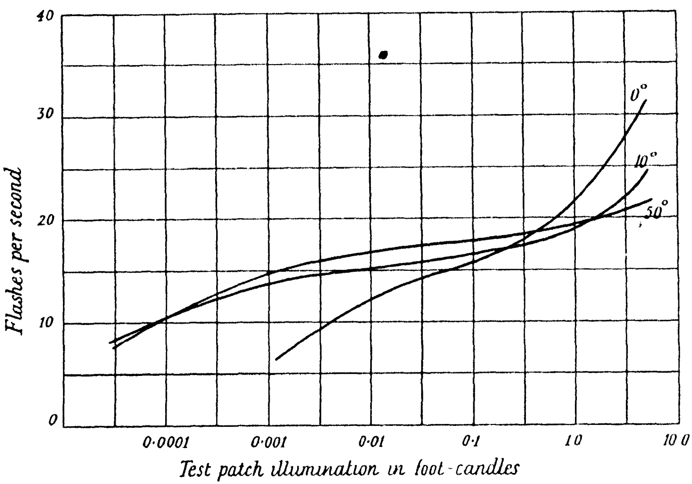

Fig. 13.—Variation of critical frequency of flicker with illumination for dark-adapted eye. (Lythgoe and Tansley)
Angular distance of test patch from fovea shown in diagram

field exerts a profound effect on the flicker, as shown in fig. 15 for an area of the retina 10° from the fovea. This type of curve is explained by Lythgoe as a resultant response from the combined actions of the rod and cone mechanisms, which are assumed to react to variations in surround illumination according to the curve in fig. 16.

From these results it may be generally concluded that light-adaptation increases the speed of response of the cones, whereas dark-adaptation increases the speed of response of the rods for low-intensity stimuli. The cone mechanimsm is the receptor which responds rapidly to intensity changes, while the rods give a more sluggish response. This is in agreement with the findings of Granit from retinal potential observations (18). It is also neces-

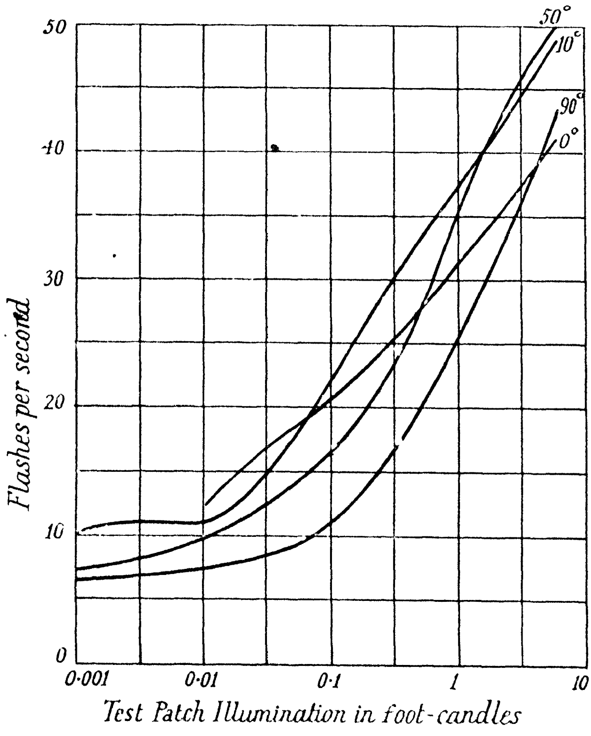

Fig. 14.—Variation of critical frequency of flicker with illumination for light-adapted eye. (Lythgoe and Tansley)

Surround illumination equal to test patch illumination was used in all cases
Angular distance of test patch from fovea shown in diagram

sary to assume that the peripheral cones, e.g. at 50° from the fovea, respond more rapidly than foveal cones.

It is useless to try to formulate conditions for improving the perception of movement unless these facts are taken into account. That they are undoubtedly complex and

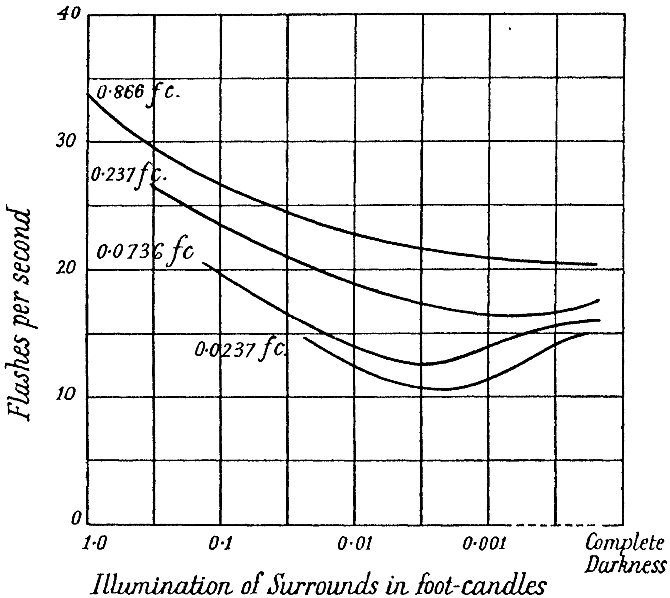

Fig. 15.—Variation of critical frequency of flicker with surround illumination (Lythgoe and Tansley)
Test patch viewed 10° from fovea. Test-patch illumination shown in diagram

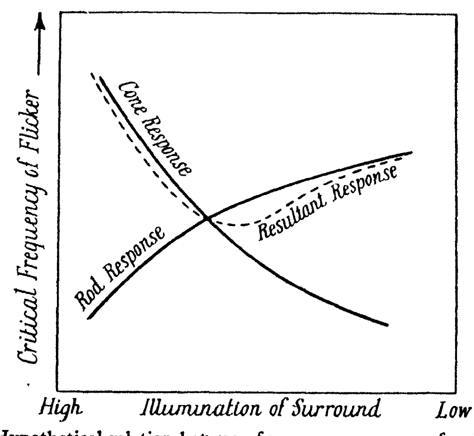

Fig. 16.—Hypothetical relation between frequency response of rods and cones (Lythgoe and Tansley)

confusing can be seen even from this summary; their application to practical problems will depend on the nature of the problem. Lythgoe's original report should be consulted, also similar work by Hecht and his colleagues (13).

Observation of Steady and Intermittent Point Sources.

It is a matter of considerable practical importance to know the optimum conditions for observing navigation lights, rotating aircraft beacons, lighthouse beams, and so on. As a general rule for the conditions obtaining in such circumstances and provided the flashes are short, it can be taken that the eye is sensitive to the total amount of light falling on the retina. There will no doubt be some conditions where an increase in intensity and proportional decrease in time of exposure would be better than a change in the opposite sense, but such special cases are not of great importance. The state of the weather and the distance at which the lights are likely to be observed vary to such a great extent that the system can only be designed to work under optimum conditions for the general case.

Other considerations than purely visual ones may determine the time of exposure. For instance, the speed of rotation of an aircraft beacon must depend to some extent on the distance a plane will travel between successive flashes and the distance from one beacon to the next.

Psychological questions of attention may also be involved. In observing a flashing light it is important that the observer should know for certain that he has seen the flash as well as merely to catch sight of it. Thus it might in some cases be desirable to use a double flash, one to attract the observer's attention, the second to confirm the observation. This might be of more value to some types of observer than to others.

The relative merits of steady and intermittent beams to attract the attention are not easy to assess. So much depends on the background against which the lights are seen, the presence of other lights and the other matters occupying the attention of the observer when on the look-out, so that while a flashing light may be preferable in one case, a steady light may be of more value in another. In this connexion the initial rise of the response to a maximum and the subsequent decline as illustrated in fig. 6 should be noted. This suggests that intermittent illumination might prove to be more efficient, but as the optimum time of exposure is dependent on the intensity, it is impossible to make use of this increased response for all conditions of observation.

The part of the retina most sensitive to picking up these point sources is again dependent on their intensity. When bright, the fovea is the best; when faint, some 10° or 15° from the fovea is likely to be the most sensitive region. The choice of the colour of the beam depends almost entirely on its apparent brightness under the conditions in which it is to be observed. When the eye is dark-adapted and the light is faint, the scotopic luminosity curve shows that, for a given energy, blue-green is most easily seen. Red is certainly to be avoided. In photopic vision, for a given energy, yellow-green is the brightest colour. But it must always be remembered that no gain is to be had from the insertion of a colour filter in front of a white source; that merely reduces the energy and lowers the intensity. A coloured beacon would only be of greater value than a white beacon if it were derived from a source which itself emitted the coloured radiation and which had a greater apparent brightness than the white source for the same energy.

Vision at Night under varied Street Lighting Conditions.

The level of illumination of different systems of street lighting may vary at least from 2 to 0·01 foot-candles on the road surface. The brightness of the surface will depend on the reflection factor of the material of which the road is built, and this factor varies very considerably with the angle of illumination and the angle of view. The brightness may be as high as 1 candle per sq. foot or as low as 0·001 candle per sq. foot. Thus under the best conditions vision is obtained entirely through the cone mechanism; under the worst conditions, vision is almost entirely rod vision. In any given lighting system, the range between maximum and minimum brightness on the road surface and the surround is of the order of 20 or 30 to 1.

The criterion of a well-lit road is that objects should be seen quickly, should be easily recognized, and should be sufficiently outstanding to keep the observer's attention. This in general calls for good contrast between the object and its surround, the contrast to be at as high an intensity level as possible. An object is usually seen dark against

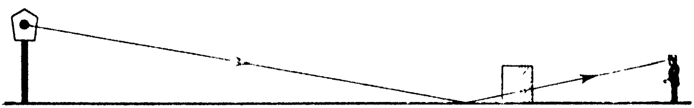

Fig. 17.—Visibility of object on roadway as dark area against light background

a light background. This is illustrated in fig. 17. Good contrast therefore calls for a bright, uniform road surface. Uniformity is especially important, as the ability to discriminate intensity differences is greatly diminished if the field is non-uniform. Very dark areas must also be avoided, both on the road and on the footpath.

These conditions are now well understood and officially recommended (19). The chief visual problems outstanding concern the effect of glare from the light sources themselves, the most efficient colour of illumination to use, and the effect of the adaptation changes that occur when a person is transferred from one level of illumination to another. There are two main types of modern lighting system. In the first, exposed sources are used so that light can fall on the road surface at an angle approaching grazing incidence (fig. 18*a*), and an advancing car will then see the road very well illuminated owing to the high reflection factor of the surface for light incident at such an angle.

On the other hand, the driver of the car will be exposed to the full glare of all the lights along the road. In the second system (fig. 18*b*), lights with a horizontal cut-off are used; that is to say, the sources are screened so as to be invisible to the oncoming driver until he approaches quite close to the lamp standard. He is thus no longer exposed to the glare from a great many sources. The brightness of the road surface, however, is lower than in the first system, because the light now falls more nearly normally and advantage can no longer be taken of the

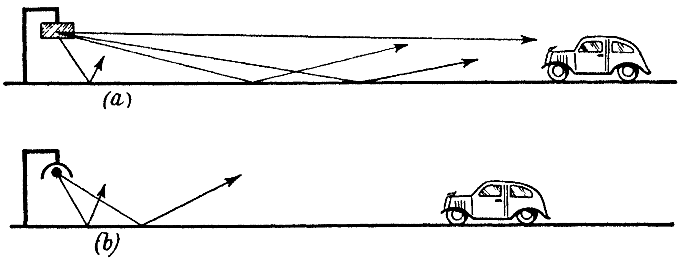

Fig. 18.—Two systems of street lighting

(*a*) Exposed sources utilizing high reflection factor of road surface at angles approaching grazing incidence, to give bright road surface, but giving no protection from glare from sources.

(*b*) Screened sources giving lower road surface brightness but no glare.

high reflection factor at grazing incidence. Methods of evaluating the deleterious effects of glare have not yet been developed to a sufficient extent to warrant any authoritative conclusions as to which of these two systems is the best. The problem is discussed further in Chap. IV.

The colour of the illumination is a relevant problem at the present time because there are three main sources available, one having a continuous spectrum and giving a white light, such as the incandescent mantle or the tungsten filament lamp; the second, the mercury lamp, having a discontinuous spectrum and giving a desaturated blue-green light; and the third, the sodium lamp, also having a discontinuous spectrum and giving a saturated yellow light. Assuming identical light distributions from the three types of lamp, it is necessary to determine which lamp, for the same intensity of source in each case, gives the best illumination on the road surface, the greatest uniformity, the best contrast and the least glare. At first, it might seem that if each lamp had the same intensity and the same distribution, then the illumination on the road surface and its uniformity would be identical for all three case. This is not true because of the change in luminosity curve in passing from a high to a low intensity (fig. 1). Thus, while the equation of the intensities of the sources would most probably have been made under photopic conditions, the viewing of the road surface would be made under scotopic conditions or, more probably, under conditions intermediate between the scotopic and photopic states. Hence, because of the shift of the luminosity curve towards the blue, the apparent brightness of the road will tend to be lower in the case of the sodium light than in the case of the other sources. On the other hand, the contrast will tend to be greater, since an object seen dark against the lighter background of the road surface will be even more affected by the luminosity shift than will the road surface, and the difference will be in a direction tending to enhance the contrast.

Other factors, such as the speed of vision and visual acuity, may also favour the use of the sodium light (see Bouma (20)), but visual acuity is not a very important consideration in this connexion. Glare is referred to in Chap. IV, but it is impossible to state at the moment which colour, for a given intensity, produces the least effect of glare.

The time to adapt from one illumination level to another has received scant attention, and its importance does not seem to be realized. It has, for instance, received no mention in the M.O.T. report (19). In passing from a brightly-lit to a poorly-lit street the eye, adapted to one level, may be called on to operate at a level only $\frac{1}{20}$th or $\frac{1}{50}$th as high. In the case of a person alighting from a well-lit vehicle, the change may easily be greater than this. The time required for effective recovery to have occurred will depend on the actual intensities involved and the relative predominance of rod and cone vision. From fig. 11 and from further discussion in Chap. III, several seconds, and possibly one or two minutes, may be required. This suggests that, from considerations of safety alone, apart from the question of comfort, a gradual transition from one illumination level to another should be provided.

