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'An Investigation and Analysis of Visual Sensitivity Under Conditions of Glare'

Thesis submitted for the degree
of

Doctor of Philosophy (Physics)

by

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July, 1968

ABSTRACT.

Glare is defined, and a brief discussion of ocular anatomy is given, together with some report and discussion of previous work in the field of disability glare. An investigation of the practical aspects of white and yellow glare in situations encountered while driving at night is described, and the two colours are shown to have very similar glare effects under certain conditions. A discussion of 'equality' of white and yellow stimuli is included to show that redefinition of these conditions can affect the conclusions.

A binocular comparison instrument and ancillary equipment are described. Behaviour of sensitivity during recovery from short exposures to glare was investigated with this instrument for white and yellow glare sources and subsequently for purer spectral colours, with the aim of isolating chromatic effects.

Measurements were made of the 'equivalent veils' from glare sources of different colours and an hypothesis is propounded concerning the intraocular location of scatter of different wavelengths. This agrees well with the earlier work of Le Grand and is here substantiated by separate methods. That different predominant wavelengths should be scattered by different elements within the eye can explain some inconsistencies in past reports. Definitions of stimuli which are adequate on the assumption of white light scatter in the eye must be expanded to include information about spectral composition as well as luminance.

The concept of 'equivalent veiling luminance' as a method of specifying glare is found not to be valid for rapidly changing situations and this is used as an argument in support of neural inhibition as a contributary cause of glare, together with entoptic scattered light. This is quantitatively tested by an experiment using the Stiles-Crawford effect to reduce the receptoral response from a glare pencil admitted through the limb of a dilated pupil. This showed that neural inhibition may be small, but is not negligible over small angles.

GLARE

We may define glare as the reduction of sensitivity of visual perception by excess light, real or apparent, which, although in the field of view, does not add to the image quality.

There are three types of situation in which glare is most significant :

1) Night driving
2) Crepuscular phenomena
3) Excessive luminance

If we further divide glare into that which produces disability and that which produces discomfort we can discuss briefly the application to the above situation.

1) Night driving involving low ambient lighting with bright sources randomly distributed, involves both disability and discomfort glare to an extent which may vary from person to person, but where both are significant.

2) Crepuscular phenomena occur where part of the visual field contains a high level of illumination but the part of primary interest is more dimly illuminated. This involves mainly disability glare without discomfort, since the adaptation state, dictated by the mean light level (very approximately) will mean that the fine detail in the dim part of the field is below threshold.

3) Excessive luminance gives mainly discomfort but little disability until the level goes higher still,inducing snow blindness etc. This can be cured immediately by wearing dark glasses, and as such is worthy of note only in that it illustrates the increase of Fechner fraction again at high luminance levels.

Introduction.

The visual phenomenon of glare has become of greater general interest in recent years as the performance by humans of certain tasks in a strictly artificial environment depends strongly on the input of visual information. Since it is possible to design the environment within limits to give the best performance when used in conjunction with a human visual system, it is as well to be able to define the performance of the latter as closely as is possible.In optimising efficiency many factors, psychological, physiological and physical must be taken into account.

In this work the purpose is to consider the phenomenon of glare from a physical, and to a lesser extent physiological viewpoint, (with respect to its influences on visual ability). An attempt is made to discover and analyse the causes of glare, and a special importance is placed on the glaring properties of lights of different spectral composition. Some consideration is given to the old controversy over whether white or yellow filtered light is preferable for such demanding situation as vehicle headlighting, and the reasons for any preference are discussed.

Some investigation of recovery from glare is made, particularly with respect to age and individual differences. From here the trend of investigation is more with respect to the fundamental nature of glare.Time dependence of equivalence, as in 'equivalent veiling luminance' is investigated and discussed, and some experiments on chromatic dependence are illustrated. Mention is made of the dichotomy between scatter theories and lateral inhibition theories on the origin of glare and an attempt at reconciliation is made.

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CHAPTER I.

Anatomy, Physiology and History.

In investigation and analysis of visual performance under conditions of glare a necessary pre-requisite is a brief outline of basic anatomy, (fig. 1), and some physiology of the eye. Of particular relevance here is the nature of the entoptic media with respect to their physical structure and hence their respective rôles in physiological performance. It seems logical to proceed through the eye from cornea to retina in the same way as a beam of incident light, Special attention is given to particular structural details which affect, or may affect, light scattering properties. Physical measures of scattering are discussed in the first section. Some of the possible consequences of lateral inhibition at a retinal level are mentioned, and in the last section the psycho-physical performance of the eye as a whole is considered.

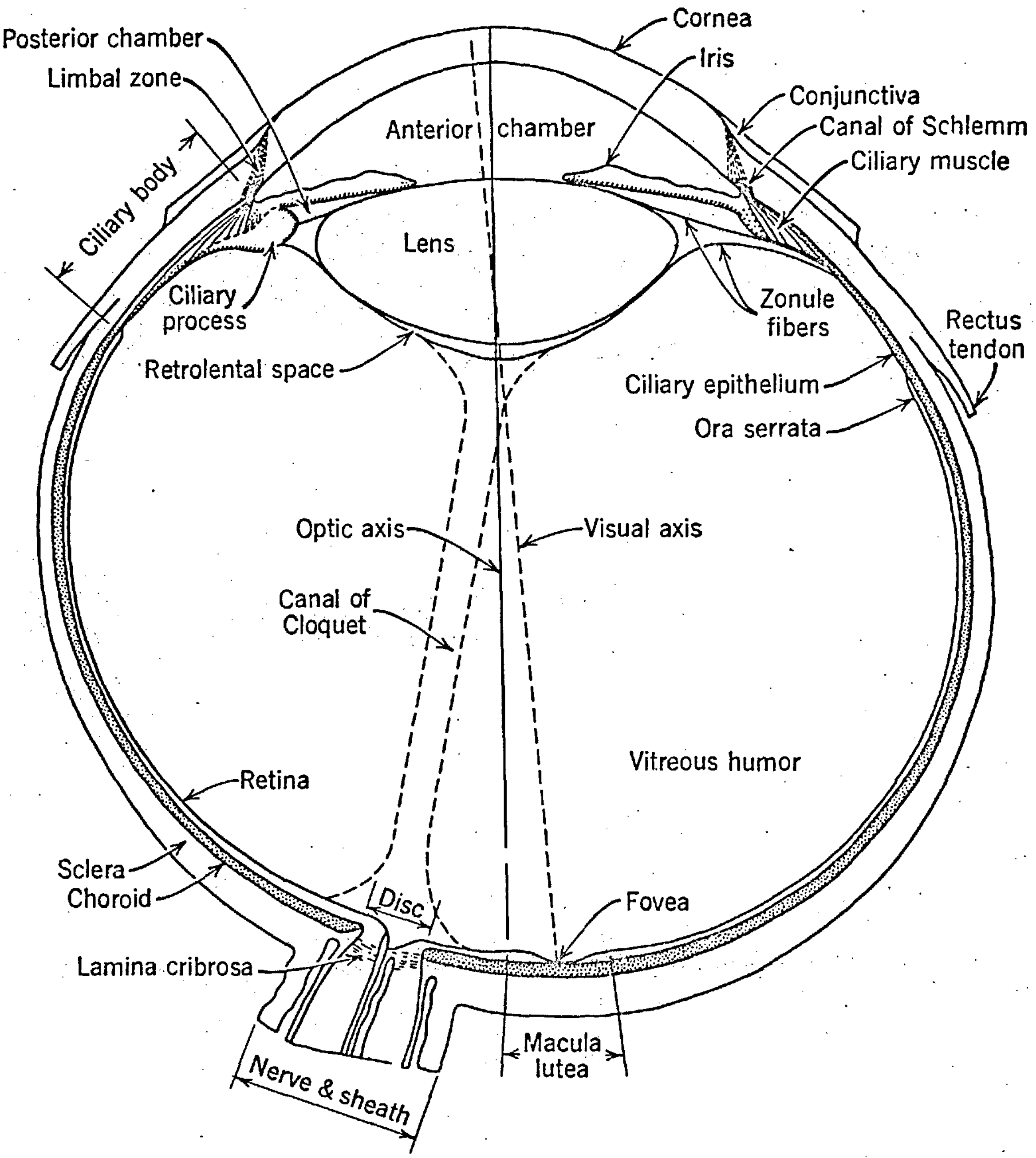


Fig. 1 Horizontal section of the right human eye. (From Walls, 1942, as modified from Salzmann, 1912.)

1) a. The Cornea.

This first element of the human optical system is responsible for most of the refracting power of the eye. It averages some 0·8mm. thick at its centre and has a mean refractive index of 1.377. It is very transparent in the healthy individual but the fact that it is not perfectly so is a cause for much investigation.

1) The outermost layer of cells, or epithelium, is exceedingly transparent, except under conditions of pathological disorder, e.g. oedema, but has an uneven front surface. This is rendered of optical quality by a few microns of aqueous fluid produced continually by the lachrymal glands (tears), covered with an oil film derived from the Meibomian glands. The plate-like epithelial cells are typically 40μ. diameter along the surface and some 5μ. to 7μ. thick: a few regular layers of these make up the 50μ. to 100μ. of the total thickness of this tough, almost impermiable, membrane.

2) Bowman's membrane, quite structureless at the optical microscope level, is some 10μ. to 13μ. thick and represents a condensation of, and boundary to the

3) Stroma, or 'substantia propria', which constitutes about 90% of the total corneal thickness. From electron microscopic examination by Maurice (1957), and others, the stroma appears to consist of fibrils (basically collagen) having a diameter of 25mμ. when dry, arranged in regular array, successive layers being arranged at right angles. There is conjecture as to the overall structure of this layer. On the basis of scattered light measurememts on exised rabbit corneas and polarisation microscopic studies, Kikkawa (1960) propounds the hypothesis that a lattice structure exists at two levels, i.e. regularly arranged fibrils collected

into larger fibres, both infilled with a matrix of the same, or very similar refractive index, probably a mucopolysaccharide.

Maurice (1962), however, finds no trace of these 'fibres' as such, or a second regular lattice structure, but considers that fibrils are grouped into the much larger (light microscope) lamellae. He suggests an explanation of the observations of Kikkawa on the basis of possible fine lamellar corrugation due to waviness in the fibrils.

Both workers agree that scatter is introduced in this layer of the cornea and say something about its distribution. Were the scattering particles very much smaller than the wavelength of light, an approximately $1+\cos^2\theta$ function might be expected, where θ is the angle of scatter. In fact the observed scatter follows a very much steeper function than this and is a result of complex processes in the corneal layers. The scatter is observed to be essentially in the forward direction within fairly narrow angles.

Maurice observes from microscope (as a collecting system) and photocell measurements of back scatter 'in vivo' from the cornea that the reflex light scatter constitutes some 0.3% if the light be blue and 0.1% if the light be red. This is just the chromatic dependence that might be expected in both back and forward directions in the case of pure Rayleigh scattering with a $1/\lambda^4$ distribution. We shall have cause to refer to these data at a subsequent time. It does not seem unreasonable that the typical scattering in this medium is of a very approximately Rayleigh type.

When dried the cornea becomes almost perfectly transparent; if excess hydration is permitted opacity increases. The two membranes sandwiching the stroma serve to prevent this hydration except when damaged or when loss of intraocular pressure causes the stroma to be less compressed and hence become more able to absorb water, the latter change being reversible. It would be expected from this that there might be some differences in corneal scattering between healthy persons, and many between persons suffering from ocular disorders.

4) Descemet's membrane, has a similar structure and behaviour to Bowman's membrane and is somewhat thinner, 5μ. to 7μ.

5) The Endothelium is a single layer of cells about 20μ wide and 5μ thick, which again has good optical properties except in the case of oedema. This pathological condition gives rise to coloured haloes due to diffraction and scattering in the epi- and endothelial layers. (Maurice).

By a photographic densitometric method De Mott and Boynton (1958 b) arrived at a figure of 70% for the corneal component of scatter for an excised steer's eye. It is possible that the lachrymal film very quickly disperses after death causing an extra component from the anterior or epithelial face of the cornea which is not optically smooth. This might lead to post mortem changes which could occur very rapidly at first (loss of film) and then proceed very much more slowly (change of hydration of stroma).

1) b. The Anterior Chamber.

Behind the cornea there is a region, some 3.5mm. deep, which is filled with a liquid which slit lamp observation shows to be optically clear, i.e. that there is virtually no light scattered within this medium. Seidel (1921 a,b) showed that this liquid is replaced continually. Duke-Elder (1932) supposed it to be obtained from blood by a process akin to dialysis, which removed all colloidal particles and left some of the smaller protein molecules in solution.

Davson (1962) proposed a much more complex system, and, as a result of careful analysis, suggested that this fluid is of a more secretary nature, as it contains much less protein than does the dialysate of blood plasma.

There is no Tyndall effect to be observed due to the almost complete absence of large protein molecules and cationic colloids. Physical measurements by Boynton, Bush and Enoch (1954 b) confirm this and we may therefore be justified in neglecting any light scattering within the anterior chamber compared with that in other ocular elements.

1) c. The Lens.

This element is responsible for the 'fine control' of focussing and will 'accommodate' the eye to give an optimal retinal image regardless of object distance (within limits). This accommodation is excellent when young (14 dioptres) but falls with age, as the lens becomes less pliable, to about 2 dioptres at 50 years or so (Gregory 1966). This is clear evidence of pathological change. The lens consists of a complex structure supported by the ligament or 'zonule of Zinn' within the ring of cilary muscle. The structureless lens capsule (an elastic non-cellular membrane, quoted by Van Heyningen (1962) to be secreted by the epithelial cells) contains a matrix of these cells at all stages of development, the older cells being compressed towards the centre, instead of being sloughed as is usual for epithelial (dermal) cells. This growth from the outside in is a consequence of vesicular invagination of surface ectoderm in the embryo to form the lens (Duke-Elder 1932). Each shell of this onion-like structure is composed of radial cells arranged with fair symmetry. These fibres measure some 7mm. to 10mm. long (pole to pole of the lens), by 8μ. to 10μ wide, and 2μ. to 5μ thick, and are thus rather too large to exhibit Rayleigh type scattering in the classical case, i.e. particles with one dimension comparable to the wavelength of the radiation concerned.

The typical proteins have a molecular weight up to 10^6 (Van Heyningen, 1962) and hence would be expected to fall below the dimensions required for strong Rayleigh scattering dependence. However, Wanko and Gavin (1959) in electron microscopic studies found that there are structures of the order of 0.5μ. to 1.0μ. of material somewhat denser that its surroundings. These nucleoli are apparently more opaque than their environment of nucleoplasm within cell nuclei.

The lens is practically transparent but has a marked yellowish tinge, even in youth. Examination of excised eyes shows that the lens yellows with age (Weale 1963). (Note: A pigment can transmit and reflect one colour, absorbing the rest. With wavelength dependent scatter, and no absorption, if blue is preferentially scattered away from the axis, the on axis beam will be observed to be yellowish.) For the purposes of visual study a competent survey of lenticular properties was given by Ruddock (1964). McEwen (1959) attempted an analysis of the pigment in the human lens and found no evidence that it was melanin. Instead he found a similarity to urochrome, probably a degeneration product of non-specific protein. This pigment is also present in very young lenses, but it is possible that its quantity increases with age.

However, There are many structures within the human lens, which, although basically transparent, may be expected to exhibit small refractive index differences and hence scatter significantly. There is a noted increase with age in the deposition of insoluble protein in the lens. This might lead to an increase in scatter with age.

The absorption is not of particular concern in this study; the scattering is of paramount importance. One point worthy of note is that the human lens continues to grow throughout life whereas that of other mammalian species ceases to contain mitotic epithelial cells at a relatively early age (Weale, 1963). Many workers who have dwelt on the physical examination of excised lenses have used the eyes of steers, cats, sheep,etc.. It is of some doubt therefore that these data are unqualifiedly applicable to human lenses. De Mott and Boynton (1958 b) found that scatter is chiefly introduced by the central core (or nucleus) of the lens (fibres laid down pre-natally) and again by the outer regions just below the epi-thelium for steers eyes. A similar property in the human eye can be discerned from the slit lamp photograph of his own eye published by Vos (1964) with perhaps less emphasis on scattering in the core, so perhaps the species differences are not significant.

Wolf and Gardiner (1965) measured by slit lamp photometry the scatter properties of the lens 'in vivo' and the subject's sensitivity to glare by assessing the contrast increase necessary to resolve Landholt rings. They found a linear relation between glare susceptibility and lenticular scatter. They also found that the lenticular scatter increased steadily with age above 40 years but was almost independent below this.

1) d. Posterior Chamber and Vitreous.

The vitreous body is a clear, jelly-like substance filling the posterior chamber of the eye, between the lens and the retina, which it partially serves to support. It is a three dimensional net of fibrous protein (collagen) comprising but a small percentage by weight (0.1 to 0.2 mg./ml., Pirie, 1948, quoted 1962) for ox eyes. (There is no reason to suppose that any significant difference would be manifest in human eyes.) This net supports a bulk of water (99% of the whole) made viscid by a solution of hyaluronic acid. This structure inhibits the diffusion of large molecules from the blood (which would cause opacity) but permits small nutrient molecules to diffuse readily.