Many other questions in road construction and street lighting may be affected by visual factors. The lighting at bends in the road, the visibility of the kerb, the colour of the road surface, the visibility of lines on the road, are examples, but it will be impossible to refer to these here in detail.

Vision in Fog.

Vision in fog is almost entirely a question of the detection of contrast; visual acuity becomes unimportant, since the scattering of light by the fog particles inevitably blurs the outline of objects at which we are looking. One condition in fog helps the observation of contrast, namely, the uniformity of the field. The scattered light produces a uniform background against which we appreciate the presence of an object by a change in intensity of part of the field.

There are three main conditions under which we may be involved in fog: (*a*) in daylight, (*b*) at night when the observer is without a light, and (*c*) at night when the observer is himself provided with some means of illumination. In (*a*) there is little that can be done to improve the viewing conditions. The eye is light-adapted, the background is fairly uniform and frequently very bright, and as objects will be seen by virtue of only a small intensity difference relative to the background, the fovea will be the most sensitive part of the retina to use. In (*b*) the eye is dark-adapted, and if there is no source of illumination in the neighbourhood, non-luminous objects will be invisible. If there is a source of illumination near by, objects may appear as either light or dark against a dark or light background, according to the relative locations of light source, object and observer. The most important practical problem is the observation of light sources through fog, e.g. navigation lights or airport lights. These lights will first be seen as a diffuse light area against a dark background, and a region of the retina some 10° or 15° from the fovea is likely to be most sensitive. Physically there is very little to be gained in the average fog by the use of a coloured radiation. The fog particles are usually so large that there is very little difference in the scattering or light transmission for different wave-lengths through the visible spectrum. As the eye is in the scotopic state, it will be insensitive to low intensities of red or yellow light and most sensitive to the blue-green. In the case of a thin haze, the red end of the spectrum is likely to be transmitted more readily, and the use of a red source may be advantageous.

The outstanding example in (*c*) is the case of a car in fog. With a headlight or even with side-lights alone, the fog is brightly illuminated, so that non-luminous objects will appear through a veil of bright light. The eye will almost certainly be in the photopic state, and the fovea will be the most sensitive part of the retina. The aim of the lighting system should be to get as high an illumination on the object and as low a fog illumination as possible. It is difficult to satisfy both these conditions simultaneously, and the optimum arrangement can only be determined by experiment. It can at least be said that the headlight should be as far out of the line of sight as possible, and it is usually the experience that with a powerful headlight the fog is so brightly illuminated that objects in the road are invisible. The perception of objects in a fog is not, however, merely a static observation of an intensity difference; as the car advances, the object will suddenly appear, and the time elapsing between its just noticeable appearance and when it is quite easily visible may be very short, depending on the speed of the car and the thickness of the fog. In that event, the important question is the speed with which the eye can detect an object seen with a contrast well above the threshold contrast. It is therefore legitimate to criticize the recent report on the use of coloured headlights (21) for the emphasis on results obtained from threshold measurements, when in many cases it is not the threshold observation, but the rapid recognition of objects with considerable contrast, that is all-important.

Vision in Mines.

There are many instances in industry where work is carried out under very poor illumination, but the conditions in mines are so abnormal that they call for special discussion. The practical and economic difficulties of providing adequate lighting in mines without incurring risks of explosion lead to the use of a very low level of illumination. In some cases, notably in coal mines, this unsatisfactory condition is seriously aggravated by the fact that a coal surface reflects only some 5 to 10 per cent of the incident light. The brightness of the surface itself is thus extremely low.

Prolonged working at such low illuminations frequently leads, after a number of years, to the development of nystagmus, a disease in which, apparently, the cones and fovea are out of action, and the eye-ball is subject to continual small oscillations. The victim experiences great difficulty in fixating, there is a marked loss of visual acuity, and many normal occupations, such as reading, are difficult. The disease is not solely, and may not be primarily, a visual disease, but is in the nature of a nervous disturbance having many symptoms similar to "shell-shock". It is generally agreed that the fundamental cause is the low level of illumination, and it is of obvious humanitarian, as well as economic, importance to determine the minimum illumination necessary to prevent the development of the disease.

It is a reasonable assumption that if the brightness of the coal surface were sufficiently high for vision to be mediated by the cones rather than by the rods, the disease would be very much less prevalent. This is the view taken, for instance, by the Nystagmus Committee appointed by the Medical Research Council (22). It thus becomes important to know the point at which vision changes from rod to cone vision.

From the data given on p. 23, it is apparent that there is considerable overlap of the rod and cone processes; that, in fact, from 10^{-4} to 10^{-1} candles per sq. foot, both rods and cones are functioning. This overlap is demonstrated by the absence of a sudden change-over from the scotopic to the photopic luminosity curve (23), and is supported by interpretations of flicker phenomena such as that illustrated in fig. 16.

In some experiments there is evidence for a sharp change-over, e.g. in some visual acuity measurements and in some flicker experiments. It is quite feasible that in certain types of observation the action of one set of neurones might tend to inhibit the action of the other set and to accentuate and sharpen up the change-over point, but the gradual development of the scotopic luminosity curve is conclusive evidence that in normal working the overlap of the rods and cones is considerable.

It can probably be taken as certain that at some point between 10^{-2} and 10^{-3} candles per sq. foot the cone process becomes more important than that of the rods; a closer estimate than that is of doubtful significance. The Nystagmus Committee (22) use a figure of 0·002 candle per sq. foot; Sharpley (24) criticizes this value as being too low, and suggests 0·01 candle per sq. foot as more correct. Both authorities would no doubt agree that a precise estimate is impossible, and that in any case the level is bound to vary from person to person.

Not only is the actual illumination level on the surface a critical figure, but the light distribution is also important. To raise the brightness of a local area of the surface and to leave the surround illumination very dark is to provide a bad distribution. In such circumstances the miner can have no knowledge of what may be happening to right or left of him, and if he turns round to see what is going on behind him, he will see nothing. An indiscriminate increase in the candle-power of the lamps is also not likely to be a satisfactory solution to the problem. The coal surface must always be dark, and the glare from a high intensity source against a dark background will produce much discomfort. An increase in the number of lamps of small candle-power is likely to be better than an equivalent change in the intensity of the lamps with no change in their number.

Very great improvements have been made since Davy first invented his safety lamp, and the latest development is that of the mercury discharge lamp which has now been officially approved so far as its safety is concerned, and which, in view of its increased efficiency, may mark a new stage in mine lighting. The use of discharge lamps brings the Purkinje phenomenon to the fore, since, as we have seen, the colour of the source very materially affects the apparent brightness when that brightness is low. The mercury source, with its blue-green radiation, is favourably placed in this respect.

Vision in Theatre, Cinema and Television Studio.

The condition here is essentially that the observer views continuously a fairly brightly illuminated area in a dark surround field. Visual experiments show that the perception of detail, the perception of contrast, and the perception of movement are all improved by the use of a light surround field, and the improvement continues until the surround is of the same order of brightness as the test field. In addition, after images, which can be seen if the eyes are turned to a dark surface after steadily gazing at a bright surface, are no longer apparent when a surround field is used.

The use of a light surround to the screen or stage therefore seems to be called for, but it would have a marked effect on the æsthetic and artistic appearance of the scene.

In the cinema, it would, through contrast, enhance the blackness of the blacks and diminish the whiteness of the whites. Because of this and neglecting the question of stray light falling on the screen, a lower contrast or gamma of the picture would be necessary for correct reproduction with a light surround. On the other hand, the presence of the light surround would make the screen image very much less striking and impressive. On the stage, the richness of a scene is enhanced by being viewed against a black field; if the lights in the auditorium were raised, the scene would lose much of its glamour.

As the audience is primarily present to be entertained, the seeing conditions are only of secondary importance. If it is desired to satisfy both points of view, then a light surround of considerably lower intensity than the scene or screen is called for. Lythgoe (25) recommends a surround illumination of only $\frac{1}{50}$th of the central value.

Pathological Dark-adaptation.

It is well known that certain people have a very much smaller range of dark-adaptation than the normal observer. In extreme cases the person is night-blind, that is, he is unable to see at all at the low intensities normally encountered at night. This state is assumed to be due to some failure in the rod mechanism, and one cause is known to be vitamin-A deficiency, which in turn affects the visual purple secreted in the rods. The dark-adaptation curve of such a person is shown in fig. 19, curve A; if this is compared with the normal curve B, it will be seen that the threshold is higher by a factor of 1000 or more.

This is a serious condition for persons affected in such a manner. It is also serious to the illuminating engineer if the number of night-blind persons is excessive. The information on this point is uncertain, although recent investigations suggest that some degree of abnormality may be fairly common (26), and night-blindness is known to be associated with certain, by no means rare, visual diseases (27). Where discomfort alone is concerned, the lighting expert can only be expected to design his system for the average observer, but where danger is implied if the illumination is not adequate, it might be necessary to

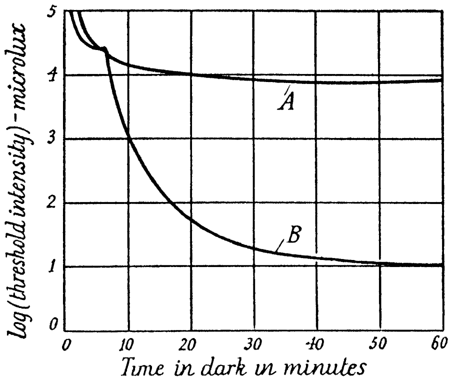

Fig. 19.—Dark-adaptation curve for night-blind person, curve A, compared with corresponding curve for normal observer, curve B. (Dieter)

provide a level of illumination safe both for night-blind and normal observers, or else restrict the activities of night-blind persons. This is a question that calls for further investigation.

CHAPTER III

Vision at High Intensities

Foveal, Chromatic Vision.

At high intensities, vision operates through the cones, and the fovea is the vitally important area of the retina. The peripheral regions are of use in giving a general idea of any scene at which we may be looking, but the real information of the contents of the scene is derived from the fovea as it sweeps rapidly over the field of view.

The perception of colour originates primarily in the fovea, and the characteristics of chromatic vision can be best described in terms of the spectrum. The colours in the spectrum are not spaced uniformly with respect to wave-length; at some points there is a rapid transition from one hue to another, at other points the transition is more gradual.

If we view a photometric field which is illuminated in one half by a radiation of wave-length λ and in the other half by a radiation $(\lambda + \Delta\lambda)$, the value of $\Delta\lambda$ can be adjusted until a just noticeable colour difference is produced between the two halves of the field. In carrying out such an experiment, care has to be taken to keep the intensities of the two halves equal throughout the observation, as it is possible to mistake an intensity for a colour difference. From experiments on these lines made at various points through the spectrum (28), the variation of $\Delta\lambda$ with λ can be found, and the result for a typical observer is shown in fig. 20. This curve shows that the eye is very sensitive to colour changes in the yellow ($0{\cdot}59\mu$) and in the blue-green ($0{\cdot}49\mu$), but is less sensitive in the red, green and blue.

It can also be calculated from this curve that, under the conditions used in measuring it, the normal observer can distinguish some 150 different hues in the spectrum.

The brightest part of the equal-energy spectrum is at 0·555μ (see fig. 1), but in addition to differences of hue and intensity, the spectral colours also differ in their saturation. A desaturated colour may be qualitatively described as a pale, whitish colour, whereas a saturated colour is one which has a deep, rich hue. Yellow, for example, is very

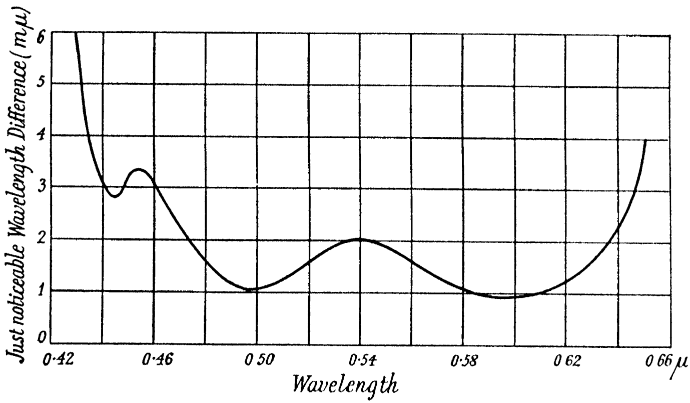

Fig. 20.—Hue discrimination curve for normal observer. (Wright and Pitt)

much less saturated than red. One way of recording saturation is by the number of just noticeable steps between each spectral colour and white (29), and the type of result obtained is shown in fig. 21.

In addition to the qualitative description of a colour in terms of its hue, luminosity and saturation, it is possible to specify a colour on a quantitative basis in the so-called trichromatic system. It can easily be demonstrated that any colour can be represented by a suitable mixture of three physical stimuli; that a colour can be matched by the correct mixture of, say, a red, green and blue stimulus. The explanation of this phenomenon is almost certainly that at some point along the visual path, but most probably in the cones themselves, the response is subdivided into three independent responses travelling along separate paths to the brain. According to the amount by which each of these paths is stimulated, so the colour sensation will vary. It is at present impossible to measure the actual stimulation of these postulated fundamental responses; the best that can be done is to observe the amounts of three defined, physical radiations that, when mixed

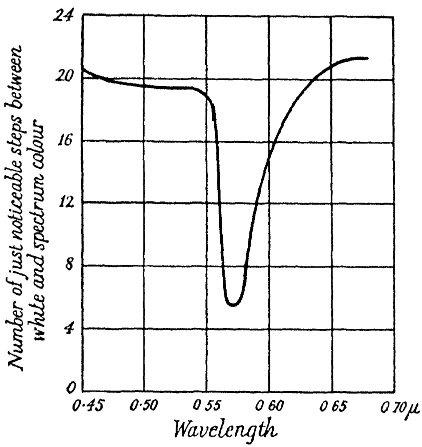

Fig. 21.—Saturation discrimination curve for normal observer (Martin, Warburton and Morgan)

additively, arouse the same colour sensation as the colour under test. It is to be noted that this does not measure the sensation; it merely specifies the necessary physical stimuli required to reproduce it. An internationally agreed framework for specifying colours in this way on the trichromatic system was formulated in 1931 by the Commission Internationale de l'Éclairge (30).

Photopic Adaptation and its Measurement.

There is little literature on the subject of the photopic adaptation process. Compared with the scotopic process, the changes in sensitivity with normal intensities of adaptation are comparatively slight, and the process of adaptation and the recovery from it are rapid processes that do not readily lend themselves to measurement by threshold observations. During the last few years I have used a method (4, 5) for its investigation, in which the observer uses both eyes, one being kept in a constant state of dark-adaptation, the other being subjected to varying degrees of light-adaptation.

The effect of the light-adaptation on the appearance of a test patch is then measured by matching it against a mixture, seen in the dark-adapted eye, of three stimuli from a trichromatic colorimeter (see Chap. VI). The dark-adapted eye is thus used as a reference standard against which changes induced in the right eye are recorded.

It is not strictly true to regard the dark-adapted eye as being unaffected by the light-adaptation in the other eye, but any changes in sensitivity are comparatively slight. The method requires rather elaborate apparatus, at least if colour effects are to be included in the measurements, and the observations are by no means easy until the observer has had adequate practice. On the other hand, so far as I am aware, no other method has been developed by which such detailed records of the photopic process can be obtained, and it has the very great advantage that the sensitivity of the eye is not derived from threshold observations, but from the apparent brightness of a patch of light of an intensity considerably above the threshold value. This condition is so very much closer to that normally encountered in illumination practice that, as we shall have occasion to mention in succeeding chapters, the method seems likely to become a powerful aid to the solution of various practical and technical problems.

The simplest type of observation is as follows: Both eyes are dark-adapted for 30 min., after which the apparent brightness of the test patch seen in the right eye is measured by comparison with the colorimeter primaries viewed in the left eye. Suppose the apparent brightness is a. The right eye then views the adapting radiation, say a white of intensity A, for 3 min., and at the end of this time the apparent brightness of the test patch is again measured by comparison with the left eye. Suppose this new brightness is a_0. In general a_0 will be much less than a, and a_0/a gives the factor by which the sensitivity of the eye has been reduced. The sensitivity normally recovers very rapidly after the adaptation source has been removed, and in order that a_0 should be measured satisfactorily, the comparison between the test patch and the primaries can only be made for 1 or 2 sec. in every 10 sec.; in the intervening period the viewing of the adapting radiation must be continued. Once a_0 has been measured, the adaptation is permanently removed and the course of recovery of sensitivity can be recorded by making a series of rapid matches at various times from the end of the light adaptation. Thus throughout the observations the sensitivity is registered by the apparent brightness of the original test patch.

A great variety of results have been obtained according to the colour and intensity of the adaptation and of the test patch. A typical result for a white adaptation (approximately 4400° K), giving a retinal illumination of 6000 photons, is shown in fig. 22. As $a = 10$ in arbitrary units, and $a_0 = 0{\cdot}8$, the sensitivity is reduced to $\frac{1}{12 \cdot 5}$ of its initial value. The recovery follows a linear path for the greater part of its course, and after about two minutes have elapsed, the recovery is practically complete so far as the magnitude of the sensation is concerned. If the recovery process has a photochemical origin, then fig. 22 presumably represents the photochemical regeneration process directly, and the return to the initial concentration is not quite complete after two minutes. But plotted on a scale of sensation intervals (see Chap. V), the curve would show almost complete recovery in that time.

It is found that, when A is varied, the product A . a_0 is roughly constant for a given a. This result, which has been confirmed by Schouten (8), can be shown to lead to the conclusion that, within limits, once the eye is adapted to any given condition of illumination, the apparent brightness of the scene is apparently the same over a wide range of illuminations. This is in agreement with the statement

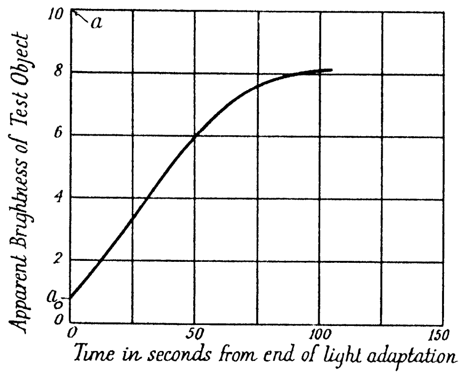

Fig. 22.—Recovery of sensitivity of photopic mechanism after light-adaptation to white radiation giving retinal illumination of 6000 photons

(25) that between 5 and 5000 foot-candles it is extremely difficult, when once adapted, to judge the absolute level of illumination.

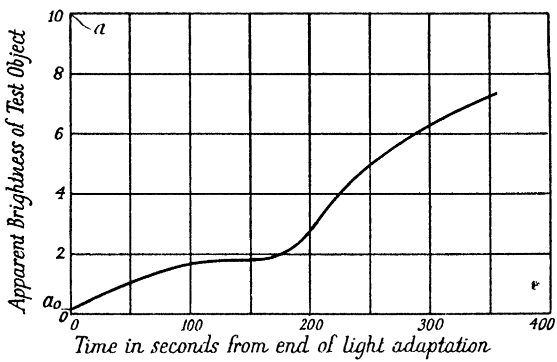

Fig. 23.—Recovery of sensitivity after adaptation to 23,000 photons

At high intensities of adaptation, above 10,000 or 15,000 photons, the recovery curve is no longer linear, but may have the shape indicated in fig. 23. This non-linearity is almost certainly associated with some breakdown in the photochemical system in the cones.

With coloured adaptations, the results are complex, but may become important in connexion with heterochromatic photometry. If two light sources of different colour are compared in intensity instantaneously, as, for instance, in a flicker photometer, the result will almost certainly be different from a similar comparison made when the eye is adapted to each source in turn. For many purposes it is

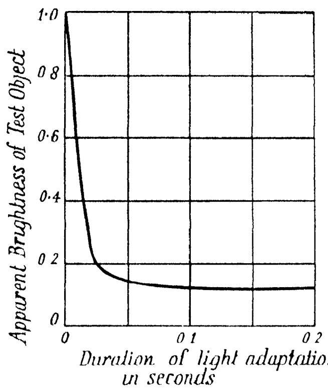

FIG. 24.—Development of rapid adaptation process when bright source illuminates retina. (Schouten)

really the "adapted intensity" that is important, and although the difference between the two methods of comparison may prove to be of no practical significance, such a statement cannot be made until experimental tests have been carried out.

Schouten's measurements of the electrical adaptation (8) show that the sensitivity of the retina is lowered very rapidly when a fairly intense beam of light enters the eye, quite apart from the slower photochemical reactions just described. The observation is made by viewing a test patch in the right eye and a comparison patch in the left eye, a second bright source of light being projected into the right eye to one side of the test patch. This additional source lowers the sensitivity of the right eye, as recorded by the reduced apparent brightness of the test patch in that eye relative to the patch in the left eye. By means of a rotating shutter, the bright source can be viewed at one instant, and the two test patches a moment or two later, and by appropriate adjustments of the shutters, the development of the rapid adaptation can be measured. From fig. 24, it can be seen that a source which produces an illumination of about 17 foot-candles at the eye and is situated 6° from the test patch will lower the sensitivity to about $\frac{1}{8}$ of its initial value after only 0·05 sec.

Measurements of this effect are so recent that their significance to illuminating engineers cannot yet be fully appreciated. They are particularly important in problems on glare, since the change in sensitivity grows with the intensity and is, in fact, not very large until intense sources are involved.

Visual Acuity and Illumination.

The most important function of the eye is to see detail, see it clearly, see it quickly and see it easily. This especially is the supreme function in photopic vision. The measurement of visual acuity under various conditions is thus of great technical importance, not only for the direct information that may be obtained, but as a valuable indication of the merits or otherwise of a given system of illumination.

We cannot do better than refer to Lythgoe's thorough investigation of the subject (31). The acuity is recorded by the recognition of the orientation of Landolt's broken circle, the dimension of the circle being noted when a certain percentage of correct answers is given. Perhaps the most striking result in this report is that which relates to the effect of the surround illumination on the acuity. Thus for a given brightness of the test object, the acuity improves as the surround illumination is increased, until the brightness of surround and test object are equal. A further increase of surround illumination then causes a rapid fall in acuity. This is illustrated in fig. 25.

The relation between acuity and illumination is therefore only significant when the surround conditions are also specified. Results for three surround conditions are shown in fig. 26. The most remarkable feature of this diagram is that, when surround and test-object illumination are equal, there is no indication that the acuity has reached a saturation value even at an illumination of 1000 foot-candles.

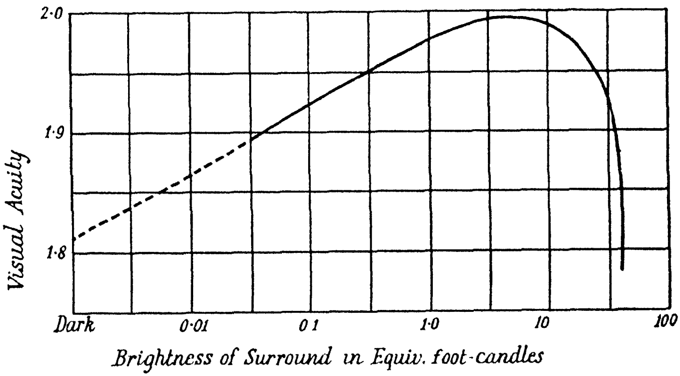

Fig. 25.—Variation of acuity with surround illumination. Brightness of test object 12.6 e.f.c. (Lythgoe)

We suggested in Chap. I that the time course of the nerve impulses along each fibre must be an important element in the acuity function. This suggestion is supported by the effect of the surround on acuity, in view of the fact that a surround improves the sensitivity of the eye to flicker, and that a light-adapted eye gives a more rapid retinal potential response (18).

The practical conclusion to be drawn from the results is that a system of illumination which provides local illumination of the work in hand, without at the same time lighting the surrounding parts of the room, is bad. This is emphasized later in this chapter. It is also to be concluded that, provided the surround illumination is adequate, the efficiency of the eye continues to improve with increasing illumination, at least up to a level of 1000 foot-candles.

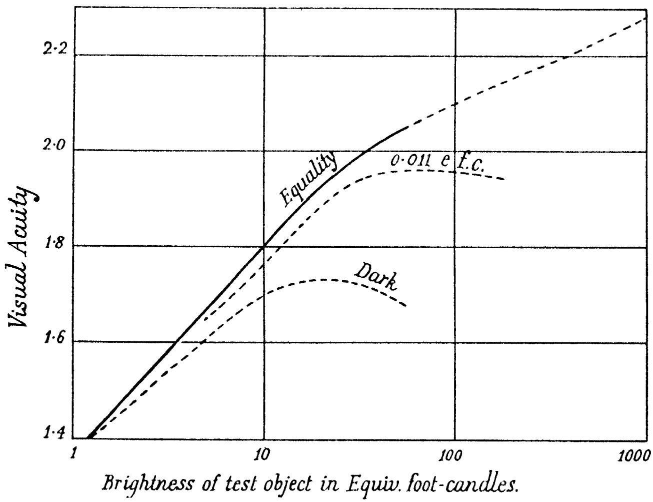

Fig. 26.—Variation of acuity with illumination of test object for three surround illuminations. (Lythgoe)
Value of surround illumination shown in diagram

Lighting in Home, Office and Factory.

Lighting conditions may be discussed from two angles, namely, (*a*) the *optimum* conditions for the work in hand and (*b*) the *minimum* conditions that are adequate for the performance of that work. In practice (*b*) may be further subdivided into an " economic minimum " and a " social minimum ". The economic minimum is the level below which the efficiency of the work is hampered to such an extent that it would be unprofitable to work at such low levels; the social minimum is the level below which the workers would be subject to eyestrain and would themselves complain of inadequate illumination.

Consider first the optimum conditions. From Lythgoe's results we may conclude that for fine work we can raise the illumination to 1000 foot-candles and still improve the performance of the eye. At certain times of the day and year we are, in fact, accustomed to working under daylight illuminations of several thousand foot-candles. On the other hand, 100–125 foot-candles was found as the mean choice of 800 observers to be the most comfortable level of illumination at which to read (32). Also the distribution of the light and its psychological association either with a form of daylight or artificial illumination affects the optimum value (33). Further, an illumination of 1000 foot-candles in a room at night would be very glaring and uncomfortable for a person on first entering the room after leaving a dark street, while for a person passing from the room to the street a dangerous minute or two of partial blindness would occur. For reasons such as these, it is doubtful whether an artificial illumination above 100 foot-candles is in general ever likely to be called for, and this figure may accordingly be regarded as an indication of the optimum illumination. For special purposes, the optimum may be higher, and the most notable instance of this is the operating table, where an illumination of 500 to 1000 foot-candles is provided.

The economic minimum cannot be determined very readily from laboratory tests on visual acuity. It is necessary to make the tests for any given industrial occupation under normal working conditions. Even then, there are usually so many factors which control industrial efficiency that it is difficult to obtain a clear-cut answer regarding the effect of improved illumination.

The investigations of Weston, in particular those on typesetting and weaving (34, 35), are sufficient indication of the economic importance of good lighting, and in view of Lythgoe's work it is especially interesting to find that Weston's industrial investigations show the improvement that results when a good general illumination is provided, in addition to a high level of local illumination on the work in hand. Not only does the output improve with increased illumination when the work involved calls for high acuity, but Adams (36) has found that even in quite rough work, such as tile pressing, there is an important increase in output with improved lighting. Lythgoe (25) suggests that this may be due to the speeding up of vision and of our movements under high illumination. It is certain, too, that the psychological effects of good lighting are important in providing a better mental background for the worker, leading to a more contented outlook and, presumably, to a greater output.

It is quite impossible to give any figures here for a general value of the economic minimum of illumination; that is to say, the point at which the cost of increased illumination is no longer balanced by the increased output. So much depends on the nature of the individual industry, the conditions of the factory, and so on. But it is safe to say that this minimum is much higher than the general practice in many factories at the present time.