Fibres, some 3μ. in diameter are to be found in the anterior portion of the vitreous but those found towards the rear are considerably finer. Posterior to the zonule is the hyaloid canal (Cloquet's canal). This remnant of embryonic development contains a primary vitreous, divided from the secondary vitreous by the hyaloid membrane. Little information is available about the light scattering properties of this vitreous body in the living eye. Measurements have been made on excised steer eyes (De Mott and Boynton, 1958 b) by photographic densitometry and little scatter component was found from the vitreous. Boynton, Bush and Enoch (1954) found that for the eyes of steer, cat and human some not insignificant amount of scattering occurs. Some scattering probably takes place 'in vivo', and this may increase after death, due to changes in the vitreous gel.

Wolf and Gardiner (1965) found that the scatter from the vitreous did not increase with age, although sensitivity to glare did. They measured optical density with a slit lamp and microscope.

1) e. The Retina.

The retina surrounds the vitreous body and lines the inside of the globus as far forward as the ora serrata. It is about 400μ to 500μ thick at its thickest just outside the foveal depression, where it is much thinner due to the sweeping aside of the neural net serving the receptors of this region. This foveal pit, where cones are densest and there are no rods, is relatively free of the nerve tissue and processing cells that obtrude between the incident light and the receptor layer.

The retina is composed of ten histologically identifiable layers (fig. 2, fig. 3.). Working from the incident light direction we have the hyaloid membrane which is the boundary of the vitreous body and not strictly to be included in the retina. In the retina proper we have the

1) Inner limiting membrane, composed of the flattened ends of the radial support fibres of Müller.

2) The layer of nerve fibres, which are not in general myalinated, lead the visual information to the optic disc and thence to the optic nerve, from the retinal nerve cells and ganglia of

3) The ganglion cell layer, which contains at least five types of ganglion (Polyak, 1955). These cells are similar to those found in the brain and higher parts of the nervous system.

4) The inner plexiform layer is a region of amacrine cells which have been found electron microscopically by Pedler (1965) to be a complex system of synapses (Gray, 1967) and circuitry.

5) The inner nuclear layer primarily contains bipolar cells with some ganglia and amacrines. This, and the preceding layers contain blood vessels and are supplied with blood from the inside

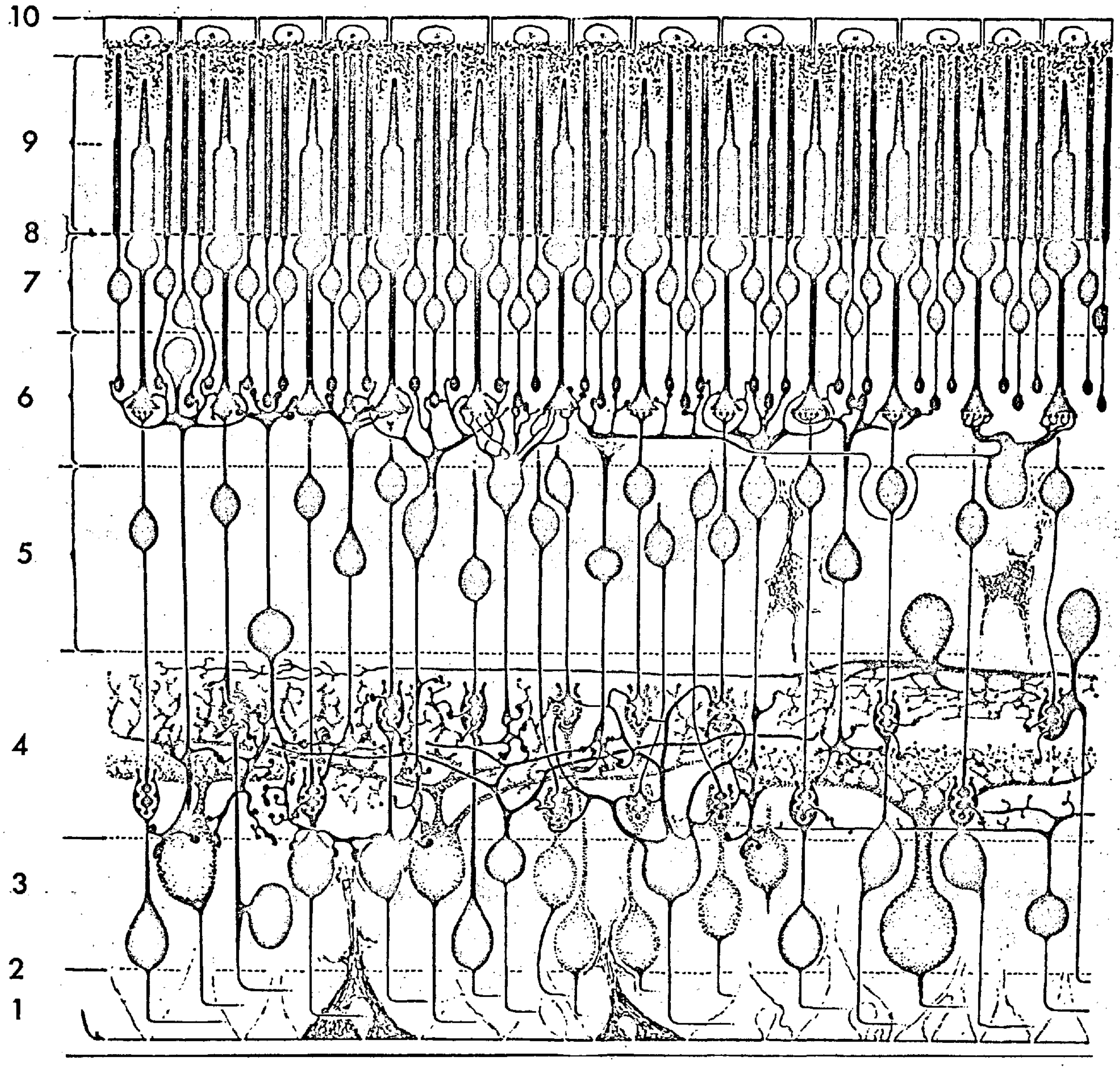


Fig. 2 Diagram of retina (After Polyak)

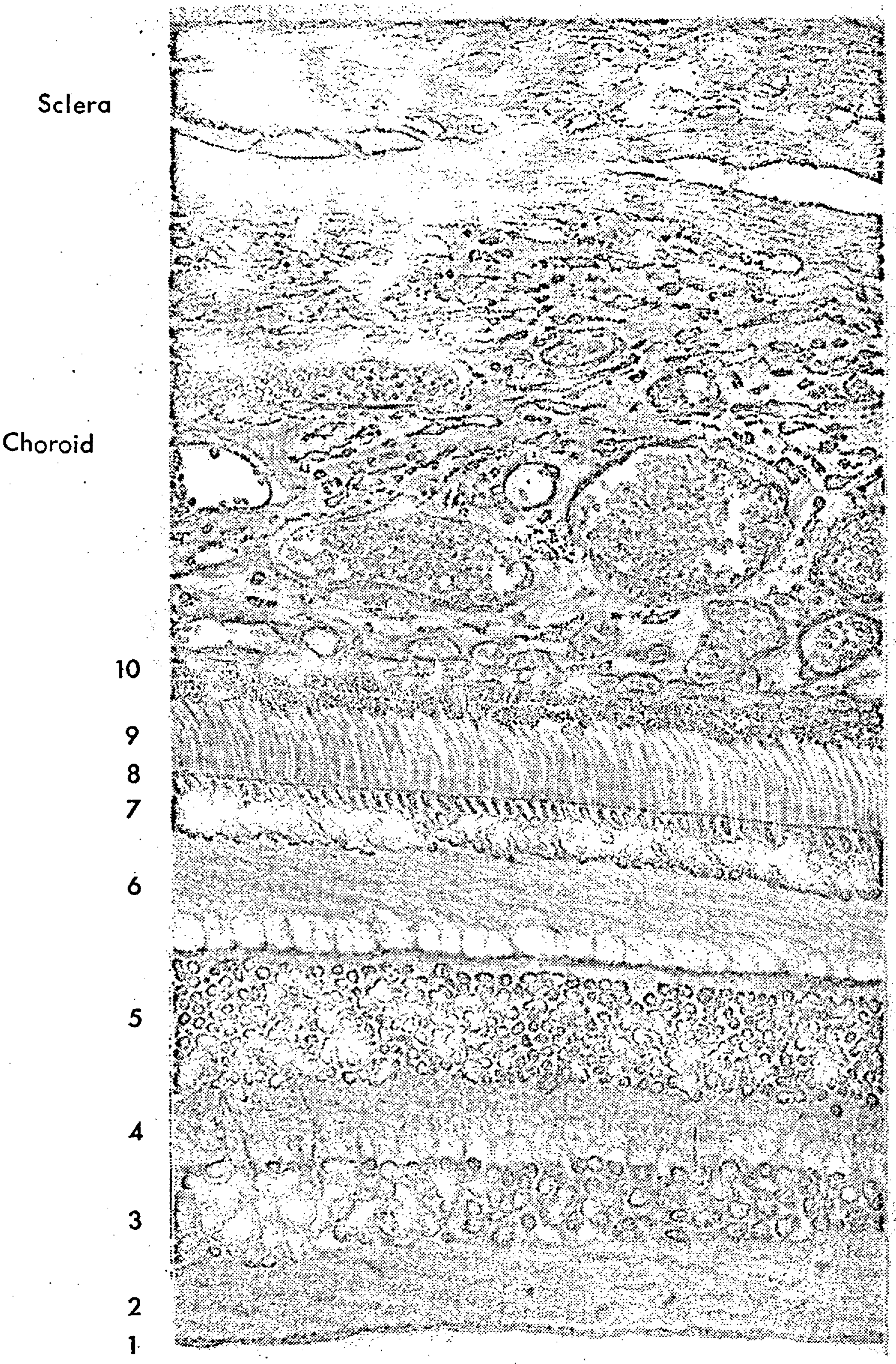


Fig. 3 Micrograph of retinal section (After Polyak)

of the eye via blood vessels emanating from the optic disc. Outside this layer the nutrient supply is derived basically from the choroid.

6) This is another region where light microscopy yields essentially a layer of fibres in the direction of information transfer (i.e. perpendicular to the plane of the retina) after light reception (like 4)). Again Pedler (1965) finds many cross links in this layer. This will be mentioned later in connection with the neurophysiological performance of the retina.

7) The outer nuclear layer contains the nuclei of the receptor cells (rods and cones) divided from their active processes by

8) The outer limiting membrane. This reticulated net of supporting fibres of Müller (c.f. 1)) allows the rods and cones proper to be securely anchored at the bases, the active component being behind the membrane and thus kept 'in register'.

9) The receptor units (bacillary layer) are the light sensitive transducers which convert light into information trains capable of interpretation by the rest of the retinal/neural/cerebral system.

10) The pigment epithelium is a mat of cells, hexagonal and pentagonal in section, heavily doped with the dark brown pigment, fuscin, in granular and hastate form. Polyak suggests (with references) that the pigment, which is known to migrate to affect light and dark adaptation in the lower vertebrates may do a similar thing (to a lesser extent) in mammals (including primates).

Although, following the path of the incident light, we have now passed through the detector layer not all the light has been absorbed in these sensors. The next anatomical layers are therefore worthy of consideration because of possible back scattering effects, the 'halation' of photography.

Around the globus interior outwards from the pigment epithelium is the choroid, a highly vascular layer some 200μ thick containing blood vessels and more, heavy pigmentation. This has a nutritive function for the region containing the receptor cells. If this blood supply is restricted vision deteriorates immediately due to lack of replenishment of visual pigment (rhodopsin, iodopsin, etc.).

The outermost envelope of the eye, the tough sclera, is whitish and fairly reflective.

If the retina consisted only of a receptor layer, and was accordingly thin the optical image would undergo only small degradation due to internal scattering in the elements. However, since there are several layers of cellular material prior to the receptors and an imperfect absorber behind them other things may happen. The retina is transparent (even the receptor cells!) but there is evidence to suggest that image degradation takes place within the retinal layers. The nerves from the foveal pit are led across the surface of the retina to bring them clear of the central receptors and present the minimum impedance to the light falling on this area. Over a similar area to that which contains radial nerve fibres in dense plexi is the 'macula lutea', or yellow spot, visible as a lemon yellow discolouration in a freshly dissected retina and as a brownish yellow patch in ophthalmoscopic examination with white light; in red free illumination it appears with a higher contrast as a dark zone. These histological data are related to the subjective illusions of Haidinger's Brushes and Maxwell's Spot, both discussed by Helmholtz (1909).

Wald (1945) isolated the hydroxy-carotenoid protein xanthophyll from the macular region and spectral absorption curves for this have been found by separate methods (Ruddock,1964). Judd (1952) suggested a plausible reason for the presence of the pigment at all, when it would seem to be in a position to reduce sensitivity. He said that it may serve to protect the rods near the fovea, which are low threshold, blue sensitive receptors, from possible deleterious effects of high intensity illumination.

To get an idea of the order of magnitude of scatter to be explained let us consider that a fair visual acuity is represented by a retinal resolution of 1 minute of arc or about 7μ in the receptor plane. The thickness of the retina at the fovea is about ten to twenty times this value, and a few degrees away goes up to fifty to eighty times (but the acuity is much less here anyway, due at least to the lower density of receptors). From this may be deduced that a small amount of scatter in the inner retinal layers may cause substantial loss of image quality.

The pigment epithelium acts as an anti-halation coating, but since it is not a perfect absorber light which passes through this layer may scatter within the choroid or reflect off the sclera to re-impinge on the receptors. Such light will be predominantly red as the blood in the choroid will have absorbed blue and green light. There is some possibility that the blood (specifically haemoglobin) in the retinal inner layers will also scatter red light and absorb green and blue. In support of this the ophthalmoscopic fundus image is quite red, illustrating that in the incident direction the reflected light has suffered substantial loss of its green and blue wavelength components.

2. Lateral Inhibition.

So far we have dealt with physical scattering, but for the purposes of discussion of glare phenomena the concept of lateral inhibition may be important. From the observations of Schouten and Ornstein (1939) it was deduced that lateral inhibition, or the suppression of sensitivity of receptors due to stimulation of nearby ones, is a large contributory factor in disability glare. Unfortunately their observations were not susceptible to repetition by Alpern and Fry (1953) who favoured the straylight hypothesis to explain glare. Ratliff, Hartline and Miller (1963) performed electrophysiological experiments on the optic nerves of the 'limulus' crab and found evidence that the light stimulus change on one ommatidium affects the signal detected from the optic nerve fibre corresponding to a nearby ommatidium, which was not having its stimulus changed. This points to a type of lateral exchange of information between circuits corresponding to different receptors.

This type of phenomenon is detected in many parts of the nervous system and Taylor(1956), in a paper on information theory, postulated the relation between parallel sensory input channels :-

$$o(n) = i(n) + k\sum_{n-s}^{n+s} o(m) .$$

in the case of one dimension; where o and i correlate with output and input and n,s and m define receptor cells in the one dimensional rank. k may be a constant which depends on a variety of conditions imposed upon the system. He used this to explain the experimental work of Beitel (1936) (which he quoted).

There is a danger in applying such information theory (which is linear) to the eye, a notoriously non-linear device. Perhaps one could overcome this danger by postulating another 'constant' multiplying o(m) which may depend on $|m - n|$ and obtain a more realistic proximity dependence. (Lateral inhibition would not be expected to operate significantly over the sort of distances which Schouten and Ornstein found).

In the case of the retina the formula must be extended to a two dimensional array (the principle is the same) and observations could be explained by saying that at low levels of illumination k is positive (increase in summation area with dark adaptation), and at higher levels k goes through zero to negative, where inhibition will result.

Von Békésy (1960) used an assumption similar to the above, and assigned a value to r, the radius of the zone of influence over which inhibition is thought to take place. He submits that a typical value for r would be 0.9mm. at 25cm. (40' arc or 90μ at the retina) under the condition of field luminance of 100 milli-Lamberts at 60Hz. presentation frequency. r increases in an unknown or unspecified way with field luminance. His statements are based on measurements of the Mach-band effect, which has been recently investigated by Rowe (1967). Fry (1963) also suggested that this type of contrast phenomenon is explicable in terms of retinal interaction.

Recently Pedler (1965) has found great complexity of lateral interconnection in the amacrine cells (up to 75 connections/cell) and this is more evidence that the concept of the retinal nerve cell matrix as a parallel access computing device is a tenable one. Certainly it would be unwise to neglect the possibility of lateral information transfer with in the retina, but it is difficult to assess its importance as a contributary cause of glare.

3. Psychophysical Investigations.

The important parameter of glare is its effect on the human visual system 'in toto'. It is dangerous to assume that if broken down into its constituent parts, these parts will represent a complete explanation of the phenomenon. It is also impossible to investigate the function of various parts in isolation. Many psychophysical experiments have been performed and the data used to deduce mechanisms which are applicable to the explanation of the 'gestalt' performance of the living organism. In so far as these measurements can be construed to refer to particular media we will proceed through the eye as before, concluding with a few remarks as an historical summary and survey of present knowledge.