Neither is it very much easier to state the value of the social minimum. It is well recognized that the use of the eyes for precision work under poor conditions of illumination imposes a strain that sooner or later has to be corrected by spectacles. Any precise investigation of the relation between poor illumination and consequent eye-strain must obviously be difficult to carry out. If the reactions of the workers themselves to various levels of illumination were tested, some indication of the social minimum could be derived. For example, in one investigation (37) the illumination was recorded at which artificial lights were switched on as the daylight began to fail. This indicated that typists desired a daylight illumination of at least 5 foot-candles, although it is found that the general illumination in the room also affects the minimum acceptable. The method of investigation is interesting, however, because it depends on the reason for a remark such as "It's getting dark; I must switch on the light". For what reason does a person normally switch on the light? Is it because of failing visual acuity or because the apparent or subjective brightness of objects begins to drop? We have already referred in this chapter to the fact that when the eye is adapted to a given level of illumination there is little difference in the subjective sensation when that level lies between 5 and 5000 foot-candles. We shall see in Chap. V that at lower levels of illumination the subjective sensation does diminish, but whether the point at which this diminution commences is the same as the onset of eyestrain is problematical. I should myself feel that an illumination of 5 foot-candles was certainly not too high for a social minimum.

Special Glasses.

It is not inappropriate here to refer to an attempt that has been made in the weaving industry and elsewhere to reduce eyestrain not only by the use of adequate illumination, but by the employment, in addition, of special glasses (38). In fine work eyestrain may develop through the constant effort to fixate and examine the detail of some fine structure; when the fine work is viewed, as it frequently is, from only a short distance away, the normal observer has to use his power of accommodation so as to focus the object sharply, and his power of convergence so as to fuse the images seen in the two eyes. Although these two actions are usually carried out without any conscious effort on the part of the observer, they do involve the exercise of two sets of muscles, and if the exertion is great and prolonged, a feeling of fatigue will ensue, which would, over an extended period of time, be liable to lead to a permanent refractive error. In certain weaving operations, the work has to be examined very close to the eyes and the strain is correspondingly great.

An attempt has been made to overcome this strain by providing spectacles in which each glass combines a prism and a lens of such power that, when the object is viewed at a given distance, the images in the two eyes are sharply defined and properly fused, provided the observer is using none of his accommodating or converging power, in other words, provided the eyes are at rest. The optical action of the spectacles is illustrated in fig. 27.

It has been found that these glasses, when properly designed for each person according to the refractive conditions of his eyes and the state of his muscle balance, greatly relieve the strain normally associated with this special work and produce no harmful effects. There are certain disadvantages in wearing them; at first, it is difficult to dissociate the act of accommodation and convergence from the viewing of a near object, and for the first few days the opposition between these two tendencies

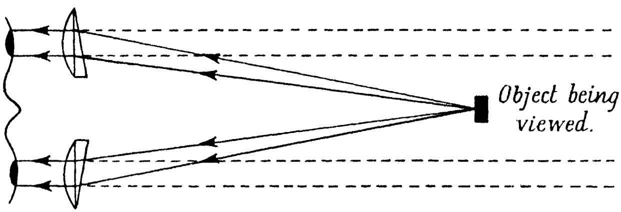

Fig. 27.—Diagram to illustrate optical action of glasses designed to relieve eyestrain with close work

may cause some difficulty to the wearer, but it is only a matter of time before this trouble disappears. It is also impossible to see distant objects clearly when wearing the spectacles, so that their use is only to be recommended for concentrated near work.

In view of their success in industry, it is likely that there are other applications. In particular, with young people, a great deal of refractive trouble arises through intensive study; it is true that this may be due not only to the abnormal use of the eyes, but to the constant stooping over books and to being indoors. Yet the greater part of the strain almost certainly originates in the continual exercise of the power of accommodation and convergence, and the use of these spectacles might obviate much of the fatigue and prevent the development of refractive errors. Here at least is a very promising line of investigation in preventive medicine. I have myself worn such glasses with a considerable feeling of comfort.

Colour Blindness.

Of the abnormal conditions of the photopic mechanism, we should consider the pathological state of the light-adaptation process and colour defective vision. We cannot deal here with the defects of visual acuity and refractive errors; this subject is very adequately treated in many

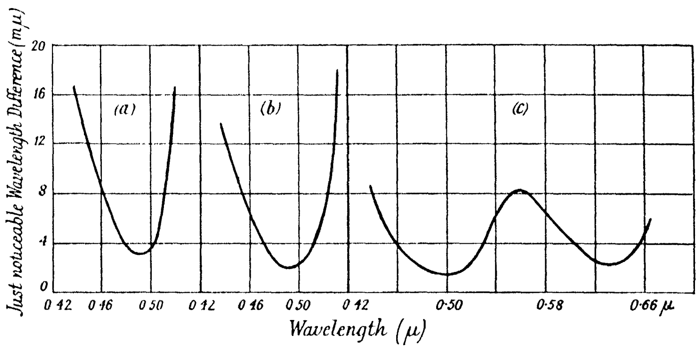

Fig. 28.—Hue discrimination curves for three types of colour blindness. (Pitt)
(*a*) Protanope. (*b*) Deuteranope. (*c*) Anomalous trichromat

other books. The subject of defective light-adaptation, especially photophobia, the state where high levels of illumination produce a sense of dazzle, will be referred to in the next chapter on Glare. In this section we will only deal with colour blindness.

The inherent defect in a colour-blind person is an inability to differentiate colours that to a normal observer are clearly distinguished. This is shown, for instance, by the measurement of the just noticeable wave-length difference at various points through the spectrum. The curves for three types of colour-blind observer as measured by Pitt (39) are shown in fig. 28, and if these are compared with the corresponding curve for the normal observer in fig. 20, it will be seen that the most marked deficiency is in the red-yellow-green part of the spectrum. Thus neither the protanope nor the deuteranope can distinguish a red from a green when the intensities of the two colours are adjusted to be equal. Again, the anomalous trichromat requires a much larger wave-length difference than the normal in the yellow and yellow-green region. The photopic luminosity curves of the deuteranope and some forms of the anomalous trichromat are not very different from the normal curve, but to the protanope reds appear very much darker than

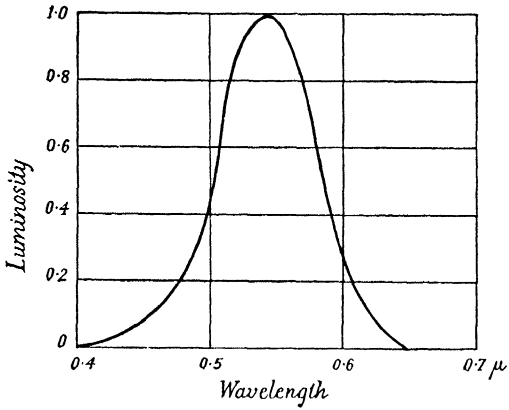

Fig. 29.—Luminosity curve for equal-energy spectrum for protanope. (Pitt)

they do to the normal eye, as can be seen by comparing fig. 29 with fig. 1.

In a rare type of colour blindness, the observer is incapable of distinguishing any differences of colour at all. A scene appears in monochrome, colour differences being seen only as different degrees of greyness. It is believed that with the monochromat, vision is mediated through the rods and visual purple, the cone mechanism for some reason being inoperative. This is supported by the fact that their luminosity curve is similar to the normal scotopic luminosity curve.

For scientific investigations of colour blindness, it is essential to carry out tests on the spectral radiations themselves. All the effects that can be observed with coloured materials, paints, light sources, and so forth, can be deduced from the fundamental observations made on the spectrum, but it is not always the case that tests with coloured objects will reveal the true nature of the defect. On the other hand, for many working tests, it is not necessary to resort to spectral observations, and the use of such charts as the Ishihara tables is generally sufficient to demonstrate the existence of any abnormality.

Very often, a colour-blind observer will be able to distinguish between two coloured surfaces that one might have anticipated would have been confused; that is due to the fact that they are using an intensity difference to make the distinction.

In some industrial occupations, especially in certain forms of inspection test, a colour-blind individual may be noticeably less efficient than a normal person. In such cases, as some 8 per cent of men have some degree of colour deficiency, it may be desirable to use a simple test to eliminate them. It is, of course, as inefficient to use a poor observer as to use a poor system of illumination, and as only a very small percentage of jobs involve colour perception, it implies no material hardship for a colour-blind person to avoid these, and he will in all probability be very much happier if he does so. In some cases, where public safety is concerned, as on the railway, at sea, or in the air, it is imperative that prospective railwaymen, seamen and airmen should be tested, and the tests have to be sufficiently strict to prevent the admission of any colour-blind applicants, without at the same time obstructing those whose vision is only slightly different from the normal. In these cases the Ishihara test is usually followed by the lantern test, and sometimes also by the Nagel anomaloscope.

CHAPTER IV

Glare

Nature and Cause of Glare.

Glare is essentially the dazzling effect associated with a source of light of high apparent brightness. It is the apparent brightness, and not the physical brightness, that matters; in other words, a light source which causes an effect of glare when the eye is at one adaptation level may not be glaring when the eye is at a different level. For example, a motor headlight is no longer glaring when seen in daylight by the light-adapted eye.

We have to distinguish two kinds of glare, simultaneous glare and successive glare. Simultaneous glare occurs when one or more sources are present in a field of view which has, in general, a brightness very much lower than the intrinsic brilliance of the sources themselves. The adaptation level will largely be governed by the low illumination of the major part of the field; hence the sources will constantly be seen by a retina adapted to a photochemical concentration that is too high for their intensity. They will therefore continually evoke an abnormal response and a sensation of glare will be produced.

Successive glare occurs when a person passes into a new level of illumination much higher than that to which the eyes had just been adapted. Again, the glare arises from the fact that the light reaching the retina is reacting with a photochemical concentration that is too large for the new intensity. Successive glare is only of temporary duration except in very severe cases. In due course the eye becomes adapted to the new level, and the nerve currents are no longer of an abnormal magnitude.

It is customary to distinguish two effects of glare, a discomfort effect and a disability effect. The discomfort may, more especially in the case of successive glare, amount to actual pain and produce a strong desire to shut the eyes; in the case of simultaneous glare, it may only amount to a general sense of dissatisfaction or possibly of irritation. The disability effect, as the name implies, refers to the actual loss of visual efficiency, such as a reduced capacity for concentrated observations or a raising of the light threshold and a consequent inability to see faintly illuminated objects.

The disability is partly due to the physical scattering of the light by the optical media of the eye. Around an intense source of light, a halo is formed which is sufficiently bright to mask any faint objects that fall within its boundaries. In addition, the glare source exercises a strong contrast or inhibitory effect on the surrounding parts of the field and tends to reduce the apparent brightness of any objects in the neighbourhood. Lastly, the disability may arise from local changes in the photochemical concentration in the retina; if the eye, which normally darts about over the field of view, should remain stationary for an instant or two, an appreciable change in photochemical concentration can develop at the points where the glare source is imaged, owing to its high intensity. As a result local " blind spots " will develop on the retina and may prove to be very annoying. The effect may be aggravated further by the development of after-images on the same areas.

Glare is most serious when the source is focused near the fovea (*a*) because the test object in general has to be viewed at the fovea and the glare effect is greater the nearer the glare source to the object, and (*b*) because the apparent brightness of any light in photopic vision is greatest when viewed at the fovea and least when seen at the periphery (see Chap. I). Some recent work by Stiles and Crawford (40) suggests that, provided the glare source is always at the same distance from the test object, the glare effect is no different whether the glare source is at the fovea, in the periphery, or even on the blind spot, the area of the retina where the optic nerve enters the eyeball, an area insensitive to light. These results could be explained on the assumption that the whole of the lowering of sensitivity is due to the veiling effect of the scattered light. In view of Schouten's experiments, there can be little doubt that a glare source does lower the sensitivity of the retina quite apart from any question of light scattering, and the discrepancy may be due to the use of threshold observations by Stiles and Crawford, and much higher-intensity test objects by Schouten. It can easily be seen that, with a low-intensity test object, the veiling action of the scattered light may exert a much greater effect than the lowering of sensitivity, but with the high-intensity patch, the veiling action may be relatively unimportant. In any practical problem, it may be desirable either to know the apparent brightness of an easily visible object or to know the value of the just visible intensity, but it has hitherto been the custom to rely almost entirely on measurements of the just visible intensity. This has given much useful information, but its use has probably been dictated more by the fact that it gave a result that could be measured, rather than because it gave just the information required. For this reason, I would again emphasize the value of the binocular-matching method as a means of arriving at a value of the apparent brightness.

The Measurement of Glare.

Nutting (41) determined the just visible intensities and the blinding white intensities for a very wide range of adaptation levels. The results are illustrated in fig. 30. They can be applied to the problem of successive glare to determine the change in sensitivity that occurs in passing from one adaptation level to another, and as an indication of the intensity that will produce an intense dazzle at different adaptations.

Corresponding binocular measurements of the apparent brightness of various test objects have already been referred to in Chap. III (figs. 22 and 23). Curves of the type

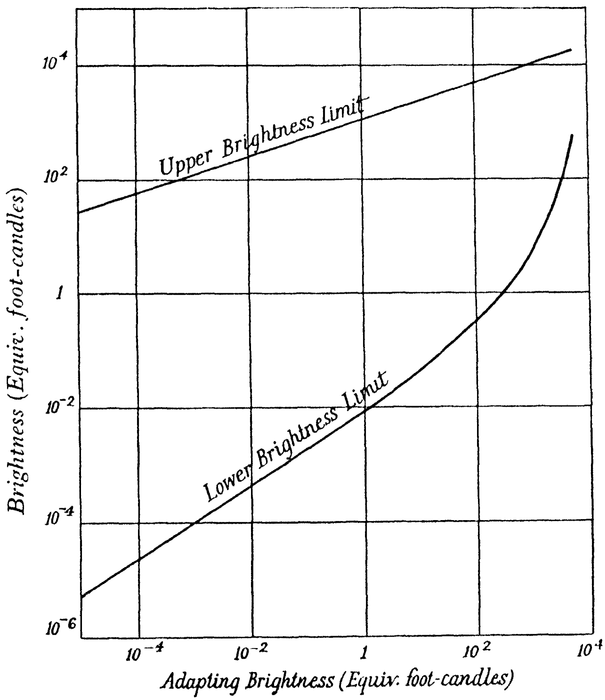

Fig. 30.—Upper and lower brightness limits for various adaptation levels (Nutting)

in fig. 23 suggest that the sensation of dazzle is associated not only with an abnormally large visual response, but also with a qualitative abnormality in the nature of the photochemical reaction.

Apart from Schouten, measurements of simultaneous glare have usually been made by means of threshold observations, and the results of Stiles (42) and Holladay (43) should be consulted. δB, the just noticeable brightness of a test object, is measured for various angles, θ, of the glare source from the test object. The sensitivity is then expressed by the equivalent uniform field brightness, β, that would require the same brightness increment, δB, to produce a just noticeable intensity difference in that field. If the glare source is defined by the illumination E which it produces in the plane of the observer's eye, and if B is the background brightness of the field of view in the absence of the glare source, the following relation is found to hold approximately:

$$\beta = \mathrm{B} + k \, . \, \frac{\mathrm{E}}{\theta^2}.$$

When B is expressed in candles per sq. foot and E is in foot-candles, the value of k for foveal and near-foveal vision is found to be 10, and for the periphery 16. A high value of β indicates excessive glare and implies that for an object to be visible it has to be illuminated to a correspondingly greater extent. The weakness of the formula is that it is based on threshold observations, but when applied to suitable problems, such as the headlight problem, in which the illumination of objects on the road may not be far above the threshold, it can be used to determine the relative merits of different types of headlight beam.

A great many problems connected with glare are concerned not so much with the lowering of the light sensitivity as with the loss of the efficiency of a person in some task he is undertaking. A diminished light sensitivity would contribute to a lowered efficiency, but in many problems it is not a very important contribution. The glare from street lamps is of a different order of magnitude from that of headlights, but nevertheless contributes to inefficient driving. Unshaded lamps in a composing room have been shown conclusively to increase the number of typesetting errors made by a compositor (35).

Is it possible to obtain any quantitative measure of this error-producing discomfort? We have seen that visual acuity usually provides a fair index of good observing conditions, but in the case of glare this is not the case. Lythgoe (31) has shown that the presence of a glare source may even improve visual acuity under some conditions, and for this reason acuity would obviously be an unsatisfactory measure of the glare. At the moment there is no agreed method of assessing this discomfort effect. Investigations of the kind made by Weston on errors made in typesetting show that the seriousness of the trouble can be assessed quantitatively, but there would obviously be much uncertainty in transferring results from one problem to another. If quantitative results are required, each lighting installation must be subjected to tests appropriate to the purpose for which the installation is intended.

Summary of Conditions Aggravating Simultaneous Glare.

1. Glare is greater the more intense the glare source. For a source not exceeding about 2° angular subtense at the observer's eye, the glare depends only on the candle-power of the source. For a subtense greater than 2° and for the same total candle-power, the glare tends to diminish.

2. Glare is greater, the lower the intensity of the main field, as this produces a lower adaptation level and a higher contrast.

3. Glare is greater, the closer the glare source approaches the test object.

4. Prolonged viewing of the glare source produces excessive depression of sensitivity of local parts of the retina, and leads to " blind spots " and after-images.

Æsthetic Effects of Glare.

In addition to the discomfort, an exposed source can also produce a harshness of contrast that can be very ugly. The artist would probably describe this as due to a lack of balance in the subject. An outstanding example is the solitary lamp at the corner of the street in the poorest part of a town. The glaring source, the sharply defined shadows, the deep blackness of the unilluminated parts of the road and wall combine to produce an effect of extreme ugliness. Again, unshaded lights in a building such as a cathedral may spoil much of its architectural beauty.

These effects have to be seriously considered by illuminating engineers, for successful salemanship demands that the goods to be sold shall look attractive. Apart from their technical importance, it is of theoretical interest to see that the installation that appeals to the eye from the artistic point of view is also the installation that has most to recommend it from visual efficiency considerations.

The Headlight Problem.

The headlight problem is closely linked with the problem of measuring the relative merits of different types of headlight. It is impossible to discuss here the design of individual headlights, but we will consider the basis on which some figure of merit can be derived. In this we will follow the work of Stiles and Dunbar (44).

We assume two cars are advancing towards one another, each with their headlights on, each having the same type of headlight, and that the light distribution from these headlights is known. It is then possible, for any relative position of the two cars, to calculate the glare conditions for either driver when viewing a test object on the road at some specified distance, height and lateral position. This will simply involve the determination of the illumination produced by the headlight at the driver's eye, and the angular position of the headlight relative to the test object. Suppose the threshold under these conditions is T, a value that can be derived from previous glare experiments. The visibility of the test object will depend on the illumination it receives from the driver's own headlight, and if this illumination is I, the visibility can be defined as $V = I/T$. Values for V can then be calculated as the cars gradually approach and pass one another, and a curve can be plotted of V in relation to the distance, x, between the two cars.

The general shape of the curve obtained in this manner is shown in fig. 31. As the cars approach each other the glare and visibility become worse until the cars approach sufficiently closely, and each driver gradually moves out from the most intense part of the advancing headlight. From that point, the glare and visibility rapidly improve until, when the cars are level with one another, there is a return to the " no glare " condition. This curve takes no account of any lag which may develop between the adaptation of the eye and the actual glare conditions; in the first part

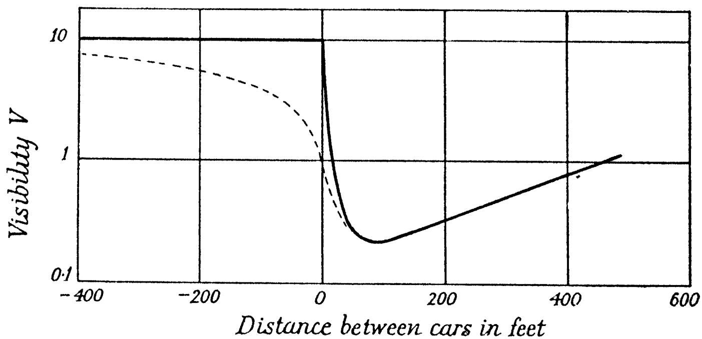

Fig. 31.—Effect of headlight glare on visibility. (Stiles and Dunbar)

of the curve it is reasonable to assume that the adaptation keeps pace with the increasing glare, but in the second part of the curve it is certain that the eye will not recover its sensitivity as rapidly as the glare condition is removed. The dotted curve represents an attempt to allow for this delayed recovery.

In fig. 32, curves for three types of headlight have been reproduced from the report by Stiles and Dunbar. For each type of lamp, the visibility is given for an object in three different positions. For the first type of beam, with an axially symmetrical distribution and a horizontal axis, the glare is bad; for a dipped and swivelled beam, visibility is very much better for two of the object positions

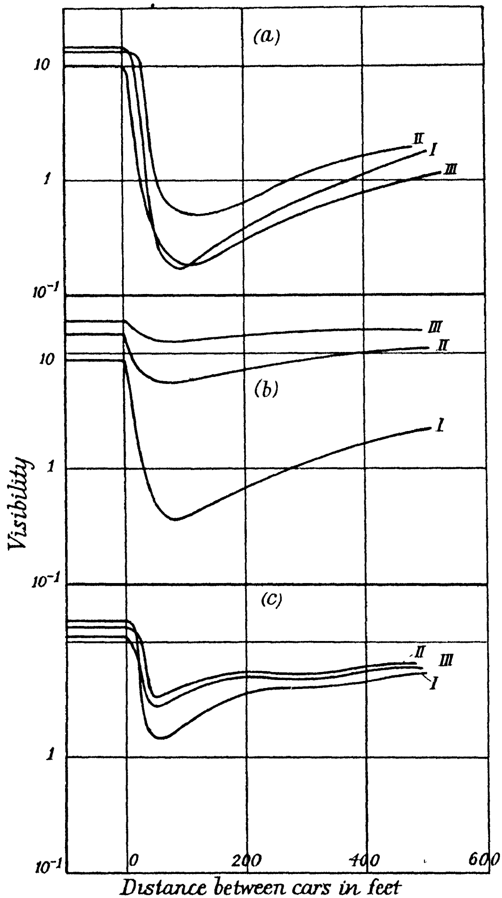

Fig. 32.—Visibility for three types of headlight and three positions of object on road. (Stiles and Dunbar)

Diagram (*a*). Axially symmetrical beam.
Diagram (*b*). Axially symmetrical beam, axis dipped 1·3° and swivelled 5° to near side.
Diagram (*c*). Flat-topped beam.

Object assumed 100 ft. away on level of road surface and axes of cars separated horizontally by distance of 5 ft.

Curve I. Object assumed to lie directly ahead of car.
Curve II. Object assumed displaced 4·5 ft. to near side.
Curve III. Object assumed displaced 9·0 ft. to near side.

and bad for the third; for a flat-topped beam, the visibility is moderately good for all three object positions.

It is only from curves of this type that the advantages and disadvantages of a given form of headlight can be estimated. Obviously no single figure of merit will apply under all conditions. Moreover, the nature of the road surface, the local street lighting, the state of the weather, the movements of the driver's eyes, and so on, will all exert modifying influences. Any attempt to allow for these factors would make the calculations impossibly complicated. At least we can say that any tendency to look directly at the oncoming headlight will make vision worse; hence the advisability of keeping the eyes glued on the road.

Sensitivity to Glare and Night Driving.

Another difficulty in evaluating glare arises from the fact that the glare effect for one observer differs from that for another. Quantitative information on this variation is very limited. In some very recent experiments, I have found considerable variations in the reduction of sensitivity of the photopic mechanism produced by a given intensity of light-adaptation, and, possibly more important, a marked difference in the rate of recovery of different observers (see Chap. VI). In the few persons tested who said they were very sensitive to glare, it usually appeared that this sensitivity arose from a very rapid photochemical regeneration process as recorded by the binocular recovery curve. This rapid recovery is usually associated with only a small initial reduction in sensitivity. Further investigation will no doubt reveal various forms of glare sensitivity. It is known, for instance, that day-blindness, or photophobia, may be due to optical defects, to pathological conditions, to eyestrain, to bad lighting conditions, to impaired central vision, and so on, and it is unlikely that these different sources of the trouble all produce a rapidly regenerating photochemical reaction. In fact, a monochromat whom I have tested had a very slow recovery curve (fig. 42), although, as I believe is generally the case with monochromats, she was sensitive to glare.

Further investigation is required into the effect of abnormal glare sensitivity on night driving. If the abnormal sensitivity were accompanied by a general raising of the sensitivity to light, of both low and high intensities, then the wearing of dark glasses would be an effective remedy. This cannot apply to every case, and may only apply to a few, but it is apparent that, from considerations of public safety, some precaution is desirable if restrictions on the driving of photophobic persons is to be avoided.

CHAPTER V

Visual Sensations

The Problem.

It is becoming widely recognized that problems of lighting are often as much concerned with the magnitude and quality of the visual impression or sensation that any installation may produce, as with the amount of light expressed in physical terms that the installation may be radiating. It has recently been suggested (45) that lighting engineers will in the future be turning their attention more and more to measurements of subjective sensations and contrast. Visibility depends on contrast, so that in order to measure visibility we have to measure contrast; we have to know whether the contrast between intensities A and B is greater or less than the contrast between intensities C and D, and if so, by how much. Another aspect of the same problem arises in the artificial reproduction of sensations, as in photography or by television.

Relation between Myself and My Sensations.

This relation seems to be capable of many interpretations according to the training and outlook of each individual. I can only state my own views and emphasize that the remainder of this chapter deals with the evaluation of sensations in the light of these views.

I regard my consciousness as a mechanism which exists in order to receive, be aware of and interpret sensations. My sensations cannot exist apart from my consciousness, yet they are entities in themselves of which, in some way, I become conscious. My mind or my consciousness experiences these sensations, which have both quality and magnitude. I regard myself as fundamentally distinct from my sensations. I am not a sensation, but a receiver and interpreter of sensations.

The Measurement of Sensations.

Because it is impossible to get outside the mind, it is impossible to determine the magnitude of a sensation. It is impossible to devise a sensation yardstick to lay alongside the mind to make the necessary measurements. The only method we have of knowing anything about the magnitude of the sensation is by a process of mental estimation. It is easy to say when one sensation is greater than another, and some persons are prepared to make a quantitative estimation of the number of times the one may be greater than the other. There is very little likelihood that this quantitative estimation has any real meaning, and it is certainly extremely variable and unreliable, but such as it is, it is the only method we have.

The issue has been confused by Campbell and Marris (46) by their suggestion that sensations are not additive; they maintain that under some circumstances it is possible to add sensation *a* to sensation A and obtain a new sensation A′ which is less than sensation A. This might just possibly be true, but it is unlikely; in any case it is quite impossible to demonstrate experimentally, because we have no means of isolating sensations and adding them together. Campbell and Marris based their conclusion on experiments with superimposed stimuli, but the addition of stimuli is a very different thing from the addition of sensations. A reduction in sensation on changing the stimulus might very well arise from some purely physical or chemical interaction in the physiological sense organ.

An analogy may help to clarify the position. Suppose we send £1 to a farmer in the country in order to have some strawberries sent up by rail. In due course we receive a certain number of baskets of strawberries. Now suppose on another occasion we send £1, 5*s*., then we shall receive another consignment of strawberries which may be equal to the first consignment, or may be more or may be less than before. For on the second occasion the price of the strawberries may have altered, or some of the baskets might have fallen off the wagon, or some dishonest porter might have stolen a few baskets. Yet merely because we sent more money but received fewer strawberries, we should not be justified in concluding that strawberries were not additive; that if you added two baskets to two baskets you might have only three baskets. We should, on an average, expect to receive more strawberries when we paid out more money, but the one is not a measure of the other.

This analogy, with the money corresponding to the stimulus and the strawberries to the sensation, is a close parallel to the perception of visual sensations. Many persons seem to regard the sense organs as physical instruments in which, when you put a given stimulus in at one end, you always obtain the same sensation at the other. This is entirely erroneous. Campbell and Marris were not really concerned with measuring sensations, but were endeavouring to establish a stimulus-sensation relation. For this to be possible at all, the observing conditions must be very severely restricted.