Some estimates of corneal scattering have been made: Vos and Boogaard (1963) used a method of compensating for the iris shadow produced when a narrow pencil of light is scattered at the cornea and thus showed that the corneal scatter accounted for some 30% of total entoptic scatter. A similar, rather sophisticated, method by Boynton and Clarke (1964) arrived at a value of 25%. These results show excellent agreement and, but for the fact that neither datum showed any chromaticity dependence of scattered light, support well the earlier work of Le Grand (1937).

Psychophysical observations on the Haidinger Brush and Maxwell Spot phenomena give some information about the retina. The former is manifest in plane polarised light (the plane of which is rotated slowly to prevent chromatic adaptation from suppressing the illusion) as a brightish blue dumb-bell shape on a darker yellow ground (blue in the direction of the electric vector of the polarised light) centred on the point of fixation and visible as such in white light. For chromatic light the illusion is discernable only in blue. The 'yellow' region then appears much darker. The Maxwell Spot illusion is visible as a yellowish brown zone extending into the parafovea (4^{o} to 5^{o}) under a variety of natural conditions. More specifically it can be measured by colourimetric comparison of monochromatic blue-green light with blue-green made up from blue and green wavelengths. The degree of 'pigmentation' varies considerably between people.

The Haidinger Brush phenomenon has been explained by Helmholtz by supposing that the nerves fibres (radial to the fovea) exhibit uniaxial birefringence with the optic axis parallel to the fibre axis. Some materials polarise by absorption, e.g. tourmaline, tin and titanium oxides, the proprietary 'polaroid' etc., and if the extraordinary ray were to be preferentially absorbed in this radial net of nerve fibres around the fovea, then the phenomenon described could result. It will be noted that in natural light a a reduction in intensity of transmitted blue as above might contribute to the 'yellow spot'illusion.

These considerations demonstrate that the optical behaviour of the retina is complex (the neural perhaps much more so !) and it would be surprising if the scattering properties are negligible. Vos and Bouman (1964) have given an elegant theoretical exposition of retinal scattering behaviour based on models which, although complex, must still be oversimplifications of the true case. In connection with this Vos (1963) discussed (with experiments) the phenomenon of Boehm Brushes, which give rise to bright 'wings' around a plane polarised glare source. It transpires that the origin of this polarisation dependent scatter is in the inner retinal layers and the effect is visible up to 10^{o} extrafoveally. Vos did not find any significant variation in scattering action with chromaticity. It is surprising that this should be so considering the marked red colour of the ophthalmoscopic image, which colour is considered to be a consequence of the spectral absorptivity of haemoglobin. It should be noted that Vos, who took the measurements in question himself, is strongly protanomalous.

Holladay (1927) and Stiles (1929) did much of the early work on glare and evolved what has come to be known as the Stiles-Holladay formula;-

$$B = kE / \theta^n.$$

where E is the illumination derived from the glare source at the plane of the pupil, θ is the angular subtense and the point on the retina where B is the 'equivalent veiling luminance'. k is a constant. This concept of 'equivalent veiling luminance' is not an exact one but presents a very useful method of expressing the magnitude of disability glare; i.e. the 'equivalent veiling luminance' is that level of uniform background which would modify the retinal sensitivity at the point in question to the same extent as the presence of the glare source.

Le Grand (1937) found a slight systematic increase in k with E. He attributed this to retinal interaction and fitted his curves with a rather more complicated formula. He also noted a strong chromatic dependence, which Luckiesh, Taylor and Holladay (1925) had failed to find earlier. (Since they used highly desaturated colours this is not unduly surprising.) Schouten and Ornstein (1939) found strong retinal lateral inhibition, but a later repetition of their experiment by Fry and Alpern (1953 a) failed to confirm this.

These latter did support the straylight hypothesis (1953 b) but acknowledged (1954) that there may be retinal interaction over short distances to explain border contrast effects. There is evidence (Bartley and Fry, 1934) that retinal interaction and scattered light each have a separate functional dependence on angle. Crawford (1936) showed that the glare effect from a number of sources was additive, supporting the straylight hypothesis, of which Stiles (1929) was less convinced until Ludvigh and MaCarthy (1938) offered a transmittance measurement of the eye which was somewhat lower than he had used.

Bouma (1934,1936) discussed the Holladay-Stiles Formula and noted than n had been variously reported to be between 1.5 (Stiles, 1929) and 4 (Report Roy. Dutch. Aero. Club.). He also noted that the effect of colour is very slight. He did, however, state that blue light was responsible for the induced discomfort.

A good discussion of glare up to 1955 was given by Fry (1954, 1955) as was further mention of his modification to the Stiles-Holladay Formula which he offered the previous year as

$$B = kE / \theta(\theta + 1.5)$$

to overcome the infinite value of B at $\theta = 0$.

More recent work has tended to favour the straylight hypothesis almost exclusively (De Mott and Boynton,1958 a)(Vos 1963).

4. Comparison of White and Yellow Glare: A Survey.

Some mention must be made of the controversy about the glaring properties of white and yellow lights. The field where this has been considered of most noteworthy importance is that of headlighting for motor vehicles and accordingly the main investigations have had a very practical cant, the emphasis having been on which was better rather than fundamental reasons for the decision.

The suggestion that there was a significant advantage to be gained from the preferential use of yellow came from the French, Monnier and Mouton,(1933), and Escher-Desrivieres, Faille and Jonnard,(1934). Large claims were made; e.g. increase in acuity, reduction in recovery time and enhanced contrast sensitivity, but quite inadequate documentation was submitted. Le Grand (1934) made a more scientific investigation and found that any apparent advantage was self-cancelling in that the yellow filter was approximately equivalent to a 0.2 neutral density filter with respect to reduction in perceived luminance (less light, hence less glare). Berte (1953) put forward 'the case for yellow headlamps' but whilst it was a comprehensive summary of what advantages might possibly be gained, it was remarkably free from proven statements.

Jehu (1954) used the full scale driving situation under the auspices of the Road Research Laboratory, but his results were disappointingly inconclusive. A survey by Fisher (1965) was again inconclusive but did attribute some small advantage to 'monochromatic' sodium light. This is however quite different in character from the French specification of tungsten light filtered by cadmium sulphide yellow glass. This latter effectively absorbs all blue below 490nm. and transmits more than 90% above 578nm. (Berte, 1953). Christie and Ashwood (1965) found that the effect on acuity was small, but that it could be either for or against the advantage of yellow, and failed to find a correlation of preference with age (for 32 observers between the ages of 17 and 67 years).

Richards (1962, 1964) stated unequivocally that yellow filtering of the light (at least under the conditions of wearing yellow glasses) is wholly an impairment to vision.

Reading (1966) found a significant reduction in recovery time from white light glare rather than yellow, but lengthening of recovery from both with age. In a more recent paper (Reading, 1968) she re-emphasised this view of the advantage of white over yellow particularly for younger age groups.

It will be noted that there is a fair amount of disagreement as to which should be adopted as the standard, and this will be discussed somewhat later.

CHAPTER II.

White or Yellow? Three Experiments.

As a preliminary investigation, specifically of the white versus yellow glare problem, three short experiments were conceived and duly performed. As a result of the experience gained with these data it was practicable to establish much more rigidly what was, or was not, essential in the performance of later experiments.

In each experiment we tested an aspect of the white versus yellow controversy. The first case gave an assessment of the comparative reduction of perceived luminance (apparent brightness) of a standard test patch, when a glare source was present. The second compared the luminance difference threshold of white and yellow in a situation roughly analogous to that encountered when driving at night. The third was an attempt to measure recovery curves from exposure to white and yellow glare, for various observers.

1) Reduction of Apparent Brightness.

Object.

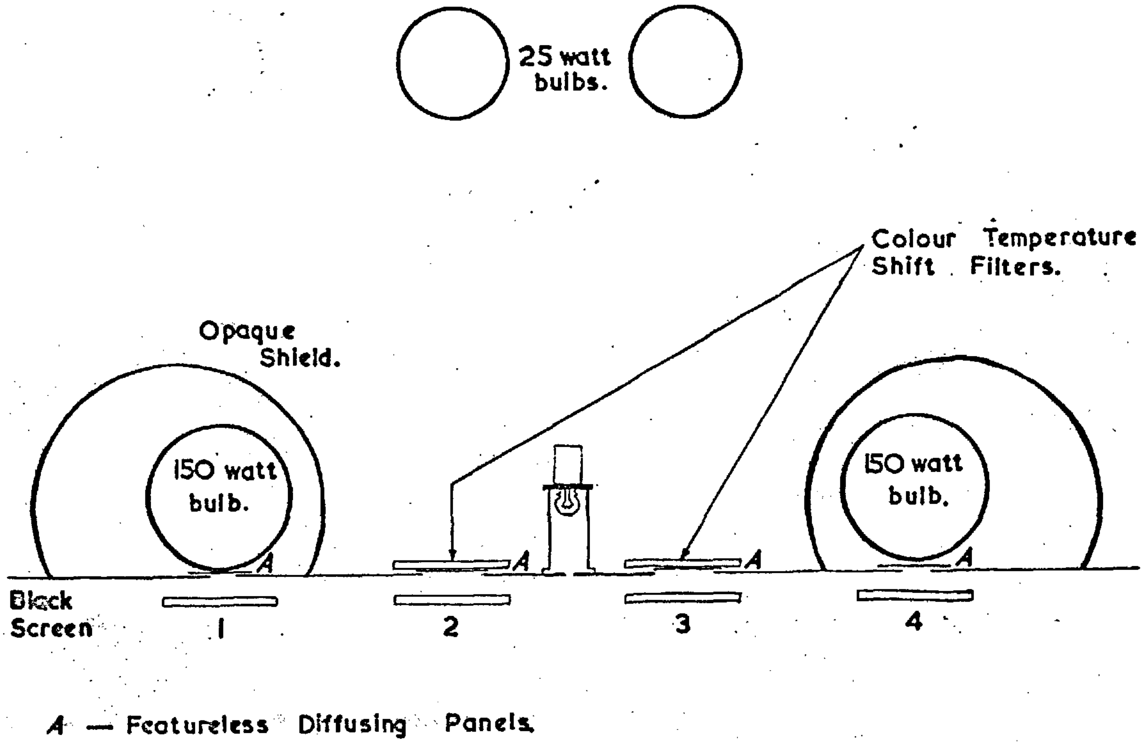
To show how the apparent brightness of a white or yellow test patch varies in the presence of a white glare source compared with yellow.

The comparison was made by means of a simple apparatus based on a ingenious idea by Prof. W. D. Wright. Since the entire comparison field was visible by one eye the need for the assumption of constancy of response characteristics between the two eyes was obviated. Also the observation did not have a very strong dependence on adaptation state (a marginal change in this between the two eyes in a binocular comparison experiment can have a large effect on the observation). Neither was pupillary size a significant factor in this, purely comparative, measurement.

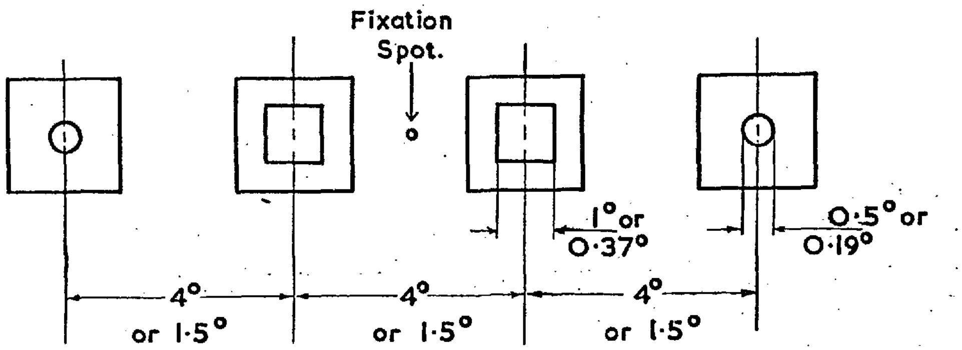
Apparatus.

A single visual field was used in the arrangement illustrated (fig. 4). The observer was seated in a darkened room at a fixed distance from the display. Four illuminated panels were visible symmetrically disposed about a red fixation spot. The outer two constituted glare sources, separated by about 12° arc, of about 15,000 ft. Lamberts luminance, and $\frac{1}{2}^{\circ}$ angular subtent. The inner two, about 1° arc square, were continuously illuminated by dimmer bulbs situated some distance behind the panels, and had a colour temperature the same as that of the glare sources without filters (pale blue filters were used to correct the energy spectrum). These two had a luminance of about 5 ft. Lamberts, and a colour temperature of 2730° K. after correction.

The panels (2) and (3) (see fig. 4) were arranged to have the same luminance according to a 'Holophane Lumeter' estimation (mean



EXPERIMENTAL ARRANGEMENT.



VISUAL FIELD.

TABLE I.

Filter Position.		1	2	3	4
Configuration.	A	W	W	Y	Y
	B	Y	Y	W	W
	C	W	Y	W	Y
	D	Y	W	Y	W

FIG. 4.

of ten readings), by adjusting the distance of 25 watt bulbs from the test panels. Panels (1) and (4) were equated with respect to luminance by an equivalent procedure.

Four filters were manufactured, two neutral and two simulating the transmission characteristics (see fig. 21) of cadmium sulphide glass (visually a lemon yellow). These had as near the same luminance transmission as it was reasonable to obtain. When used in conjunction with the light of the colour temperature stated (2730° K.) their luminance was judged to be nearly the same, again with the Holophane Lumeter. A much more satisfactory discussion of 'equality of luminance' of white and yellow stimuli is given later. Suffice it to say here that the neutral filter was used to reduce the overall luminance of the sources by roughly the same amount as did the yellow filter. The definitions of this 'equality of luminance' have not been standardised in the past, but for the purposes of this investigation the perceived foveal luminance was equated (alas, not perfectly) by direct match.

Observations.

The inner panels were initially observed in the absence of the glare sources, and the observer satisfied himself of their equality. Glare sources were then turned on and the observer asked what change he (or she) saw in either, or both, of the test panels, whilst he maintained fixation on the red spot. Several different configurations of test and glare source were used, as shown in Table 1 (fig. 4, inset) to minimise the effects of asymmetry in the display. Both monocular and binocular observations were made by several observers, but no different results were noted by using both eyes rather than only one.

Results.

Consistently observed effects were:-

(a) On application of the glare sources the panels (2) and (3) dimmed markedly, but appeared to recover slowly.

(b) Edge effects were seen on these panels, presumably due mainly to small eye movements, i.e. to imperfect fixation.

In general one panel tended to look brighter than the other when the glare sources were presented, but there was no consistent agreement between which panel looked the greater brightness, and the colour of the adjacent glare source for any (or all, collectively) of the observers.

This distinction between colours of the white and yellow test panels or glare sources tended to disappear when concentration was fixed on the estimation of luminance alone. Both panels then appeared a creamy grey colour. It is here noted that it is almost impossible to make a valid simultaneous assessment of more than one considered parameter, where psychophysical judgement is required, without severe impairment of accuracy.

It was clearly seen from the arrangement that any differences in visual effects of white and yellow glare sources are very small.

The results from 10 observers, of both sexes between the ages of 22 and 82 years showed no significant preference for either white or yellow. This showed with disappointing consistency that the detection of differences of visual behaviour under conditions of white and yellow glare is not as straightforward as it might appear.

Note. The glare sources were separated from each other by 30 cms. which subtended an angle of 12° arc at the eye when viewed from a distance of 150 cms. Since the effect of glare is known to fall steeply with increasing angular separation from the glare source the cross effects of the glare sources on the panels farthest from them were small compared with the effects to be observed on the nearer panels. This 'second order' effect would not have been expected to mask the 'first order' effect of a real difference in characteristic of white and yellow glare, if such exist.

At a very much later date this experiment was repeated under slightly different conditions. Only one observer (the author) was used, but a large number of observations were made using a forced choice technique, where the observer was presented with the array and had to select either the right hand (3) or left hand (2) panel as the brighter. A decision always had to be made rapidly and conclusively. Filters were permuted in the same way as before (see Table 1, fig. 4) but the forced choice had to be made in situations with and without glare. The filter transmissions were known with a high degree of accuracy and hence the 'without glare' situation could be used to assess any asymmetry in the light system.

The photopic V_λ (relative luminosity function at the fovea) of the observer had been carefully determined (see Chap. IV) and the white and yellow filters were arranged to give nearly the same foveal luminance for a tungsten lamp of colour temperature $3{,}000^{\circ}$ K. This was calculated from

$$L = K_m \int V_\lambda \, Le_\lambda \, d\lambda .$$

where L = luminance, K_m is a constant, and Le_λ is the spectral radiance at wavelength λ (Le Grand, 1957). In fact the integral was approximated by a finite sum from 400 nm. to 700 nm. taking $d\lambda$ as 10 nm. in 10 nm. steps through this range. Le_λ was measured experimentally with a spectrophotometer and N.P.L.

calibrated photocell. The V_λ values here were those evaluated for the observer himself (Chap. IV, sections 3) & 4)) but were in fact similar to the C. I. E. Standard Observer curve (fig. 20), with some deviation in the yellow and blue.