Assuming we are prepared to restrict the conditions of observations, can we then hope to deduce a stimulus-sensation relation? The answer is both yes and no. We cannot obtain a scale of sensations and we cannot therefore derive a direct relation between stimulus and sensation. But we are able to equate sensation intervals or, what is the same thing, contrast steps, and if, for a given state of adaptation, we selected a series of intensities, A, B, C, D . . ., such that the contrast between A and B equalled that between B and C, C and D, and so on, then we could draw a curve between stimulus intensity and sensation intervals or contrast. We cannot transform the sensation interval scale into a sensation scale, because we have no means of telling whether the mind registers contrast as a difference or as a ratio of sensations or as some other, more complex, function.

So far as I know, there has been no attempt made to determine a complete contrast-intensity relation even for one adaptation level. From general observations, it is easily seen that for a mean range of intensities, contrast depends on the ratio of intensities. For example, if we cut down all the intensities of a scene by the same factor by means of a neutral filter placed in front of the eye, we are not normally conscious of any marked change in the contrasts in the scene. Only at high and low intensities does a change become apparent.

Even if it were available, the validity of a contrast scale is suspect. Gage (47) has carried out experiments on the following lines: Two intensities A and B are chosen and an intermediate value, C, is selected such that the contrast between A and C appears the same as that between C and B. Two further intensities, D and E, are then selected to give a contrast respectively midway between A and C and C and B. Finally, the intensity, C′, required to give equal contrast between D and E is determined, and it has been found that instead of C and C′ coinciding, they may differ to an extent apparently greater than could be allowed for as experimental error. If this result were confirmed and the discrepancy were considerable, it would seriously jeopardise the production of any accurate contrast scale.

Although no contrast scale based on observations of large contrast steps has yet been put forward, a scale has been derived from measurements of the just noticeable intensity difference, ΔI, at various intensities I. Typical results on these lines were illustrated in fig. 8, Chap. I. To derive a contrast scale from these observations, the total number of steps has to be plotted against intensity or log (intensity). If log (intensity) is selected as the abscissa, then I/ΔI is plotted against log I, and the ordinate at any point of the curve will be proportional to the number of steps in any constant increment of the abscissa.

The integral of this curve will then be a measure of the total number of steps from zero intensity up to any given intensity I. The curve of I/ΔI with respect to log I, and the integral of this curve ∫I/ΔI . *d*(log I) against log I, are shown in curves A and B (fig. 33). Curves of this type have been derived by Jones (48) and Abribat (49).

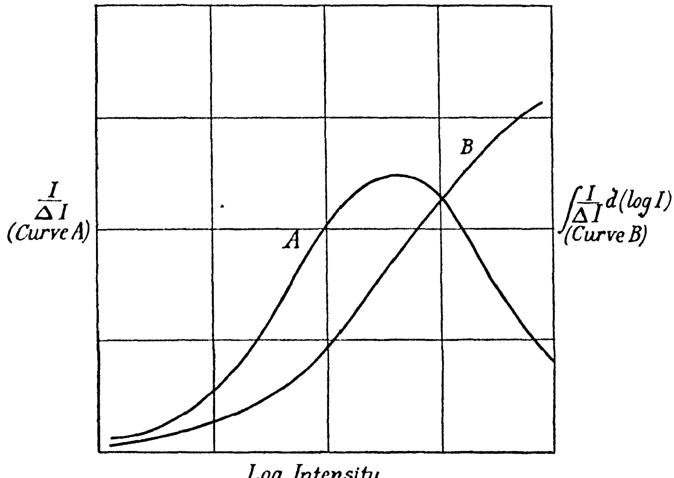

Fig. 33.—Derivation of sensation interval scale
Curve A—I/ΔI against log I.
Curve B—∫I/ΔI *d*(log I) against log I.

Leaving aside the question of the legitimacy of integrating finite differences, and regarding the process merely as one of summation, are we justified in describing the integrated curve as yielding a scale of sensation intervals? This will depend on whether the just noticeable step always corresponds to a constant contrast difference. This is by no means axiomatic. The size of step is governed by the rate at which the sensation changes with changing stimulus, but other factors must come in. For example, I have recently put forward the suggestion that finite discrimination steps are due to the non-homogeneous nature of our sensations (50), and a similar explanation has been proposed simultaneously by Crozier and Holway (51). In this theory, it is assumed that at any instant there is a small variation of sensitivity among the receptors in the retina and, further, any receptor and nerve fibre may vary slightly in sensitivity from moment to moment. The brain presents to the mind a sensation which is in reality the mean of a large number of slightly differing sensations derived from each receptor unit, and the accuracy to which this mean can be appreciated will be governed by the scatter among the individual sensation elements. When a discrimination step is observed, the difference in stimuli has to be sufficient for the mean sensations to be distinguishable from the scatter associated with each of them.

On this basis, the size of the step will depend on the scatter of sensitivity among the physiological processes, and will be only indirectly related to sensation contrasts. This may not be the true explanation, but it is obviously incorrect to assume without further proof that the just noticeable step does always correspond to a fixed sensation interval. It is true that over a mean range of intensities $\Delta I/I$ is very nearly constant, and that over a similar range of intensities, as mentioned above, contrast is largely dependent on the ratio of intensities. Within this range, therefore, the integrated curve of $I/\Delta I$ *will* correspond to a sensation interval scale, but it has still to be demonstrated that this correlation is maintained over the upper and lower intensity ranges. In the meantime, we must assume that the discrimination step does measure contrast and will regard it as legitimate to use curves such as that shown in fig. 33.

Adaptation and Contrast.

The relation between I and ΔI shown in fig. 8 was not derived for any specific adaptation level. In practical problems, it is generally necessary to know the contrast between a number of different intensities all of which are viewed under one and the same adaptation level. The direct integration of the data in fig. 8 cannot be legitimately applied to these problems; instead new data are required for a number of adaptation levels.

Abribat (49) has attempted to derive the required curves

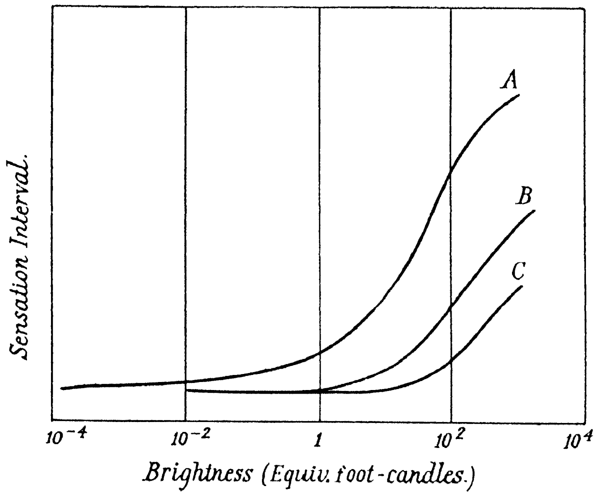

Fig. 34.—Sensation interval curves for three adaptation levels. (Abribat)
Brightness of adapting field:
Curve A—$1 \cdot 5 \times 10^{-4}$ candles per square foot.
Curve B—3·8 candles per square foot.
Curve C—38 candles per square foot.

by an ingenious method in which the whole of the observations were made while viewing a single field which varied in intensity in two directions at right angles. A surround field was also used to maintain a steady adaptation level. Three curves which he obtained by integration of his observations are shown in fig. 34. Apart from the proviso that just noticeable steps may not measure contrast, these curves are the type that are needed and the type that can be directly applied to practical problems.

An "Apparent Brightness" Scale.

For any given adaptation level, the range of sensations can be varied from subjective black to dazzling white, and for each level the sensations will be similar, although the physical intensity necessary to evoke any given sensation will vary according to that level. It should therefore be possible to select a standard level of adaptation to which the apparent brightness of any intensity viewed under any adaptation could be referred. Thus an intensity I_1 viewed under an adaptation level A_1 might have the same apparent brightness as an intensity I viewed at the standard level A. By means of a series of sensation matches for different values of I_1, the intensities for adaptation A_1 that were equivalent to the intensities for the standard adaptation A could be equated for the whole range of sensations from subjective black to the brightest white. If this were done for a range of adaptation levels, we should then have available a reference system by means of which the apparent brightness of an object under any condition of illumination and adaptation could be specified in a perfectly definite manner. Further, suppose we had also measured the contrast curve, as in fig. 34, for the standard adaptation level, then we should be able to use that curve in conjunction with the apparent brightness curves, to determine the contrast between any two intensities at any adaptation level. For example, in fig. 35*a*, a hypothetical curve has been drawn to show the apparent brightness relation between adaptation level A_1 and the standard level A, while in fig. 35*b*, a hypothetical contrast curve has been drawn for the standard adaptation. If we wish to know the contrast between I_1 and I_2 seen under adaptation A_1, it is first necessary to read off from curve (*a*) the intensities I_1' and I_2' which have the same apparent brightness seen under A, as I_1 and I_2 have when seen under A_1. Curve (*b*) can then be used to find the contrast readings, S_1 and S_2, corresponding to intensities I_1' and I_2', and $(S_2 - S_1)$ will be the required sensation interval or contrast.

If contrast is to be measured, I believe it will have to be on these lines. The production of the standard contrast scale and of the family of curves relating apparent brightnesses at different adaptation levels, although a lengthy process, would present no insuperable difficulty, especially in view of the fact that the work could be carried out under standard laboratory conditions. The practical success of the method would probably depend on the de-

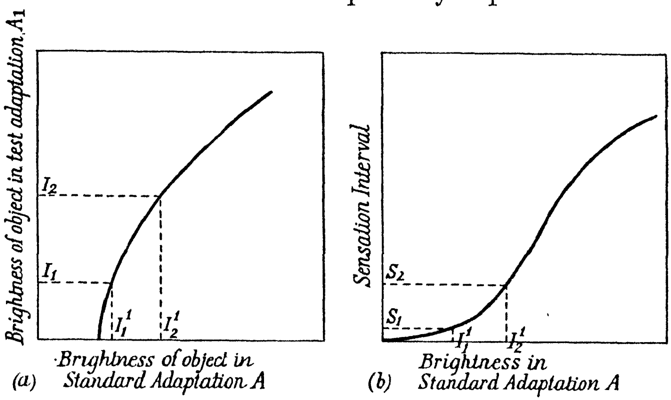

Fig. 35.—Suggested method for derivation of sensation interval scale for any adaptation level

(*a*) Relation between brightness of test object under some test adaptation level and brightness of test object under a standard adaptation level, for the same apparent brightness of object in the two cases.
(*b*) Sensation interval curve for standard adaptation level.

velopment of instruments to measure the apparent brightness of the test object and the adaptation level of the eye under working conditions. It may be possible to devise a binocular-matching instrument capable of use by the illuminating engineer to measure apparent brightnesses on the lighting installation, and some method of measuring the integrated light entering the eye might be sufficient to determine the adaptation level. Further preliminary work would obviously be necessary to establish the system as an engineering process.

It may not be premature to consider the most suitable value for the standard adaptation level. If the adapting field were made too bright, the glare might produce abnormal effects (see, for example, fig. 23), and if it were too faint, then the viewing of bright test objects would itself tend to disturb the adaptation level. On the basis of my own experiments, I would advocate an adapting field of 5000 photons. It would probably be convenient to have at least two levels as working standards, one for use at low-illumination levels, as, for example, in street lighting installations, and a second for high levels, as in daylight measurements.

Apparent Colour and Colour Contrast.

It has been tacitly assumed so far in this chapter that we have been dealing only with black-and-white sensations. Similar, only more complex, problems exist in measuring the apparent colour of a patch of light and the contrast between two colours for various radiations and adaptation levels. This again calls for the production of an " apparent colour scale " under standard adaptation conditions, and the equation of colour sensations at different adaptation levels. The latter can be done with a trichromatic colorimeter, using binocular matching (see Chap. VI), but the erection of a colour contrast scale for the standard adaptation introduces extraordinary difficulties of specification. The fundamental observation is itself difficult; for example, it involves adjusting the contrast between, say, a red and a green, until it is of equal magnitude to the contrast between, say, a blue and a white. The results then have to be fitted into some kind of quantitative scale. There have been numerous attempts to build up so-called psychological colour solids, but the amount of quantitative information available is quite inadequate for the purpose, especially as hue and saturation discrimination data have only a limited bearing on the subject.

Reproduction of Scenes.

In reproducing a scene, we aim at reproducing, under one set of visual conditions, the sensations that we received under a different set of conditions. The visual rules for correct reproduction can be solved quite easily if we are prepared to use Abribat's curves as sensation interval curves. Suppose, for instance, that we wished to photo-

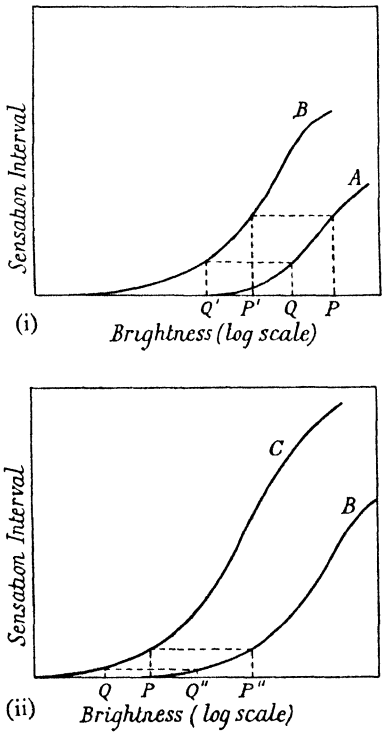

Fig. 36.—Reproduction conditions for sunlight and moonlight scenes
Curve A—Contrast under sunlight conditions.
Curve B—Contrast under conditions for viewing photograph.
Curve C—Contrast under moonlight conditions.

graph a scene in sunlight and view the photograph in artificial light and that the contrast curves for these two illumination levels are illustrated in fig. 36 (i), curves A and B respectively. If P and Q are two objects in the scene, then the intensities required to reproduce them correctly will be given by P′ and Q′, following the construction shown in the diagram. If curves A and B are parallel, P/Q = P′/Q′, and correct reproduction will call for a contrast or gamma of unity. If the curves are not parallel, then some contrast other than unity is required.

Suppose we now wish to photograph the same scene when illuminated by moonlight. Nutting's results (fig. 30) show that as the adaptation level is lowered, the adapting intensity and the threshold intensity approach one another, from which it follows that the apparent brightness of the adapting intensity gets less and less. This is inevitable, since the eye does not possess an infinite range of adaptation; as a result the moonlight scene always appears dark, even after the eye has become fully adapted to the low illumination. We shall therefore find that in the sensation interval curve for moonlight (fig. 36 (ii) curve C) the objects P and Q will, subjectively, be darker than before, and will therefore fall on the heel of the curve. Hence, for correct reproduction, they should be reproduced by P″ and Q″. Again, if curves B and C are parallel, P/Q = P″/Q″, and a gamma of unity will be required. The difference between the sunlight and the moonlight reproduction is, first, that P″ and Q″ are darker than P′ and Q′, and secondly, as P″ and Q″ fall on the heel of curve B, the contrast in the moonlight reproduction is subjectively softer.

On this basis, assuming the contrast curves at all adaptation levels are parallel, correct photographic reproduction would always call for a gamma of unity, one reproduction differing from another only in its over-all density. Actually Abribat's curves are not strictly parallel, but indicate a gamma slightly less than unity for the moonlight scene. This has also been a frequent photographic practice in the past when photographing scenes of low illumination. The data of fig. 30 show that a 1 : 1 relation certainly cannot always hold between the intensities of the scene and those of the reproduction when big intensity ranges and considerable differences in adaptation level are involved, since, for example, the intensity ratio between dazzling white and subjective black at one adaptation level is sometimes 1000 times greater than at another adaptation level.

This analysis takes no account of the effects of simultaneous contrast. In its simplest form this aspect of the problem may be stated as follows: Suppose two neighbouring areas in the original scene have intensities x and y, and are reproduced in the photograph by intensities x' and y', in accordance with the process outlined above. This process ensures, in effect, that x' when viewed by itself will have the same apparent brightness as x seen alone, each being assumed to be viewed under their respective adaptation conditions. The same will apply to y' and y. Does it then follow that, when x and y are seen together, the contrast effect which each will exert on the other will produce the same modifications on their apparent brightness that x' and y' will produce on each other when they are seen side by side in the reproduction? So far as I know there is no information yet available to answer this question, but Schouten's method of measuring simultaneous contrast may eventually provide the data that is needed.

In practice, photographic reproduction rarely has to deal with excessive ranges of intensity in any one scene, and a number of limitations in photographic processes, especially in making prints, introduce factors that modify any purely visual argument. Hopkinson (52) claims that a gamma of unity gives satisfactory results provided the density of the print is adjusted in accordance with rules which he specifies. Following these rules, he has produced some excellent photographs of street lighting installations. His conditions for correct reproduction were derived from experiments in which a number of persons selected the print which appeared to reproduce most faithfully the visual impressions created by the original scene. The selection will depend on both visual and photographic processes, and the choice of reproduction must accordingly be the result of a compromise between a number of variables.

It is a matter for photographers to decide whether a gamma of unity is, in fact, the best compromise, and in many cases their judgment will have to include psychological questions of association and the artistic value of enhancing this or that characteristic. It cannot, therefore, be regarded as sound practice to investigate the *visual* conditions of true reproduction by the examination of a series of photographs; such an investigation demands purely visual observations, as in the experiments by Abribat.

In cinematograph reproduction and in television, the position is somewhat different from that of normal photography. The picture is usually seen in the centre of a dark field, and because of the contrast between the picture and the surround, the blacks in the reproduction have to be darker than in a print, in order to produce a sufficient appearance of blackness. Further, the average brightness of the picture is the main factor controlling the adaptation level of the eye. Hence, within limits, a change in mean intensity is subjectively compensated by a change in adaptation level and can therefore be used much less effectively as an indication of transition from, say, a scene in sunlight to one in moonlight. For this reason a rigid control of the gamma to unity or any other value is no longer possible or desirable. Changes from one type of scene to another have, in part at least, to be expressed as an objective change in contrast. Another, more technical, reason necessitates a gamma other than unity, namely, the presence of stray light falling on the white cinema screen which tends to reduce the contrast, an effect which has to be compensated by using a film with a gamma appreciably greater than one.

CHAPTER VI

Some Recent Researches

W. S. Stiles and B. H. Crawford.

Stiles and Crawford (53) have recently observed the unexpected phenomenon that the apparent brightness of a patch of light depends, among other things, on the angle at which the beam is incident on the retina. For instance, if two narrow pencils of light are focused on the fovea, but one of them passes through the centre of the pupil while the other passes near the periphery, as in fig. 37,

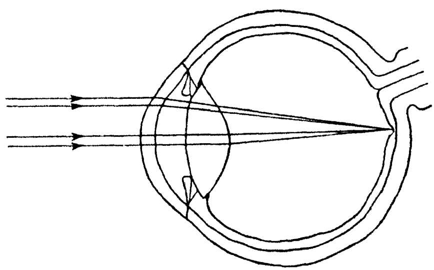

Fig. 37.—Formation of image on fovea by pencils passing through centre and edge of lens

then for equal physical intensities, the central beam will appear much brighter than the peripheral beam. The reduction in sensitivity for pencils at various distances from the centre of the pupil is shown in fig. 38.

This result can only mean that the retina possesses a marked directional sensitivity; and while Stiles and Crawford have suggested that it might arise from the more oblique rays having to travel through greater thicknesses of pigment epithelium, I prefer the suggestion (54) that the light may have to pass almost straight into a cone to produce the maximum effect. Further aspects of the phenomenon have been investigated (55, 56), and there seems little doubt that it will prove to be of fundamental importance in the elucidation of the visual processes.

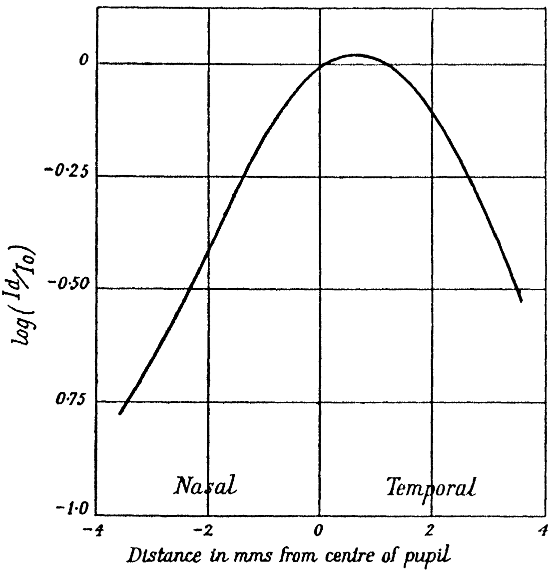

Fig. 38.—Relation between apparent intensity, I_0, of beam passing through centre of pupil and apparent intensity, I_d, of beam passing through pupil at distance d from centre. (Stiles.)

It is of special significance to illuminating engineers, since it modifies considerably the action of the iris. It also means that many photometric observations can only be properly carried out by employing an artificial pupil and fixing the observer's head, and it is not improbable that if this were done more frequently, the variations and uncertainties commonly experienced in visual observations might be greatly reduced.

J. F. Schouten.

I have already referred to certain of Schouten's results obtained by the binocular-matching method, and here I

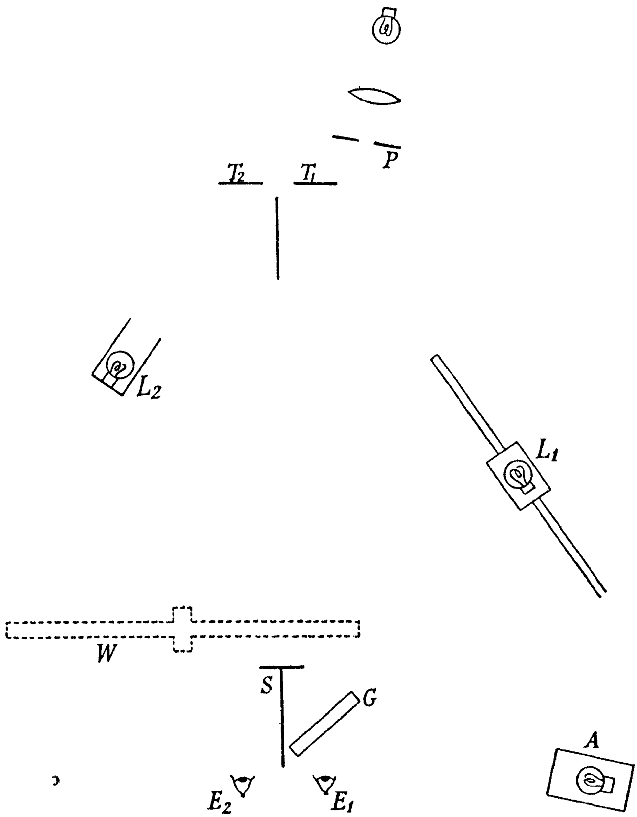

Fig. 39.—Optical arrangement for binocular matching as used by Schouten

will only describe briefly his experimental method as illustrated in fig. 39. The right eye E_1 views the test surface T_1 illuminated by the lamp L_1, and simultaneously the left eye E_2 views the test surface T_2 illuminated by the lamp L_2. A screen S ensures that each eye shall see only its appropriate patch. The distance of L_1 from T_1 can be varied until the apparent brightness of T_1 and T_2 are the same. To measure the effect of direct successive adaptation, the adapting light A can be thrown into the right eye by reflection at the glass plate G, and at the end of the adaptation the two test patches can be rematched. For measuring the indirect simultaneous adaptation, a glare source P can be imaged in the right eye to one side of the test patch, while observing and matching the two test patches. A shutter W can be rotated in front of the two eyes, if desired, in order to measure the time constants of the response.

This apparatus is comparatively simple, and requires a great deal less adjustment and operating than the apparatus described in the next paragraph. On the other hand, the absence of artificial pupils introduces the diameter of the iris as a variable, and the continuous viewing of the test patches is liable to change the adaptation level, particularly of the left eye, and so introduce an effect that is rather difficult to discount.

W. D. Wright.

I have been particularly interested in measuring the colour changes induced by adaptation, and have adapted my colorimeter (57) so that the test patch and adapting light are seen by the right eye while a mixture of the three colorimeter primaries, a red ($0{\cdot}65\mu$), a green ($0{\cdot}53\mu$) and a blue ($0{\cdot}46\mu$), are seen by the left eye. The arrangement of the actual viewing system is illustrated in fig. 40. Beam 1 comprises the mixture of the three primaries, beam 2 the monochromatic test patch, and the beam from S provides the adapting light which can be controlled both as regards intensity and colour by means of sectors and filters at T and F. In order that the right eye should be in as constant a state of light-adaptation as possible and the left eye be constantly dark-adapted, the adapting patch is viewed continuously via the mirror M, except for short intervals of a second or two when the mirror is swung out of the way to M′, to reveal the test patch, and simultaneously a shutter N rotates to N′ out of the path of the beam 1 to reveal the primaries to the left eye. By matching the patches viewed in the two eyes, the colour and intensity changes induced by various adaptation conditions can be recorded. Because artificial pupils are used at E_1 and E_2, it is necessary to centre these relative to the observer's pupils, and to maintain the observer's head in a fixed

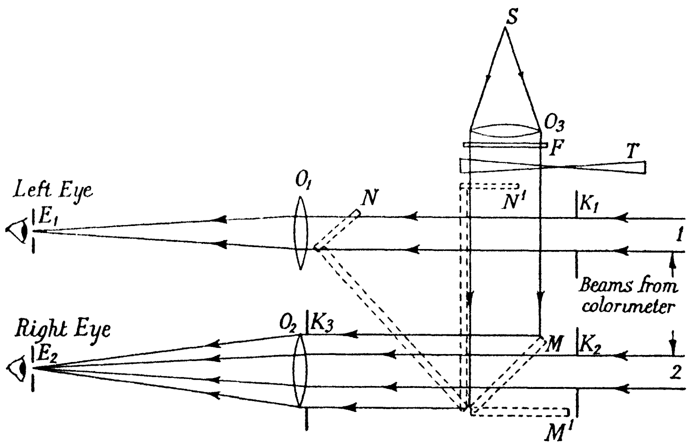

Fig. 40.—Viewing arrangement for binocular matching as used by Wright

position once the centring adjustment is complete. This introduces additional complexities into the apparatus, including the preparation of a dental impression in wax which can be fixed to the apparatus and on to which the observer must bite to maintain a constant observing position. A new apparatus in course of construction is illustrated in fig. 41. This instrument, which is being built through the generosity of the Medical Research Council, has been designed especially to ensure rigidity of both apparatus and observer, and to make the adjustments as simple as possible. The arrangement of the optical parts is slightly different from that shown in fig. 40.

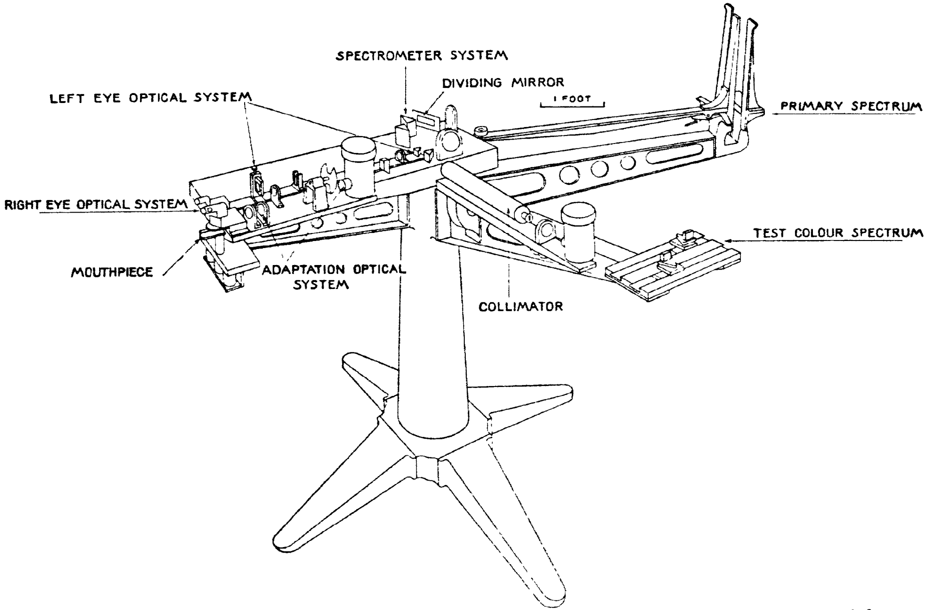

Fig. 41.—Illustration of new trichromatic colorimeter showing skeleton optical system when adapted for binocular matching. (Wright)

System consists essentially of spectrometer arrangement in which two spectra are formed by use of a dividing mirror. Three portions of the primary spectrum are reflected back through the system into the left eye and the test colour is reflected from the comparison spectrum into the right eye.