This 'equalisation of luminances' was done for a later experiment, hence the difference in colour temperature. It is likely with the colour temperature used in this experiment (2730° K) that the yellow would have a higher luminance compared to the white. From calculation (for 3,000° K.) it appeared that the luminance of the yellow was some 106% of that of the white. This introduces a curious effect because when the comparison was made without glare on average the white looked brighter.

The observations were made under two conditions, firstly as already described,from a distance of 150 cms. (CASE 1) and secondly from a distance of 400 cms. (CASE 2), thus bringing the two test panels each within 45' arc of the central fixation spot and on to the rod free area of the fovea. Only in this area will the luminnace evaluation data (depending on V_λ) be truly valid, since outside this area rod intrusion would be expected to raise the relative luminosity of the white. Results showed that in CASE 1 white was judged brighter more often than in CASE 2, but the increase is hardly significant.

The comparison in the absence of glare showed that the right hand panel (3) was judged brighter more often (suggesting a real discrepancy between left and right) but this inequality was eliminated by considering the statistics in such a way as to average over any bilateral asymmetry in the display.

Results.

		CASE 1	CASE 2
(a)	White judged brighter (no glare).	77%	72%
(b)	White judged brighter when adjacent to yellow glare.	90%	77%
(c)	White judged brighter when adjacent to white glare.	63%	47%
(d)	Brighter panel adjacent to white glare.	37%	35%
(e)	Brighter panel adjacent to yellow glare.	63%	65%

Quoted as % of occasions for which statement is valid out of total possible number of opportunities for judgement.

Each of the above data was derived from not less than 60 observations (240 observations made in all).

Discussion.

The discrepancy between the white and yellow panel luminances and brightnesses must be mentioned (a). Since the luminance of the yellow field exceeded that of the white by 6% (at the very least) the white must give the impression of being brighter only by the invocation of non-additivity of heterochromatic brightness assessment. This is discussed by Dressler (1953), Tessier and Blottiau (1951), Owen (1967) and others, and in particular it is noted that subtraction of red from one of two matched white stimuli results in an increase in the luminosity (perceived brightness) of that stimulus even though its luminance is somewhat lowered. This accounted for the brightness of our white appearing higher than that of yellow. It is also a factor which tends to complicate the investigation.

(a) In CASE 1 the separation of the fixation point and either test patch was 2° arc, and in CASE 2 only 45' arc. That the ratio of white seen as brighter in CASE 1 to that in CASE 2 should be 77% : 72% is just significant to show that the parafoveal rod response (obeying the scotopic V_{λ}') is beginning to intrude within the 2° gamut.

(d) & (e) The ratio of the apparently brighter panel closer to the yellow as opposed to the white glare was 63% : 37% for CASE 1 and 65% : 35% for CASE 2. This would appear to favour yellow significantly in the glare situation, but the comparison of yellow panel in yellow glare with white panel in white glare is really the requiredparameter for the night driving glare situation. In this case the ratio of white brighter in white glare to yellow brighter in yellow glare is shown in (b) & (c) to be 86 : 14 for CASE 1 and 65 : 35 for CASE 2. From this it would appear that white glare is less devastating in reducing apparent brightness of a white test panelthan the yellow counterpart situation, but that this distinction is less significant at 2° than 45' arc .

Emergent from this is the information that in the real driving situation it would be unquestionably better to have the oncoming traffic (glare sources) yellow (at the same - or even higher luminance than the 'equivalent' white) and to carry white headlights. This is an inadmissible solution. In the situation where all lights are to be the same colour the forgoing data would seem to suggest a marginal advantage (under this criterion) for white, but whether this would remain true if the luminance of yellow were raised the few extra percent. to make result (a) equal to 50% is uncertain.

2. Reduction in Luminance Difference Threshold for White and Yellow.

Object.

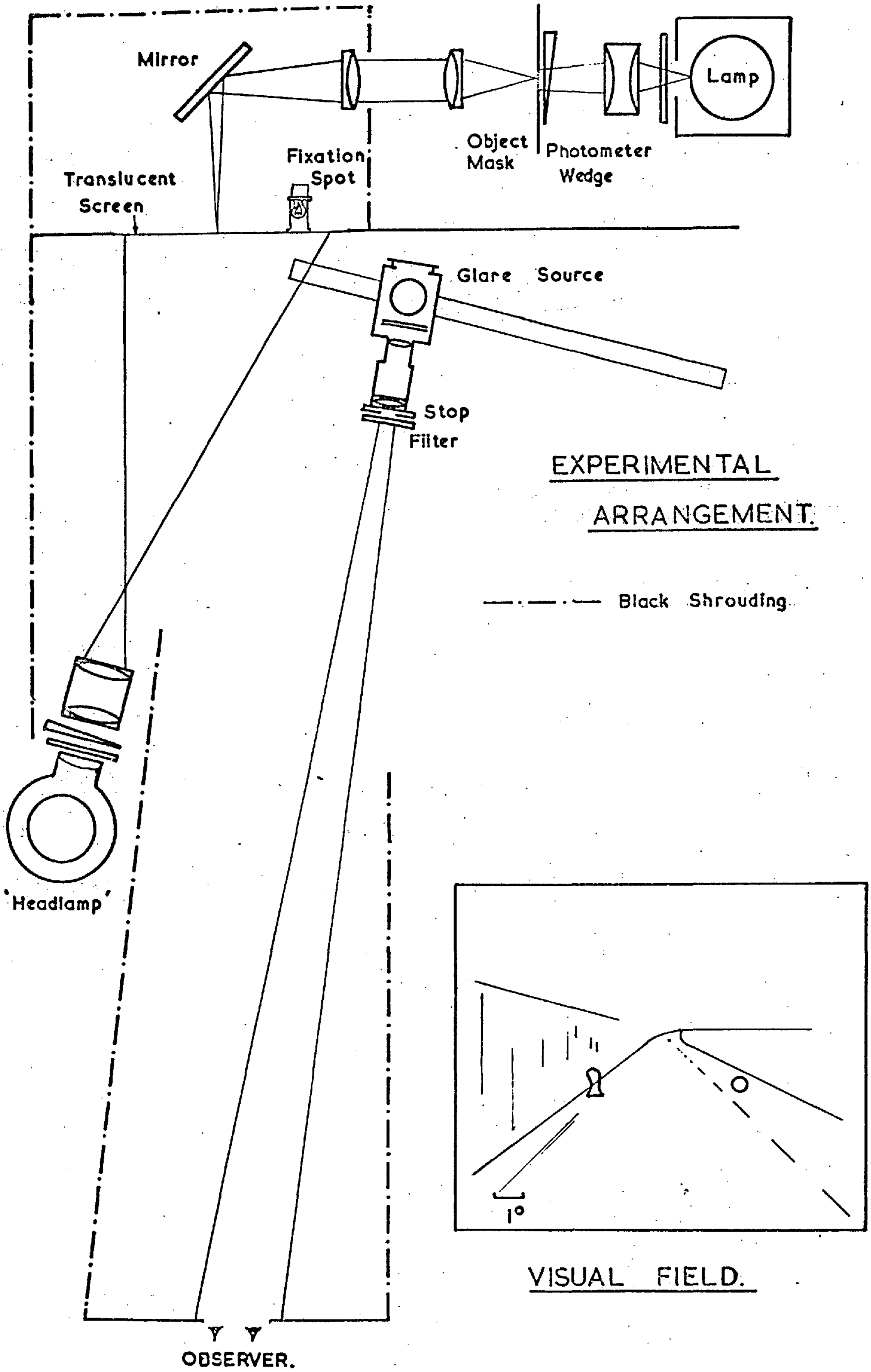
To assess quantitatively the difference in the threshold reduction produced by similar white and yellow glare sources, with special reference to the type of situation (visual field) encountered when driving at night along unlighted roads.

Apparatus.

(see fig. 5) Stylised road scene detail was faintly sketched in white crayon on a tracing paper screen mounted at a fixed distance from the observer. A patch of light, such as might be produced from dipped headlights (meeting beam) carried by the vehicle in which the observer is supposed to be, was projected on to the front surface of the screen (allowing for perspective effects). The luminance of this was controlled by a photometer wedge and/or filters, and was, in the region of the subsequently applied test stimulus, about 0.5 ft. Lamberts, as seen from the position of the observer.

From behind the screen was projected the image of a vague shape (suggestive of a pedestrian wearing a light raincoat) on to the nearside lane (fig. 5 , inset). The observer had remote control of a photometer wedge, which varied the luminance of this image over a range somewhat in excess of 0.1 to 0.01 ft. Lamberts. A small red fixation spot was provided, as shown.

A glare source was arranged to be a featureless patch of about 24' arc angular diameter, with a luminance of 110,000 ft. Lamberts. The observer's head was located on a chin rest, and all light sources were carefully shrouded to leave no spurious light or shadows anywhere near the field of view. A black panel was placed behind the screen to prevent throwback of light.



EXPERIMENTAL ARRANGEMENT.

VISUAL FIELD.

FIG. 5.

All light sources were either white or yellow, filtered by those same filters discussed in the previous section.

Experimental.

The observation consisted of fixating the red spot and raising the luminance of the 'pedestrian' slowly until it just catches the attention. The glare was switched on and a similar measurement of threshold made, using as nearly as possible the same criterion. These measurements were made in both the white and yellow situations. Each was repeated many times (80) in either situation, and the results analysed.

The observer did not specially dark adapt, but had always been, for some long time prior to the commencement of taking readings, in a room with very subdued artificial lighting at a fixed level. Dark adaptation was not necessary or desirable as one would not normally be fully dark adapted in the driving situation. A constant and repeatable adaptation state was necessary to standardise and make comparable results taken on different days.

The experiment was tried without the use of the fixation spot, but this did not give good results as the observer concentrated (unconsciously ?) on the place where the stimulus was last seen, and hence tended to anticipate, giving a wide spread of results. With the fixation spot results were more consistent, but some spread was inevitable because of the nature of the observations. It was thought that some error was introduced by the action of Troxler's effect in adapting out the stimulus at levels immediately above those which would have otherwise have been the threshold. It was tacitly assumed that this effect would have operated equally in the case of both white and yellow glare and stimuli. These experiments were performed when the angular separation of the glare source and test stimulus was about 5^{o}arc.

Results.

The data obtained from the first series of observations (again with the author as observer) were not conclusive (Table 2). The thresholds for white and yellow in the absence of glare were almost the same, while the difference in threshold in the presence of glare was considered to be barely significant; what difference there was indicated a lower threshold with yellow than with white.

Following the above, the experiment was repeated with even greater care with the results in Table 3. It will be noted that whilst the stated deviations were smaller, there was considerably poorer agreement in thresholds without glare, (which may anyway not have been the same but should have agreed, in sense at least, with those of Table 2) and in the presence of glare the earlier trend was reversed and increased in magnitude. This latter pointed to yellow glare being worse for driving purposes (from considerations of glare) than white, for similar luminance conditions.

A reasonable assumption is that this method of approach is insufficiently accurate to enable any definite conclusions to be reached. It is, however, in support of the view that there is no significant visual advantage to be gained by a universal change-over from white to yellow headlamps, and that any differential in luminance difference threshold is very small at 5° from the glare source.

Table 2

Test Condition		Luminance Difference Threshold	
		Mean	Standard Deviation
White	Without Glare	0.041	0.007
	With Glare	0.165	0.026
Yellow	Without Glare	0.040	0.005
	With Glare	0.141	0.022

Table 3

Test Condition		Luminance Difference Threshold	
		Mean	Standard Deviation
White	Without Glare	0.036	0.002
	With Glare	0.118	0.010
Yellow	Without Glare	0.046	0.004
	With Glare	0.193	0.016

FIG. 6.

3) Recovery from White and Yellow Indirect Glare.

Object.

To compare curves of recovery from adaptation to white and yellow indirect glare, where the glare level is in the region of 250,000 ft. Lamberts and is separated from the test patch by 3.5° arc.

Apparatus.

The instrument used for measuring the recovery of sensitivity curve by binocular comparison was the Wright Subjective Photometer (Wright, 1946) described in its various modified forms in Chap. III of this work. Several of the later refinements had not been added at this stage but the set up in question here is illustrated in Fig. 7. which includes a picture of the field of view when the device is correctly adjusted and the observer fresh. (Chap. III section 2)

The observer's head was fixed by means of a dental bite, and the equipment adjusted to provide centralisation between the exit pupils of the instrument and the pupils of the observer. With the above glare source luminance the illumination in the plane of the exit pupil was about 50 lux. The luminance of the test patch seen by the right eye was kept constant at 10 ft. Lamberts through out the experiment. The luminance of the patch seen by the left eye was variable by means of a 15 cm. neutral density wedge, the density gradient of which was constant along its length at 0.2 units of neutral density per centimetre, where neutral density is defined as $\log_{10}$ reciprocal transmission factor and is independent (to a fair approximation) of wavelength.

Since the glare source was small (approx. 30' arc.) it is the total luminance multiplied by subtended solid angle that

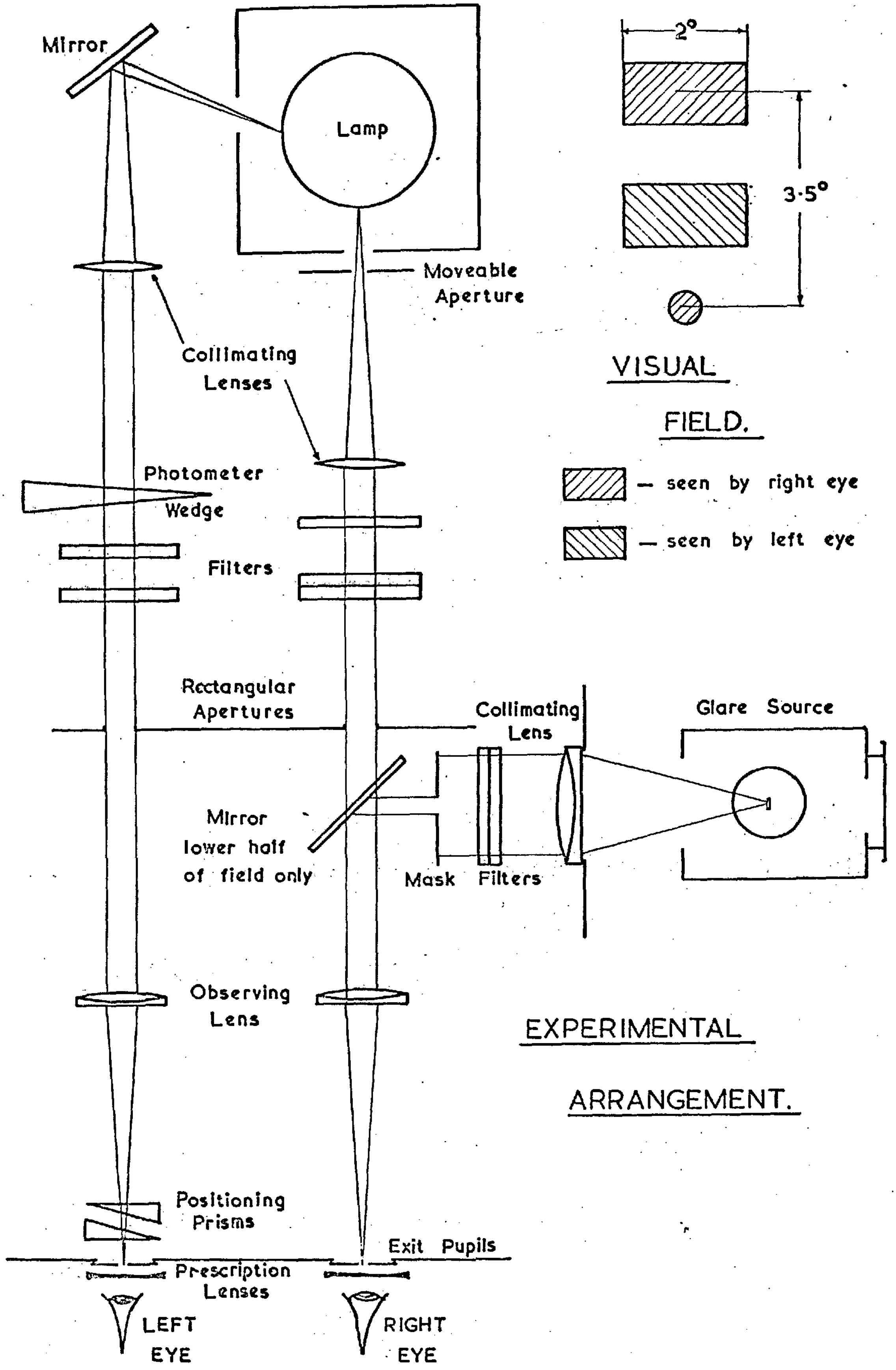

Mirror
Lamp
2°
3·5°
Moveable Aperture
Collimating Lenses
VISUAL FIELD.
▨ — seen by right eye
▧ — seen by left eye
Photometer Wedge
Filters
Rectangular Apertures
Collimating Lens
Glare Source
Mirror lower half of field only
Mask
Filters
Observing Lens
EXPERIMENTAL ARRANGEMENT.
Positioning Prisms
Exit Pupils
Prescription Lenses
LEFT EYE
RIGHT EYE

FIG. 7.

dictates the glare dependence. Bordoni (1924) states that in the case of glare sources subtending less than 3° the total luminous intensity is alone the determining factor.

Experimental.

The observer was dark adapted for 30 minutes and then asked to make a series of binocular matches of luminance between the test patches, varying the luminance of the patch seen by the left eye, by adjusting the position of the photometer wedge. The patches were displayed for two seconds in every ten in the absence of glare to prevent local adaptation to the patches. At least ten readings of the wedge scale were taken for this 'dark adapted match'. These series of readings were repeated with the glare source continually in the field of view for at least six minutes giving not less than five readings for a 'glare adapted match'. Negative wedge readings could be obtained (as was necessary for some observers whose sensitivity depression was very large) by use of a pre-calibrated neutral filter placed in the left eye system, and the effect allowed for by subtraction.

Having obtained readings for a'dark adapted' and a 'glare' match, the observer made matches as rapidly as he could after removal of the glare source from the right eye's field of view, using continuous display. This was continued until the rate of change of the match slowed sufficiently to allow return to intermittent display.

The experiment was performed with ten observers, with each observer attending on at least two separate occasions and making measurements of both white and yellow each time (white first on one occasion, yellow first on the other). Ages varied from 20 to 82 years and observers of both sexes were used.

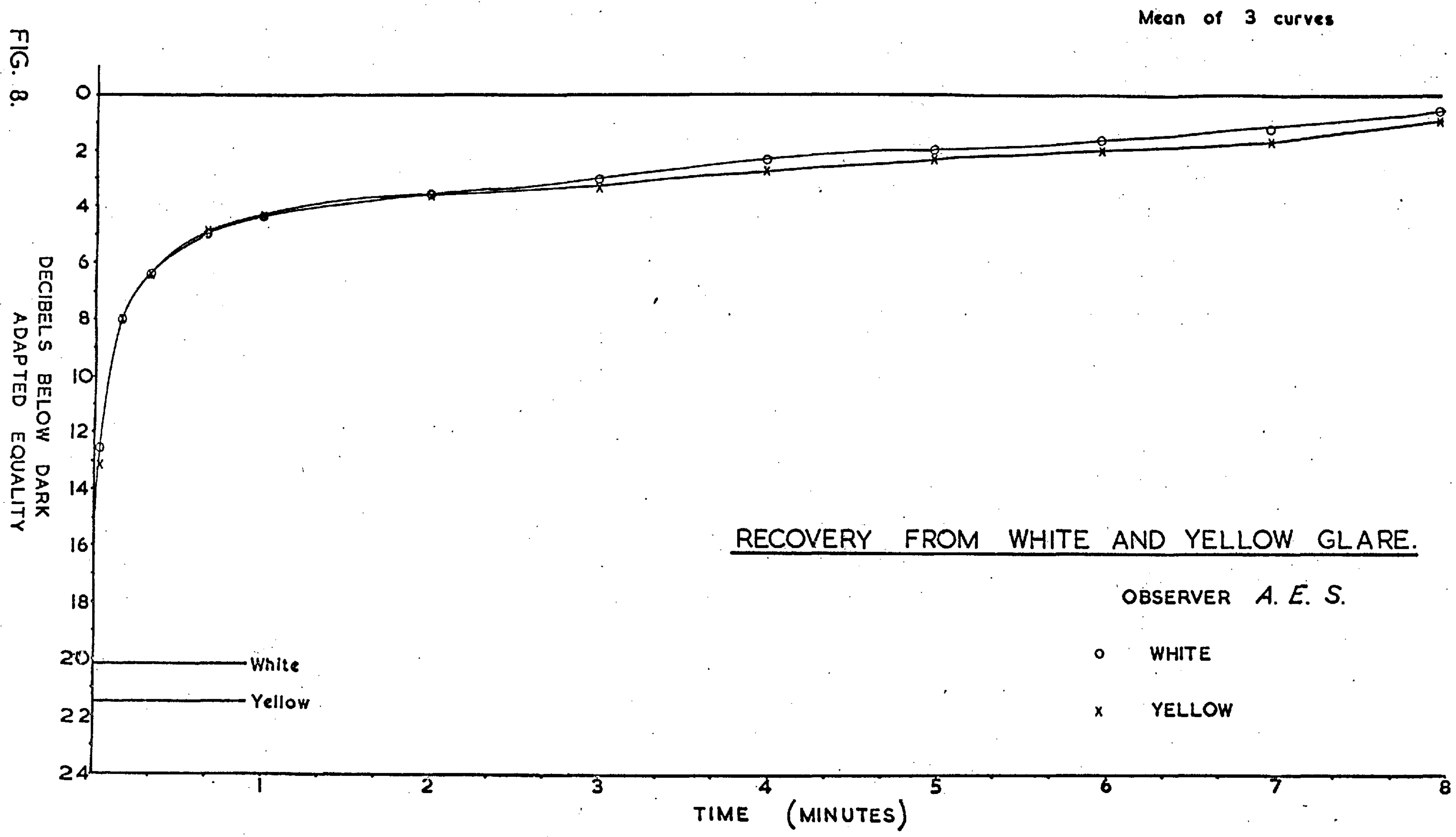
The test patches were each modified by filters identical with those used on the glare source, i.e. The whole display was either white or yellow.

Results.

The recovery data were plotted for each observer on each occasion and for each colour. Abscissae were in minutes and seconds of time and the ordinates quoted in centimetres of neutral density wedge (previously shown to be linear on a logarithmic basis) required in the left eye system to lower the left test patch to the same luminousity as the patch seen by the right eye, which had its luminousity reduced by the presence of glare. These latter units were not transcribed into luminance units since it was only the comparative values which were of interest here.

Two graphs are shown (Fig. 8 and Fig. 9) illustrating particular features. It cannot be claimed that these are typical since large differences in the form of recovery curve were found. It will be seen from Fig. 8, the recovery curve for A.E.S. (aged 23) that very rapid recovery takes place initially, but then slows markedly to take a relatively long time (10 mins.) to reach the formerly recorded dark adapted level. This general type of initially rapid recovery was shown by about half of the observers, particularly the younger ones, but correlation with age is exceedingly poor in view of the two definite exceptions and the low number of observers. (Table 4. C) The rest, however, all returned to their dark adapted level within six minutes or so whether their initial recovery rate was fast or slow. The recovery curve of W.H.K. (Fig. 9) (aged 44) shows a significantly slower recovery (Table 4. C) on removal of the glare, but the rate of recovery falls

FIG. 8.



Mean of 3 curves

RECOVERY FROM WHITE AND YELLOW GLARE.

OBSERVER *A. E. S.*

FIG. 9.

Mean of 4 curves

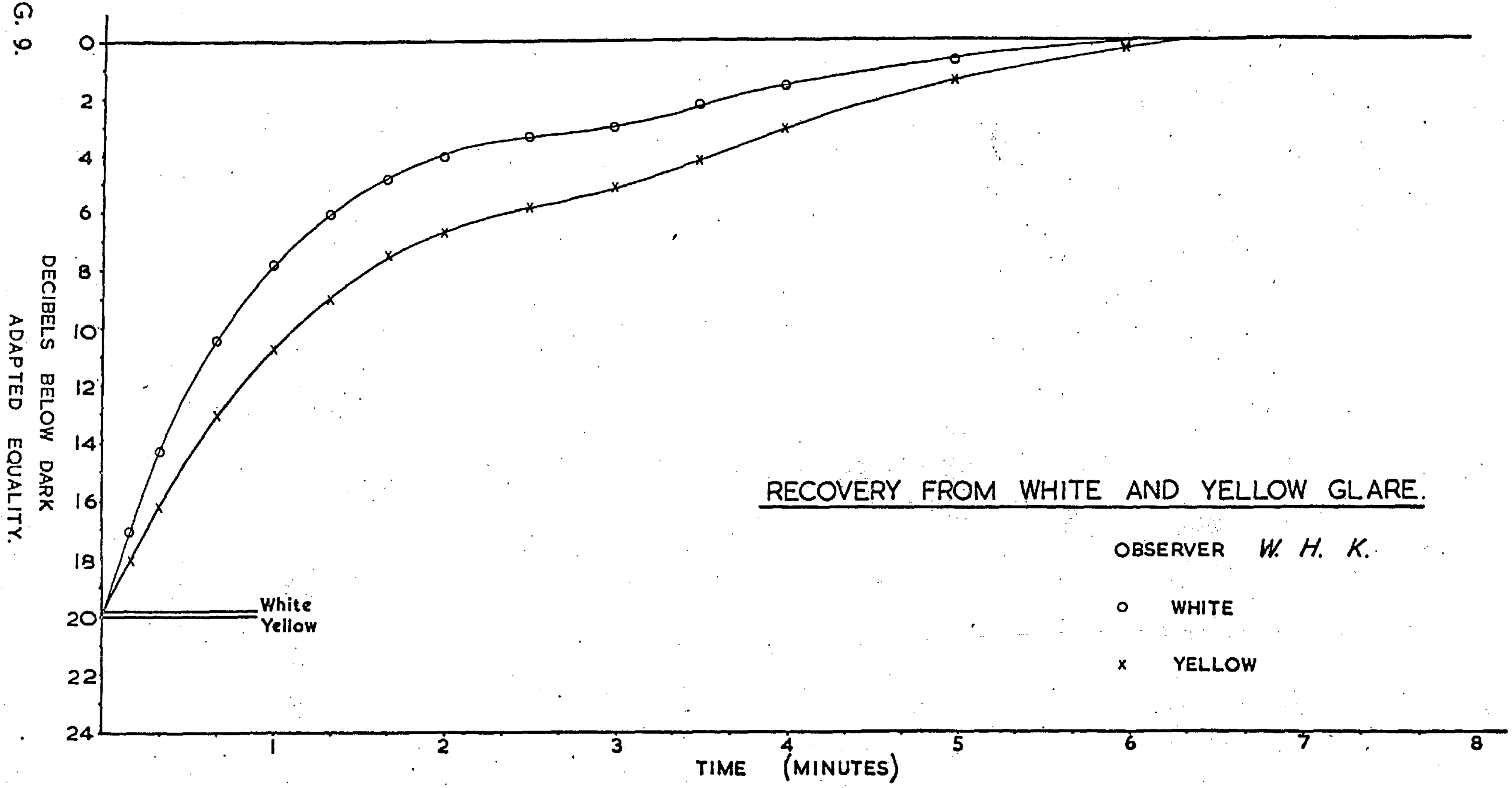

RECOVERY FROM WHITE AND YELLOW GLARE.

Table 4.

Observer	Age	Sex	$A_{(W)}$	$A_{(Y)}$	$B_{(W)}$	$B_{(Y)}$	$C_{(W)}$	$C_{(Y)}$	$D_{(W)}$	$D_{(Y)}$	$E_{(W)}$	$E_{(Y)}$
R. C.	20	M	20.4	23.0	@	@	14	21	78	150	3	5
P.R.C.	22	M	25.6	24.4	@	@	10	6	77	77	4	5
H. M.	23	F	6.8	5.6	3	4	0	0	36	60	3	3
A.E.S.	23	M	20.0	21.4	@	@	6	6	164	214	10	10
W.G.O.	23	M	23.2	22.4	@	@	2	3	31	62	1.4	2
S.H.R.	24	M	19.0	20.4	48	38	8.5	10	28	44	1	1.6
W.H.K.	44	M	19.8	19.8	8.6	11.4	45	68	170	240	6	6
W.D.W.	60	M	20.6	22.0	@	@	7.5	6.5	55	112	5	6
J. W.	61	F	13.2	11.0	6.7	8.3	150	81	210	240	5	5
C. B.	82	M	10.8	11.2	8	7	70	80	160	115	5	4
Average			17.9	18.1							4.3	4.8
% difference averaged algebraically over observers							<2% $C_{(W)}<C_{(Y)}$		50% $D_{(W)}<D_{(Y)}$			

$A_{(W,Y)}$ Depression of sensitivity below dark adapted level (db.).

$B_{(W,Y)}$ Initial rate of recovery of sensitivity (db./min.).

@ Rate too rapid to measure – asymptotic to $t = 0$.

$C_{(W,Y)}$ Time taken to recover by half the number of db. corresponding to the original loss of sensitivity (seconds).

$D_{(W,Y)}$ Time to recover to 3 db. below dark adapted level (seconds).

$E_{(W,Y)}$ Time taken for virtually complete recovery (minutes).

FIG. 10.

more slowly giving a flatter curve. Significant difference is seen in this curve between the behaviour of white and yellow.

In Table 4 are presented the data obtained from the measured recovery curves for each observer and certain general trends may be drawn from these.

$A_{(W,Y)}$ is a measure of the decrease in sensitivity caused by the action of the glare source on the relevant portion of the retina of the right eye. Since this is a ratio of the necessary luminances of the two test patches in order that they should have the same luminosity under certain defined conditions, and since these patches have the same constant area the result is conveniently quoted as a ratio of luminous intensities, hence decibels below equality of luminance under conditions of equality of dark adaptation of the two eyes.

Results show that the difference in $A_{(W)}$ and $A_{(Y)}$ for any one observer never exceeded 20% of the smaller and the magnitude of the average difference is 8.3%. However, the direction of the difference (whether white or yellow lowers sensitivity to a greater extent) was almost random, so that the average sensitivity depression for all observers for white is 17.9 db. and that for yellow is 18.1 db. - an insignificant difference. It may be concluded, at least for the small sample of observers who were used, that the sensitivity depression produced by indirect adaptation derived from a glare source is not significantly different for white and yellow sources of approximately the same luminance.

The difference between individual observers, regardless of colour of glare, was very large, and this difference did not correlate with age! Too few female observers were used to say anything about sex correlation. This lack of correlation of degree of sensitivity depression with age cannot be taken very seriously in view of the quite insufficient number of people on whom this test was carried out. There would have been a vague trend towards slower recovery and less depression of sensitivity with increasing age had it not been for two notable exceptions, H. M. and W. D. W. , about whose results more will be said.

$B_{(W,Y)}$ gives the initial rate of recovery. Apart from the five observers who recovered at a very high rate the observers showed very variable characteristics. (Table 4, B) . No consistent differences were to be observed between white and yellow. This method has no satisfactory provision for recording behaviour in the first few seconds after glare removal (see Chap. V).

$C_{(W,Y)}$ shows the time taken to recover by half the number of decibels corresponding to the original sensitivity loss. It is included merely to give some idea of the form of curves which restrictions of space prevent from being illustrated. The algebraic averages of the percentage differences of white and yellow are very nearly the same.

$D_{(W,Y)}$ gives the time in seconds required to recover to a level 3 db. below the dark adapted level. Differences between observers are still large but the difference between white and yellow now has significance. The average excess of $B_{(Y)}$ over $B_{(W)}$ is some 50% of $B_{(W)}$ for all observers (considered together), i.e.

$$\frac{1}{10} \sum_{\text{observers}} \frac{B_{(Y)} - B_{(W)}}{B_{(W)}} = \frac{1}{2} \quad \text{or} \quad 50\%$$

Only one observer showed a difference of $B_{(W)} > B_{(Y)}$, and that was C. B. (aged 82).

It would appear from this that recovery to this 3 db. point takes significantly less time for white than yellow, at least for 9 of our 10 observers.

$E_{(W,Y)}$. Complete recovery is a less accurately determinable quantity but a rough guide (given in minutes) has been attempted. Complete recovery from yellow took a longer time than from white for 5 of our observers, the same time (approx.) for 4 observers and a shorter time for C. B. The average showed a small period of time between recovery from white and yellow, but it should be stressed that this is hardly significant.

W. D. W. (60) exhibited a recovery curve which was very similar to that typical of a mid-twenty year old observer. Perhaps because of his much greater experience of discriminating psychophysical measurements his curves were highly repeatable. J.W. (61) was a rather poor observer but it was difficult to imagine that the recovery curves obtained from her were not very different from those of W. D. W., of a similar age.

H. M. (23) was something of an enigma. Her recovery data did not vary significantly between the two occasions of measurement (and showed the same behaviour on two more occasions) but still did not make much sense. As can be seen from Table 4 she experienced a very small sensitivity depression and a most gradual rise back to the original level.

Although most of the observers expressed a dislike of the unpleasant sensation of glare, H. M. expressed the most intense hatred of driving at night because of glare. She said that she found glare a very real impairment to visual ability. From the observations it would seem that her sensitivity was depressed rather less than most, contrary to her opinion.

A very tentative foray into the realms of psychology could suggest the hypothesis that the lowering of sensitivity, and real impairment of vision, caused by glare serves to minimise 'dazzle', or physically unpleasant sensation of exposure to light far in excess of the comfortable level appropriate to that adaptation state. (Discomfort glare). Conversely if, for some reason, the real sensitivity remains the same, or is only slightly reduced, the physical sensation of pain, as an aspect of 'dazzle', temporarily overwhelms the concentration of the observer/victim, which accordingly reflects on bad visual performance from causes operating at a higher level of the perceptual system.