Another instrument, a subjective photometer (58), has also been in use in which only the intensity changes induced by adaptation are recorded. Results obtained by four different types of observer are shown in fig. 42. So far, among normal observers, two general types of curve, (*a*) and (*b*), have been found, in one of which the recovery of sensitivity sets in as soon as the adaptation is removed,

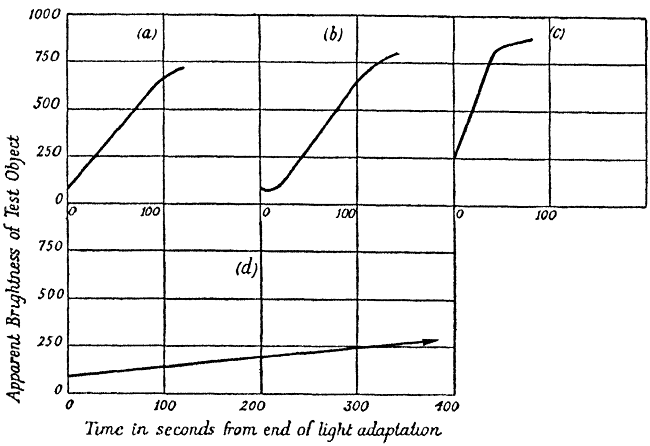

Fig. 42.—Recovery of sensitivity of photopic mechanism after light adaptation, intensity 6000 photons, as measured on subjective photometer. (Wright.)

(*a*) and (*b*)—Two forms of normal recovery curve.
(*c*)—Curve for glare-sensitive observer.
(*d*)—Curve for monochromat.

and the other in which for some seconds the recovery process is apparently inactive. It may eventually be found that for some purposes one type of observer is more valuable than the other. Curve (*c*) represents the curve for a glare-sensitive person and shows less depression of sensitivity and a rapid recovery. Curve (*d*) is the curve obtained with a monochromat, in which the recovery is very much slower than usual. Presumably the curve records the regeneration of the scotopic, visual purple, mechanism.

J. B. Feldman.

Feldman (27) has been engaged on the measurement of the dark-adaptation curves of a large number of observers

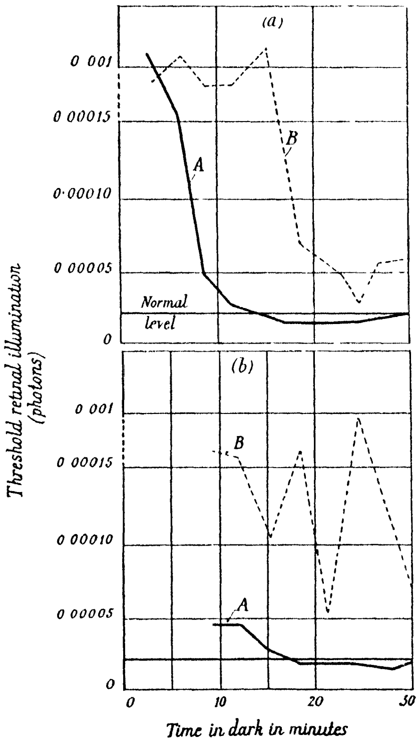

Fig. 43.—Pathological dark-adaptation. (Feldman)
Curve A—Right eye, normal condition.
Curve B—Left eye, glaucomatous.
(*a*) and (*b*) represent results obtained on separate occasions.

with both normal and pathological vision. More than 1000 cases have been tested, including those with refractive errors, those suffering from glaucoma, choroiditis and other visual diseases, and those with more general complaints such as diseases of the blood and vitamin A deficiency. The observations consist essentially of pre-adapting the eyes to a standard intensity and subsequently measuring the threshold brightness of a given light patch periodically while the observer remains in the dark. A typical curve is shown in fig. 43. This investigation is being carried out largely for the medical value of the results, but it is apparent that they may also be of considerable importance to illuminating engineers whose lighting installations may have to be used by both normal and abnormal observers.

S. Hecht.

Hecht and his colleagues have been actively concerned with establishing the validity of the Duplicity theory and in the development of a photochemical mechanism to explain such phenomena as adaptation, intensity discrimination, flicker and visual acuity. A considerable amount of experimental work has been carried out on flicker under a wide variety of conditions, and on the process of dark-adaptation for various conditions of pre-stimulation of the retina. An account of his views and theories on these subjects has recently been published (13), but I am personally in disagreement with some of his fundamental ideas (59, 60, 61).

R. J. Lythgoe.

We have already referred to some outstanding work by Lythgoe on flicker and on visual acuity, but he has also been responsible for some very interesting experiments on visual purple (1). In these he demonstrates the presence of yellow impurities in the extracts taken from frogs' eyes, but by allowing for the absorption they produce, he obtains the absorption curve for pure visual purple shown in fig. 44. On bleaching, he finds that an intermediate orange substance, transient orange, can be produced under suitable conditions of temperature and ionization, and this further decomposes to indicator yellow, which is pale yellow in alkaline solution, and a deep chrome yellow in acid solution. The absorption curves of indicator yellow for various hydrogen-ion concentrations are illustrated in

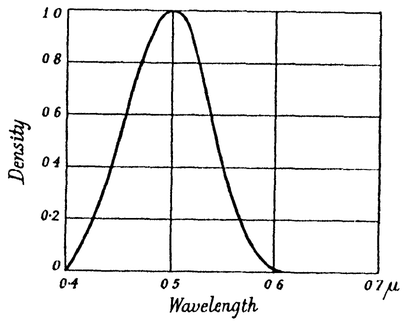

Fig. 44.—Absorption curve for pure visual purple. (Lythgoe)

fig. 45. It is found that a little regeneration of visual purple can occur under the appropriate state of ionization, but it is probable that the visual purple can only perform the complete cycle of operations when it exists in its natural

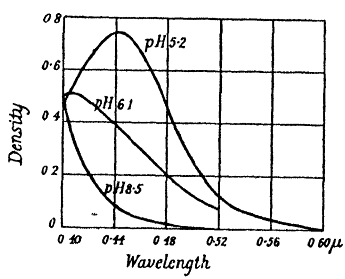

Fig. 45.—Absorption curves for indicator yellow for different hydrogen-ion concentration. (Lythgoe)

habitat, the retina. Perhaps the most important aspect of these results to illuminating engineers is that they serve as an antidote to too simple a decomposition-regeneration theory of the light reaction in the retina. Obviously, although simple ideas on these lines may be very useful to give a general picture of what is happening, the actual chemical process may be very much more complex.

Lythgoe has also been responsible for the most recent review on the structure and photochemistry of the retina (65), and this paper should be referred to for an analysis of the latest investigations on the subject.

H. K. Hartline.

Hartline has been engaged in recording the nerve discharge from the eye of Limulus polyphemus, a crab with a primitive eye containing neither ganglion cells nor synapses. By a process of successive dissection of the nerve fibres in the optic nerve, he has succeeded in recording the impulses from a single fibre, and in collaboration with C. H. Graham (7) has shown that on stimulating the eye there is a short latent period followed by a burst of impulses. The frequency of the impulses falls rapidly and eventually approaches a steady value. A typical train of impulses is shown in fig. 46. With increasing intensity, the latent period is reduced, and the frequency of the impulses is increased. The range of response of a single fibre has been found to be extremely large; for example, intensity differences of 1,000,000 : 1 have been recorded by corresponding variations in impulse frequency.

The existence of this enormous range of response is further evidence that problems of discrimination and acuity must be solved in terms of the trains of nerve impulses at different intensities. The factors controlling discrimination must be radically altered

Fig. 46.—Train of impulses along single fibre of optic nerve of Limulus polyphemus. (Hartline and Graham) Notched white line indicates time in fifths of second. Shaded strip shows duration of stimulation

when the response at one level consists, say, of some hundred impulses a second while at another level there are only five or ten pulses per second.

In another paper (16) Hartline has shown the interdependence of duration and intensity of a light beam in the response from a single fibre. In fig. 47 a series of records are shown in which both time and intensity are varied. It can be seen that within limits there is a reciprocal relation between the two; that when the intensity is increased, say, by a factor of 10, the duration has to be reduced by the same factor in order to elicit the same response. It should be noted that the similarity of response includes not only the total burst of impulses, but their frequency and the latent period. It has even been possible to adjust the time and intensity so that the response consists of only a single impulse. As mentioned in Chap. II, Hartline discusses the limits within which the reciprocity relation can logically be expected to hold, and finds that the critical duration must be appreciably shorter than the time of appearance of the particular feature of the response which is being considered.

The complexity of the visual mechanism is demonstrated in a remarkable way in Hartline's most recent paper (66). Responses from single fibres in the excised eye of the bullfrog have been recorded, and a great diversity of response among different fibres has been discovered. Thus, some fibres show the normal type of response illustrated in fig. 46; others give a burst of impulses at the onset of illumination and another burst when the light is cut off, but give no response with steady illumination; while a third group only gives a response when the light is turned off. Any valid theory of vision has got to account for these facts.

R. Granit.

Granit's work has already been referred to in previous chapters, as he has been responsible for a series of papers on retinal potential records taken on various eyes and

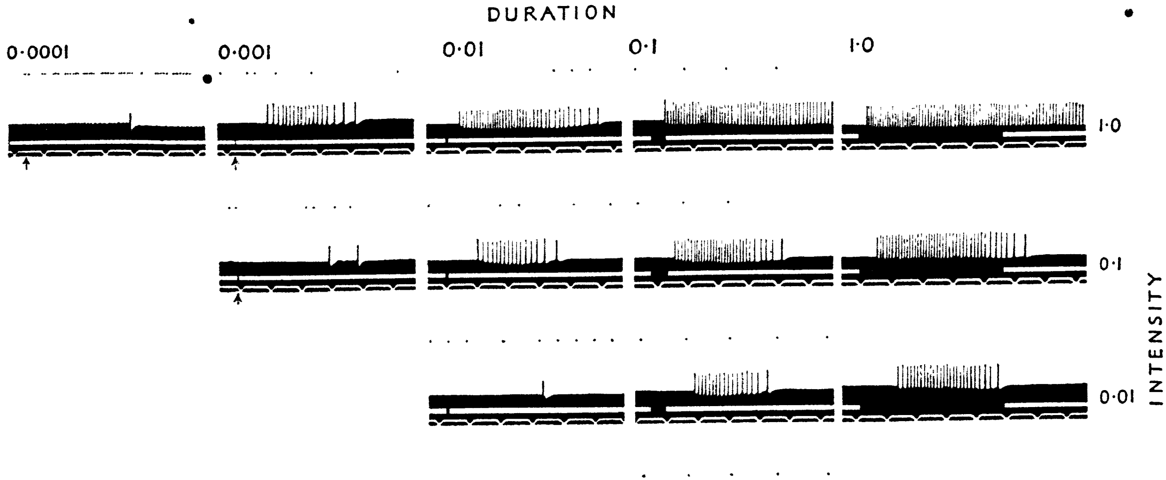

Fig. 47.—Response from single optic nerve fibre of Limulus for various intensities and duration of stimulation. (Hartline)

Horizontal rows contain responses to flashes of constant intensity and varying duration. Duration of flash is given in seconds.

Vertical columns contain responses to flashes of constant duration and varying intensity. Intensity is given in arbitrary units.

Responses on a diagonal correspond to a constant product of (duration × intensity).

The notched white lines record the time of the response in fifths of second. Above the notched line is a white line on which is recorded the duration of the light flash. For very short flashes, its position is shown by an arrow.

under various conditions of stimulation. The technique consists essentially of placing suitable electrodes in contact with the cornea and the back of the eye, and recording the potential that is developed between them when

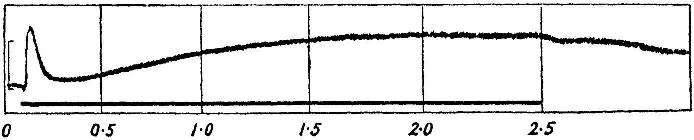

Fig. 48.—Normal record of retinal action potential. (Granit)
Lower black line indicates duration of stimulus. Time in 0·5 seconds is recorded by small black marks. Deflection corresponding to potential of 0·5 millivolt shown by vertical line on left of record.

light is incident on the retina. A typical record is shown in fig. 48. This has been analysed (62) into three components (fig. 49), the analysis being the result of experiments in which one or other of the components has been either isolated or suppressed by the appropriate method,

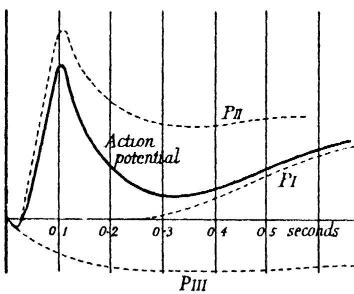

Fig. 49.—Analysis of initial part of retinal action potential into three components, P I, P II, and P III. (Granit)

e.g. by inducing asphyxia. The actual visual response appears to depend primarily on the P II and P III components, and of these P III is the negative or inhibitory reaction. It is quite impossible to summarize here the variety of effects that Granit has observed, the variation in type of response with the state of adaptation, the increase of inhibition with light adaptation, experiments with intermittent stimuli, interaction effects of different areas of the retina, the different types of response from rod and cone eyes, and so on. A review of the results up till 1936 may be referred to (63). Obviously there is a new field of knowledge here which must be understood before we can develop an adequate theory of vision.

To emphasize this we may quote Granit (62)—" Considering the complications present already at the ' sub-sensational stage ', more work with the retina rather than with sensations would appear to be necessary for the establishment of a retinal physiology on a sufficiently broad and unprejudiced basis. Quantitative correlations between sensory phenomena studied through the medium of sensations and certain assumptions as to the nature of the photochemical mechanism of the receptors can hardly give more information about the processes concerned than purely empirical equations." Perhaps the most outstanding demonstration of the truth of this statement is given by the paper by Hartline (66) to which reference has just been made.

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