In conclusion we may summarise that all differences found are rather small. What differences are to be found can usually be modified or even reversed by changes in the conditions obtaining in the driving situation. In general the environmental modifications encountered when driving during the hours of darkness are so vast as to make differences of white and yellow, which are hard to detect even under laboratory controlled conditions, pale almost into insignificance as a factor affecting visual performance.

CHAPTER III.

Apparatus.

The basic apparatus used in the experiments of the last part of Chap. II is described and the several necessary details of modifications to enable subsequent experiments to be performed with accuracy are illustrated.

It was noted early in this work that human performance is subject to many variations due to uncontrollable effects, for example whether the observer felt tired, depressed, elated, cooperative or otherwise, etc., and such effects cannot be expressed quantitatively, thus it was essential to control all physical parameters with the maximum possible rigidity, and much time was devoted to this end.

There follows a description of the equipment used and some information on measurement of luminances quoted.

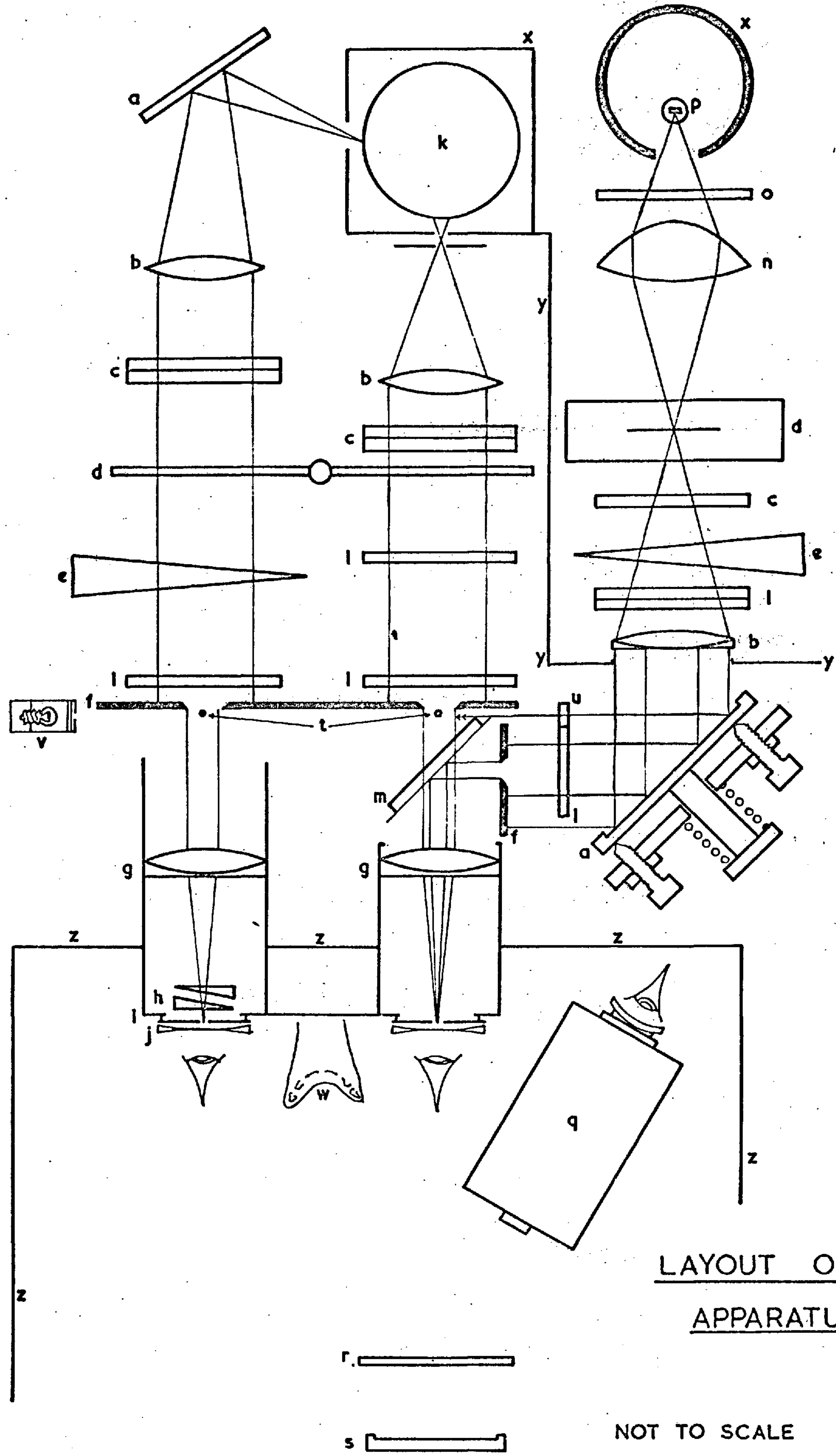
1) Binocular Comparator.

The original apparatus had been designed to produce two visual fields which could be compared binocularly, when one eye was subjected to some adapting stimulus. This was described by Wright (1946) and is now drawn to comprise part of Fig. 12, which shows the completed experimental layout. Not all the items shown were in use simultaneously, and it must be considered that the equipment is three-dimensional and not all the elements co-planar. The photograph (Fig. 11) shows the overall appearance, somewhat denuded of the black shrouding and screening necessary to exclude stray light in operation.

(see Fig. 12. and Key) For the left (or variable) comparison patch system light from a 75 watt enlarger type bulb (k) (with an opal-white surface texture) was reflected from a front surface silvered mirror (a) and collimated by the lens (b). The light was modified by colour (c) and/or neutral (l) filters and a photometer wedge (e) (controlled by the observer). A field mask (f) selected a small part of the beam which was imaged in the plane of the artificial pupil (i) by the achromatic observing lens (g) and thus appeared in Maxwellian view.

A similar arrangement produced the right eye test patch, but now had no photometer wedge, being set at the required standard value by neutral filters. Both these systems were shuttered simultaneously by an electromagnetic relay operated opaque card (d) designed to display both test and comparison patches at the same time, for a fixed known period (see later details of timing). The observer's head was fixed by means of a dental bite (w) and provision was made for accommodating refraction errors by the lenses (j) attached to the eyepieces. These prescription lenses were found necessary as

Fig. 11.



LAYOUT OF APPARATUS.

NOT TO SCALE

FIG. 12.

a short experiment to assess the invarience of the binocular match with defocussing showed that the match obtained was significantly dependent on defocussing of the image of either test patch. For uniformity of results, and to eliminate this as a possible undefined variable myopic and hypermetropic visual defects were completely corrected.

The setting up of the apparatus described so far, that is,the visual field containing the test and comparison patches,was of some importance and will be described here :-

The observer made a dental impression (particularly of the top set of teeth, which are conveniently fixed rigidly to the skull) in soft wax (warmed, flame polished, Stent's Composition) which hardened on cooling. This was clamped to the apparatus and racked to bring the observer's eyes as close as possible, with moderate comfort, to the eyepieces (in particular the artificial pupils).

The test and comparison patches were made quite bright (1,000 ft. Lamberts) and filtered by purple gelatin filters (transmitting red and blue light only). The dental bite platform was raised until no horizontal chromatic aberration was visible in the left eye. That is, the exit pupil was centralised in the left eye pupil, as specified by corneal symmetry. The entire left eye system of optics was then shifted to eliminate horizontal non-registration of the red and blue images. With the left eye pupil centred on the instrument left exit pupil the right optical system was swung round to give the correct interpupillary distance defined again by horizontal registration of the red and blue images (this time those seen by the right eye). The right exit pupil was finally adjusted vertically to correct for asymmetry of the observer's eye position in his or her head. Two purple rectangles were then visible and they were arranged into the correct format by means of rotating prisms (h) in the left eye system.

The patches did not change their relative positions very much vertically (diplopia is quite rare) but had a tendency to horizontal drift as the observer tired, sometimes so far as to make matching virtually impossible, (See details of fixation spots).

The Glare System.

The 'glare' system enabled a variety of conditioning stimuli to be presented to the right eye via the same artificial pupil. The light source (p) was a tungsten halogen lamp run from a stabilised power supply. Since this was fairly powerful, heat absorbing glass (o) was used to afford some protection to the later filters (c) and (l) and the photometer wedge (e), which was only present for some of the experiments. A condenser lens (r) focussed an image of the light source on to a thin sheet of molybdenum foil, fixed in a rigid block of aluminium, and attached to an electromagnetic relay (d). This lightweight metal sheet made a rapid and repeatable shutter that harmlessly dissipated the heat that it absorbed. Light was collimated by an achromatic lens (b) and reflected from another front surface silvered mirror (a) mounted kinematically. The kinematic platform centre could be racked in 3-dimensions. Part of the beam was further controlled by a neutral filter and reflected from yet another front surface mirror (m) (in the case of the glare source) or a very thin semi-reflecting cover slip (in the case where a uniform adapting background was required). A field mask (f) of the desired shape and size was inserted when applicable.

Items (q), a Holophane Lumeter, and (r), a standard Lambertian diffusing screen, were placed as shown to measure the luminances of the different visual stimuli, both test patches and glare sources. With the observer's head moved to one side the glare light went straight through the system falling eventually on to a barrier-layer photocell (s) connected to a maximum sensitivity P.Y.E. 'Scalamp' Galvanometer. This 'through the lens metering' enabled frequent checks to be made on the constancy of the glare stimulus, not merely by controlling the light source as is usual, but by monitoring the light output of the system, thus ensuring that the optical elements are in correct alignment and free from dust, which might increase scatter, but would be immediately apparent as a reduction in photocell output.

Because of the non-linearity of barrier-layer photocells the galvanometer reading was not itself used as a measure of the glare luminance. It was, however, used as a null reading system in which the galvanometer was kept at a scale position which had been previously calibrated against the Holophane Lumeter. Any deviation was thus detected early and negated. The Holophane Lumeter had recently been calibrated (in conjunction with the diffusing surface) on a photometer bench against standard lamps and found to be within its specification.

Quantities of black card, cloth and metal were used to protect the observer from spurious light. Metal panels (y) painted with matt black paint protected the test system from stray light from the glare system and helped to ensure that the surround of the display really looked black, even under dark adapted conditions. The observer sat in a cubicle totally enclosed by black drapes (z) which excluded all light but that entering via the artificial pupils. Lamp housings (x) served to control light spill, the house for the enlarger bulb having only two small apertures for the test and comparison systems, and that for the glare source only one that was not light trapped.

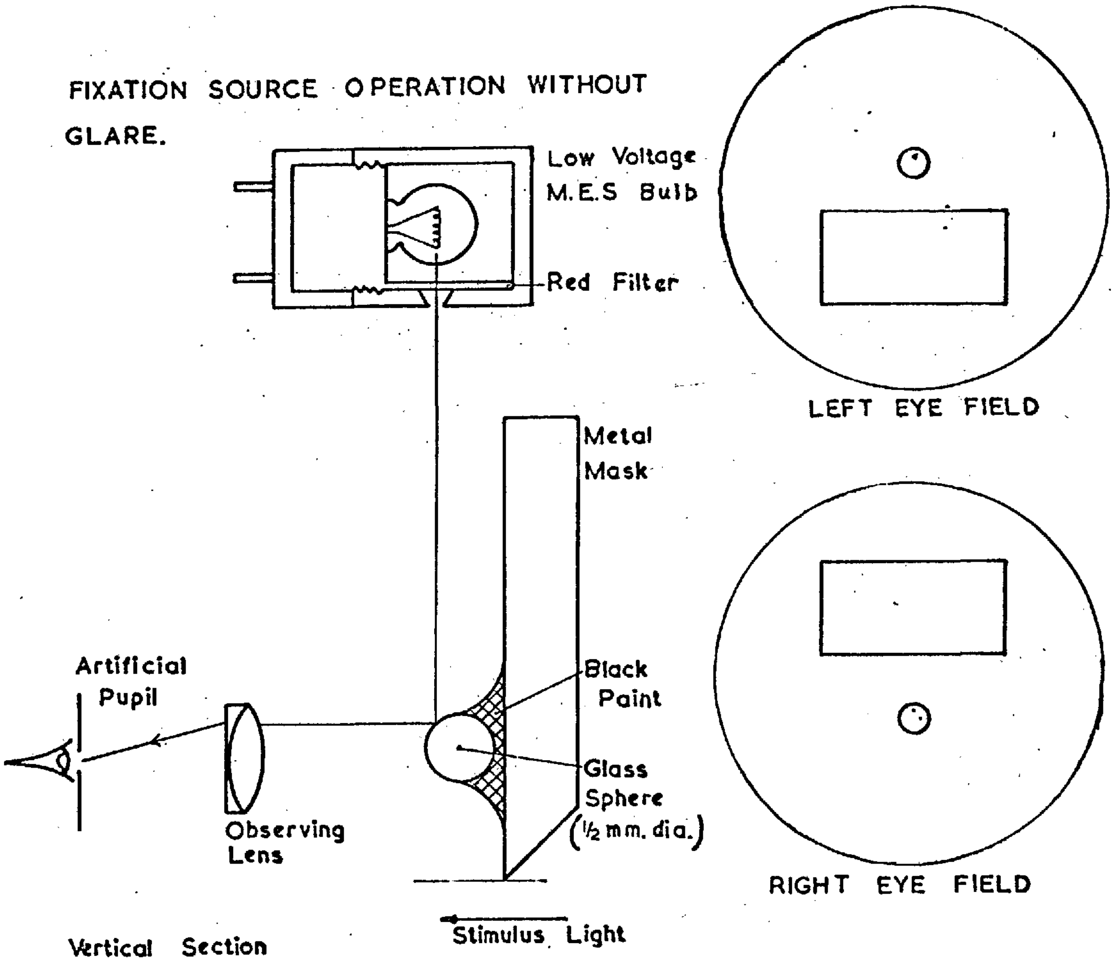
Scattered light from the apparatus was determined to be at least an order of magnitude below that introduced by entoptic media, and also colour independent. Frequent cleaning assured that this situation did not alter.

2) Fixation Sources. (see Fig. 13)

The visual field, composed as it was from images seen by different eyes, tended to drift. The vertical separation of the test patches was small problem since the tendency for a vertical separation between the visual axes of the two eyes is almost negligible in the healthy person. The horizontal drift was large, particularly as the fatigued observer lost control over convergence, making binocular matching very difficult. To overcome this, small fixation sources (t) were provided by sticking ballotini ($\frac{1}{2}$mm. glass spheres) to the field masks in the required positions so that fusion of the small reflected pinpoints of light in the ballotini can take place. The rear surface of the sphere was coated with black paint to suppress the second reflection normally present in such an arrangement. A red lamp masked to a small point (v) appeared, when viewed through the optical system concerned, to be a minute point at the highlight of the sphere which in turn is imaged, with the field mask, at infinity. These fixation sources were displayed all the time. They were so small and dim as to have negligible effect on the dark adaptation state.

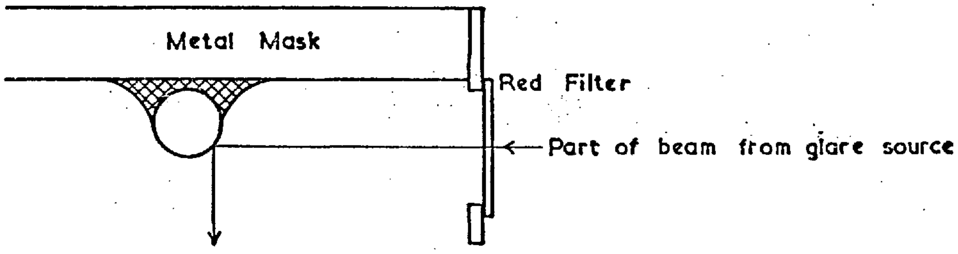
On presentation of a glare source to the right eye the fixation point became sub-liminal, and thus, to avoid drift during glare exposure, it was desirable to increase its luminance. This was effected by selecting part of the glare beam and passing it through a red filter (u) to fall at right angles to the observation direction, on to the glass sphere, thus producing a brighter highlight. There was a small change in the position of the highlight on the sphere, but, even allowing for this shift (which, surprisingly enough, took place rapidly and quite unobtrusively), the maintained fixation was very much superior to lack of any fixation, or even failure to see one spot during glare exposure.

FIXATION SOURCE OPERATION WITHOUT GLARE.



Vertical Section
NOT TO SCALE.

FIXATION SOURCE OPERATION WITH GLARE.



Horizontal Section
NOT TO SCALE.

FIXATION SOURCE DETAIL

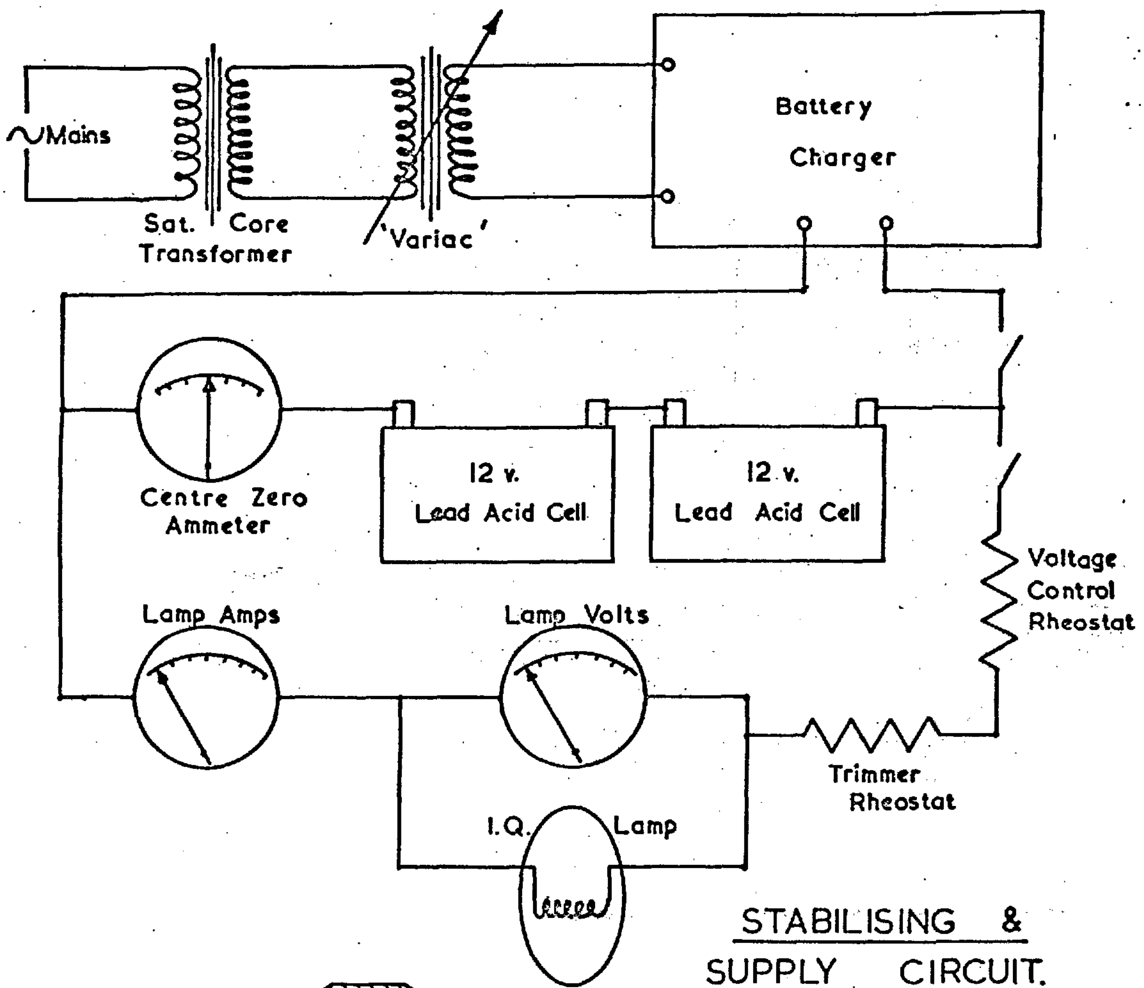
FIG. 13.

3. Lamp Stabilisation and Control.

The light source responsible for supplying the glare was the subject of some design work. It was decided to use a tungsten - halogen - quartz lamp rather than the more conventional tungsten ribbon filament lamp. These I.Q. lamps operate at a higher efficiency and colour temperature when run at the rated voltage. When underrun they have a long life with very constant output. Because of the mode of operation no tungsten is deposited on the lamp walls.

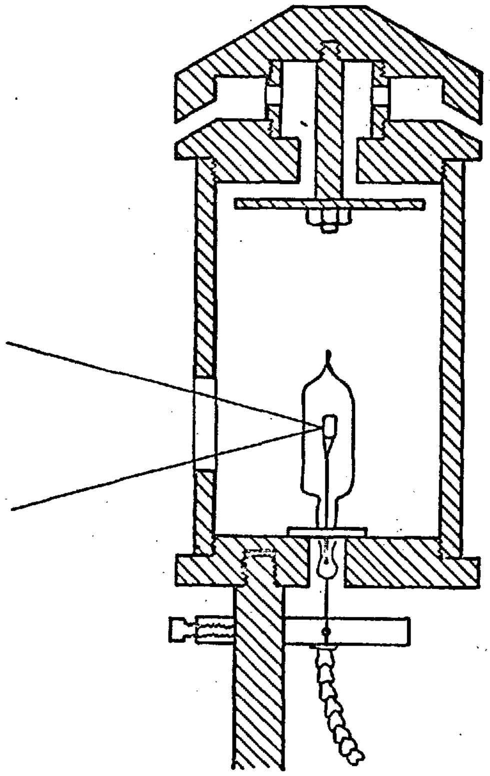
Tungsten evaporates from the filament at above 3,000 °C; deposits on the quartz walls where it immediately picks up iodine. Tungsten iodide evaporates from the walls at 200 - 300°C and diffuses throughout the envelope. In the region of the hot filament it goes above its dissociation temperature and tungsten is deposited most rapidly where the filament is hottest, where the current density is highest, and the now free iodine is returned to the environment. The above is only an approximate simplification to make the point that this construction endows the lamp with desirable life/luminance characteristics, but also necessitates a high envelope temperature, and the provision of a thermally stable environment as well as a stable voltage supply if the light output is to be constant.

The circuitry for voltage stabilisation is shown in Fig. 14. A float charged battery system was used at a nominal voltage of 24 volts. The lamp was trimmed to the desired operating voltage and the input-output current to the batteries (which were run in the middle region of their charging characteristic) adjusted to zero via the charger and a 'Variac' variable ratio transformer. A saturated core constant voltage transformer was employed to isolate our system from the mains and reduce some of the supply voltage fluctuations. Even with this precaution it was found more satisfactory to work at a time of the day when mains fluctuations were at a minimum.



STABILISING & SUPPLY CIRCUIT.

ELECTRICAL AND THERMAL STABILISATION.



LAMP HOUSE DETAIL.

FIG. 14.

Stability of thermal characteristics were harder to obtain. Finally a heavy brass lamp-house was constructed (Fig. 14, inset) with a high thermal capacity and constant convection cooling properties. A twenty minute warm up time was necessary to ensure the attainment of full operating temperature, but this was a small price to pay for the stability derived.

The 24 volt, 150 watt, I. Q. lamp was underrun at 17.4 volts at which voltage it had a colour temperature of 3,000° C and an adequate luminance. Its constant life was of the order of hundreds of hours under these conditions.

That it was not officially a 'solid source', but a close rectangular spiral did not constitute a problem as aberration introduced because of using an aspheric condenser lens defocussed sufficiently to conceal the non-uniformity expected.

4) Display Sequence Timing.

For most of the experiments the observer was dark adapted and the test stimuli were presented intermittently. To provide repeatable and precise timing of display sequences a cam device was constructed.

Basically a synchronous motor, driving a heavy flywheel, was used to rotate, via a train of gears, a spindle carrying a nest of perspex discs locked to this shaft. Variable gears and a clutch were incorporated to vary the cycle time and start at a desired point in a cycle. Three microswitches were fixed to come into contact with the perspex discs, the profiles of which were designed to operate the switches for a given interval. One operated the glare system relay, one the test and comparison system and the third a counter.

The disc controlling the exposure of the test patches was merely a circular plate with a smoothly polished edge and a notch cut out of the circumference. The roller on the microswitch arm (lightly sprung) settled into this notch as the disc rotated and operated the contacts for a fixed time. Coarse duration control was obtained by changing discs and a 'fine' control was made available by varying the proximity of the microswitch by a screw.

The glare duration was variable and controllable over quite a large range by having two thinner concentric discs, each with a section of the circumference cut away. A roller, riding on the full thickness of both discs, operated a microswitch when allowed to fall into the recessed portion of BOTH discs. The size of this portion was varied by rotating the discs with respect to each other, thus varying the proportion of overlap of the cut away regions. A scale of 'seconds of glare' was drawn on the lower disc and a fiducial line engraved on the lower surface of the upper disc. Thus, the duration of the exposure was specified and the relative timing of glare and test stimuli altered by rotating the cams with respect to each other and then locking them to the spindle.

For setting up and checking that all was well the 'make' contacts of the microswitches were connected to the relays concerned and the 'break' contacts to a sampling panel. The common lead was used to supply the necessary voltage to drive relays and provide timing pulses to the sampling panel. A centisecond synchronous stopclock was controlled by these timing pulses from our device. All intervals could then be referred to a standard event (The onset of glare was chosen to be this event.) and then measured to an accuracy of 1/100 second.

The complete cycle time could have been 50 or 300 seconds, but in practice 50 seconds was chosen as complete recovery from glare stimuli was found to occur within this period for the illumination levels used. The sampling time was set initially at 1 second, but this was found not to be very useful and subsequently reduced to 1/5 second. This latter time was a compromise between temporal resolution and degree of stimulation, and also time to make a judgement. Wheeless, Cohen and Boynton (1967) said that 0.2 second is necessary for saccadic movement of the eye to get under way and by selecting this period eye movements are less likely to interfere with constancy of readings. Glare times were not taken longer than 8 seconds as recovery was found to be completed within 50 seconds only for this duration,or less,for the maximum intensities used.

5) Measurement of Luminance and Retinal Illumination.

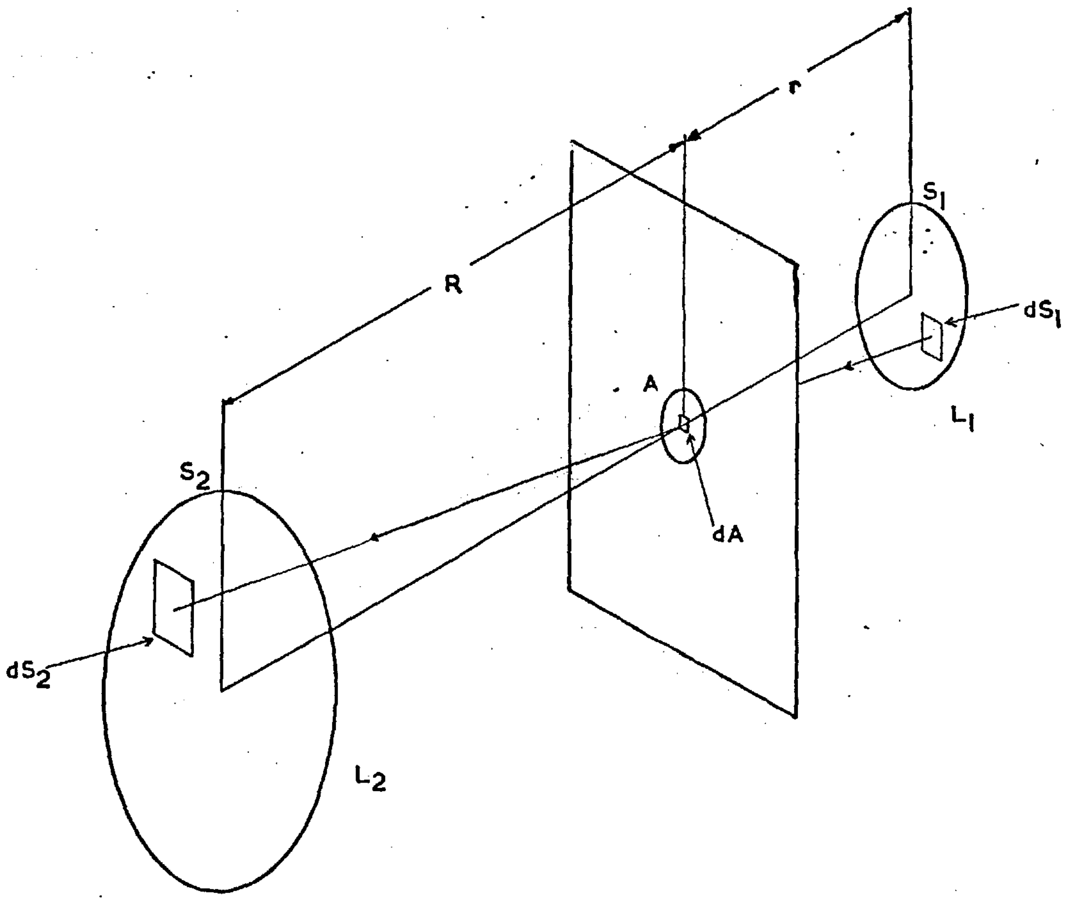
It is apparent from the layout of fig. 12 that the test and glare stimuli are seen in Maxwellian View as virtual images at infinity, since the observing lens has the field defining aperture mask in its back focal plane and the artificial pupil at the front focus. We may simplify the system for the purposes of calculation and measurement to that sketched in Fig. 15. Light radiating from the postulated radiator, S_1, (in the position of the observing lens) is constrained to pass through A to reach S_2, the surface whose luminance is to be measured. It is assumed that the spectacle lens used to correct visual defect is placed in a position so close to the stop that it will not seriously impair the accuracy of the (albeit approximate) calculation to follow. The measurements were subsequently made with the lens in situ.

Since the luminance of the glare stimulus was very high, and that of the test patches could be made fairly high by the simple removal of neutral filters it was possible to use a Holophane Lumeter to estimate the luminance of a Standard Lambertian diffusing surface in a defined position.

Light from S_1 illuminates S_2 via A. Now, if we assume that the luminance of S_1 is L_1 (that which we ultimately require to find), then dF, the flux through an area dA of the artificial pupil from dS_1, an element of S_1, is given by

$$dF = L_1 \cdot dS_1 \cdot \frac{dA.}{r^2} \qquad \ldots\ldots\ldots\ldots\ldots(1)$$

$$\text{or} \qquad F = L_1 \int_A \int_{S_1} dS_1 \cdot \frac{dA.}{r^2} \qquad \ldots\ldots\ldots\ldots\ldots(2)$$



dS_1 is an element of the radiating surface S_1 postulated to exist in the plane of the observing lens $(mm.^2)$.

dS_2 is an element of the standard diffusing surface S_2 $(mm.^2)$.

r is the distance of S_1 from the artificial pupil. (mm.)

R is the disance of S_2 from the artificial pupil. (mm.)

dA is an element of the aperture A. $(mm.^2)$

L_1 & L_2 are the luminances of S_1 & S_2 respectively.

FIG. 15.

MEASUREMENT OF LUMINANCE.

For the situation here where S_1 and A are small compared with r^2 (S_1 = 1 mm^2 , A = 3 mm^2 , r^2 = 10,000 mm^2 .) we may approximate (2) by

$$F \doteq \frac{L_1 . S_1 . A}{r^2} \quad \dots\dots\dots\dots\dots\dots (3)$$

Now this light flux falls on S_2 giving an illumination E_2 (assumed constant over the region in question) where

$$E_2 = F / S_2 \quad \dots\dots\dots\dots\dots\dots (4)$$

Now we know that S_2 is a Lambertian diffuser, scattering through 2 π steradians in such a way that L_2 (its luminance) does not depend on the angle of observation to the surface normal. Thus

$$L_2 = \frac{E_2 . \alpha}{\pi} \quad \dots\dots\dots\dots\dots\dots (5)$$

where α is the overall reflection factor of S_2 .
(the factor 2 is lost in the integration to obtain (5).)

From (4) & (5)

$$\frac{L_2 \pi}{\alpha} = \frac{F}{S_2} \quad \dots\dots\dots\dots\dots\dots (6)$$

and substituting from (3)

$$\frac{L_2 . \pi}{\alpha} = \frac{L_1 . S_1 . A}{S_2 . r^2} \quad \dots\dots\dots\dots (7)$$

Conservation of solid angle through the aperture gives

$$r^2 S_2 = R^2 S_1 .$$

∴ From (7)

$$\frac{L_2 . \pi}{\alpha} = \frac{L_1 . A}{R^2} \quad \dots\dots\dots\dots\dots (8)$$

We may now rearrange (8) according to choice.

For the luminance of the test patch or glare source, L_1 (ft. Lamberts)

$$L_1 = \frac{\pi . R^2 . L_2}{A . \alpha} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

where L_2 is given in foot Lamberts; R (mms.) is chosen for convenience, A (mms.^{2}) is measured and L_2 is measured by lumeter observation. α is a known constant.

For retinal illumination in Photopic Trolands ;-

$$L_1 . A. = \frac{\pi . R^2 . L_2 . \times 3.43 .}{\alpha} \quad \ldots\ldots\ldots (10)$$

where L_2 is in foot Lamberts and ($L_1 . A$) is in Trolands. 3.43 is the conversion from ft. Lamberts to candelas/ metre^2. incorporate in the definition of Trolands.

CHAPTER IV.

Time Resolved Glare Behaviour and Some Chromatic Effects.

1) Recovery Immediately After Glare Removal.

Introduction.

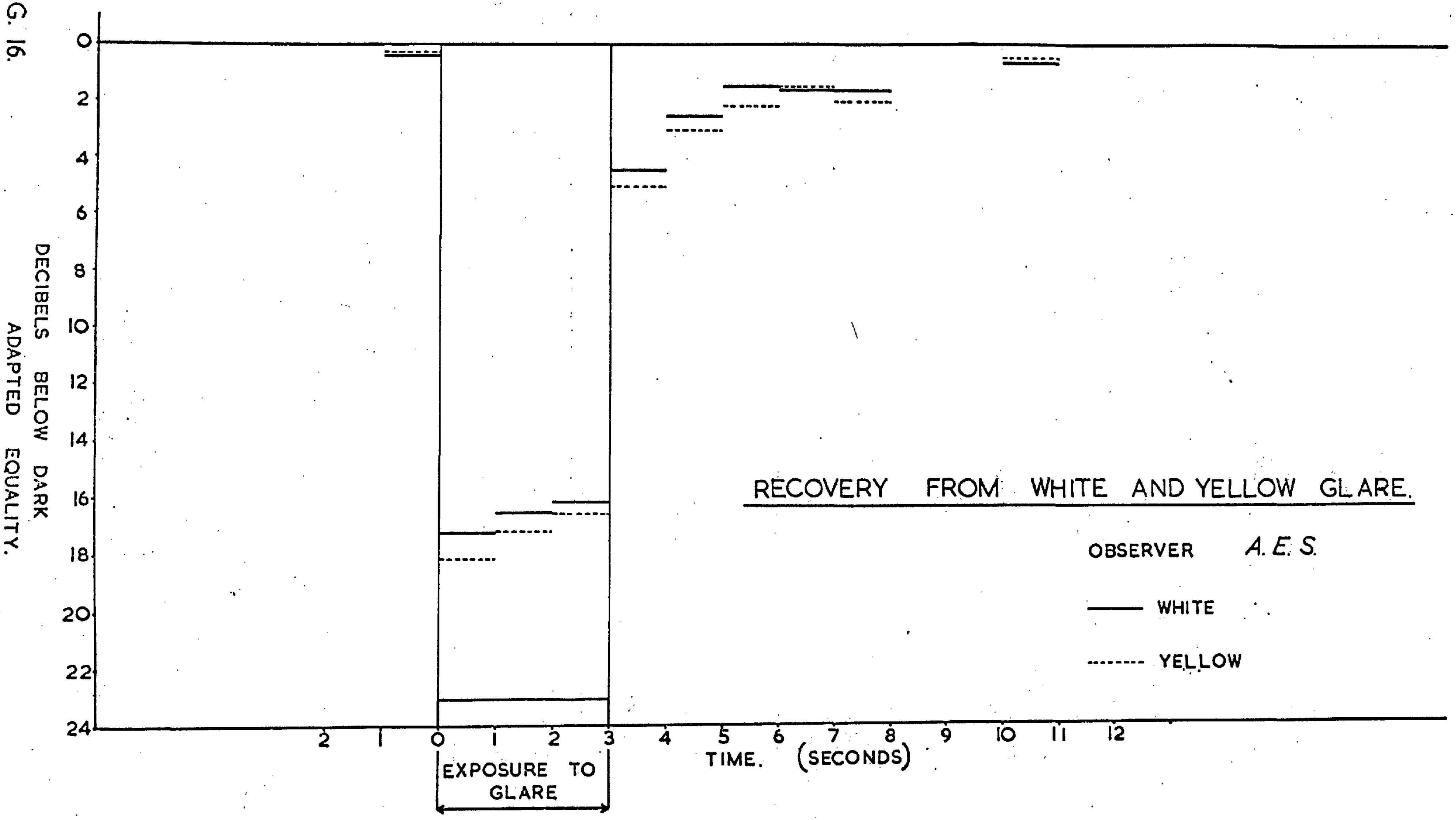
The discussion of comparative recovery from white and yellow glare in the last section of Chap. II did not entirely justify the statement that the recovery from white and yellow proceeded in almost the same way, because the behaviour for the first few seconds after the removal of the glare was inadequately documented. By use of the apparatus outlined in Chap. III it was possible to remedy this deficiency and the technique used is described below.

Experimental.

By making a comparison between stimuli seen in glared and unaffected eyes at a particular instant in time, defined to occur at a given interval after the commencement of exposure to glare, it was possible to plot a sensitivity curve against time with comparatively high temporal resolution. With the basic equipment of Fig. 12 and a visual field arranged to be as (inset) Fig. 7 the timing sequences were chosen to display the test patches at a known fixed time at a known variable delay from the onset of glare.

This method of approach gave a measure of the mean sensitivity (as determined by the equation of binocularly judged equality of luminosity) during the display of the test and comparison patches. This experiment, and those following, were performed with a display time of 1 second for the test and comparison patches. It was not thought essential at this stage to use the 1/5 second display time which required much longer experimental work. This was used

FIG. 16.


RECOVERY FROM WHITE AND YELLOW GLARE.
OBSERVER A. E. S.
WHITE
YELLOW
DECIBELS BELOW DARK ADAPTED EQUALITY.
0
2
4
6
8
10
12
14
16
18
20
22
24
2
1
0
1
2
3
4
5
6
7
8
9
10
11
12
TIME. (SECONDS)
EXPOSURE TO GLARE

later when higher temporal resolution was required.

The angular separation of the glare source and test patch centres was 3.5° arc as before (Chap. II, sect. 3) and the glare luminance was 250,000 ft. Lamberts. For the results quoted (Fig. 16) a glare duration of 3 seconds was used, in a cycle which was 50 seconds between measuring opportunities, and the match established during observation for 1 second in every 50. With a little practice it was found possible to arrive at a match after 3 or 4 complete display cycles. The whole curve therefore took a long time, since several matches were derived for each quoted point, and put a heavy strain on the observer.

Results showed that these methods were justified by their repeatability. The white and yellow curves were obtained together by the interchange of filters used at each time of sampling, thus eliminating any long term drift effects, which might have produced a systematic difference between the two curves.

Results.

Fig. 16 shows a typical recovery curve for A. E. S. for white and yellow. It is to be seen that the difference in the form of the two curves is negligible and the actual separation of them too small to be considered very significant other than that it tends to confirm the minute difference shown in Fig. 9 .

We may therefore conclude that this aspect of the white and yellow controversy is not significantly more relevant than others and that there is no striking difference to be observed in the first few seconds of recovery after removal of the glare source. (A highly critical period in the night driving situation.)

Discussion and Further Results.

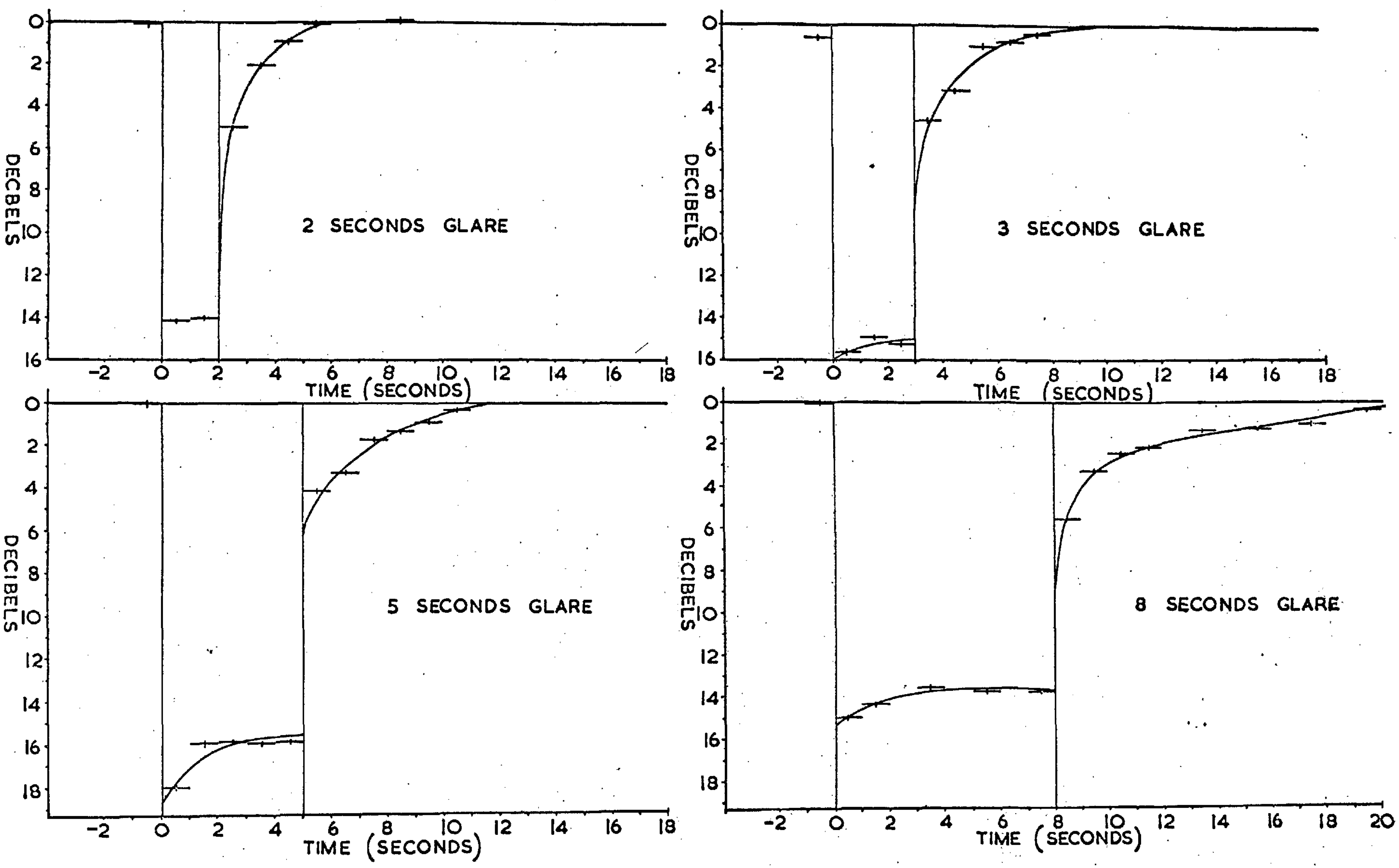
Certain factors emerge from the curve of Fig. 16 ; firstly, that some recovery takes place during the glare exposure and secondly, that a large amount of recovery takes place very rapidly (within $\frac{1}{2}$ second) when the glare source is removed. Now moving away from our preoccupation with white versus yellow glare, we proceed to consider more of the nature of glare itself.

It was decided to repeat the experiment just described with the conditions the same except for the glare duration,which was varied between 2 and 8 seconds. Only white light was used and the results are graphed in Fig. 17. Since data are relatively sparse only approximate conclusions can be reached, but from these graphs it would appear that the onset of glare caused a fixed and immediate depression (certainly less than $\frac{1}{2}$ second and , from later experiments, less than 1/10 second) of sensitivity (mean 15.5 db. under the conditions obtaining), which recovered somewhat during the exposure to glare. The degree of recovery seemed to depend on the duration of the exposure, but was fairly small (0.1 to 1.0 db.) compared with the original depression (see Fig. 17, and Fig. 18, Table 5 and Graph (1).)

Recovery was rapid within the first half second after the removal of glare, the amount of recovery appearing not to depend on the duration of glare. The glare duration did however seem to affect the time taken for sensitivity to recover to 3 db. below the dark adapted level, and also the total recovery time. (see Fig. 18, Table 5, and Graphs (2) & (3).)

There is nothing in these data to suggest that the Straylight Hypothesis as an explanation of the effects of glare is inadequate or in error. (see Chap. VI).

FIG. 17.



RECOVERY FROM GLARE.

TABLE 5.

DURATION OF GLARE Secs.	DEPRESSION IN FIRST ½ Sec. db.	FINAL LEVEL DURING GLARE. db.	LEVEL ½ Sec. AFTER REMOVAL db.	TIME TO 3db. RECOVERY Secs.	TIME TO COMPLETE RECOVERY Secs.	RECOVERY DURING EXPOSURE db.
2	14·0	13·9	4·8	0·9	3·5	0·1
3	15·4	15·0	4·4	1·3	5	0·4
5	17·8	16·8	4·0	1·35	6	1·0
8	15·0	13·8	5·6	1·85	~11	1·2

2. 3. 1.

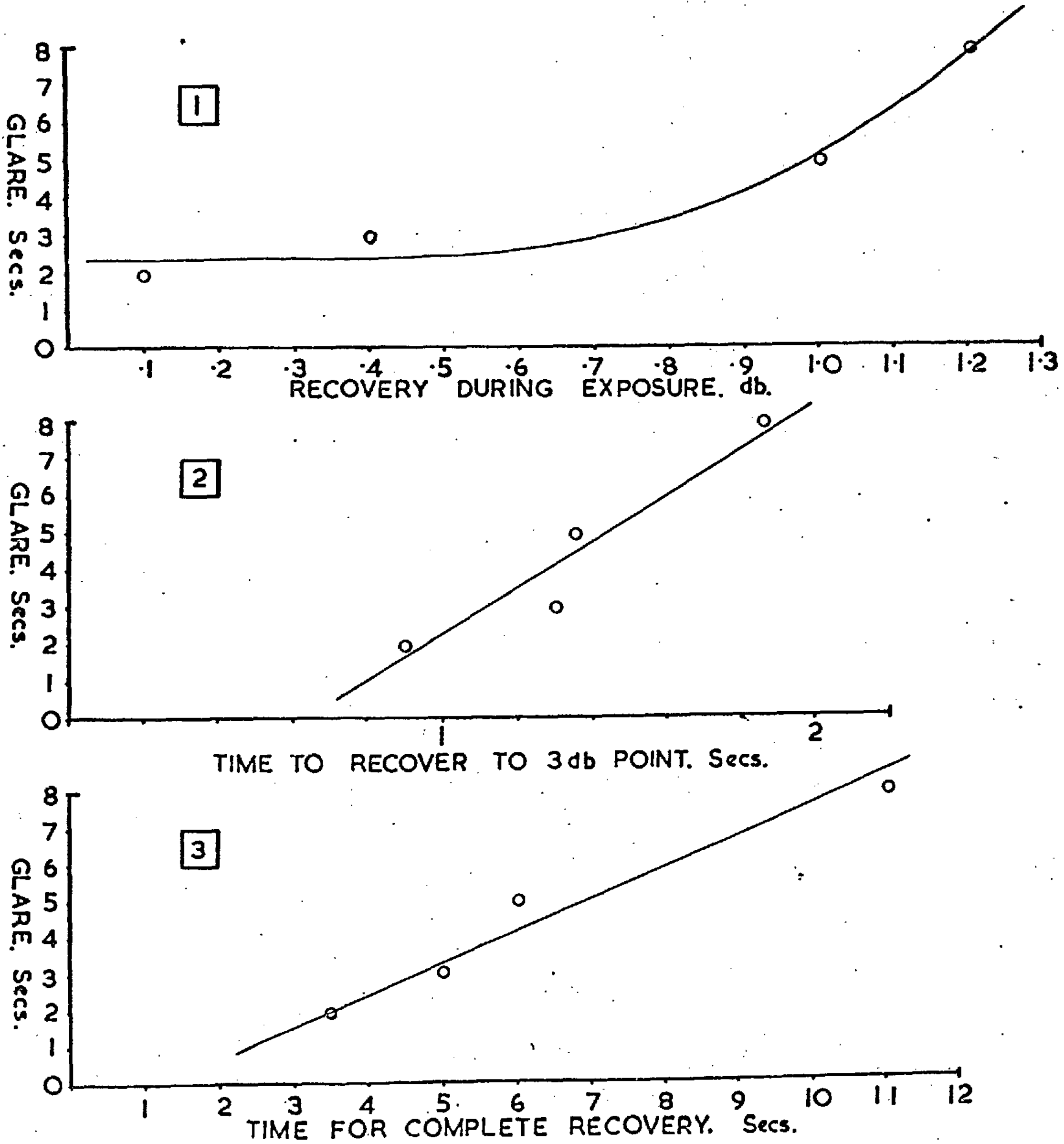


FIG. 18.

2) Chromatic Glare.

Introduction.

At this stage it was decided that an investigation of the behaviour of chromatic glare might lead to further insight into the problems with which we are concerned. The somewhat specious and artificial dichotomy between white and yellow might be approached more circumspectly by considering the behaviour of rather purer spectral components, and differences detected between these may well lead to a further knowledge of mechanisms involved. Accordingly a scheme of investigation was undertaken, commencing with qualitative estimation and leading to more sophisticated quantitative assays.

Binocular matching relies on the assumption of independence of both chromatic and luminance retinal sensitivities of the two eyes. This was discussed by Wright (1946) and a small cross effect is noted. This was stated to be a second order effect, the change in the unstimulated eye being very small.

The present author verified this by swamping one eye with a powerful coloured stimulus and noting any immediate change in appearance of a much lower intensity coloured stimulus (either the same or a different colour) in the other eye, both on presentation and subsequent removal of the brighter stimulus. This swamping stimulus was obtained by mounting a table-tennis ball with a 2 cm. hole close up to the eye and surrounding this sphere (of fairly uniform translucency) with an enclosure lined with white blotting paper and admitting collimated light through a powerful diverging lens. This presented a moderately uniform, wide field stimulus to one eye. For various colours and intensities very small changes were noted in the sensitivity of the other eye. These were quite often indetectable. It was taken from this that binocular cross effects were very much a second order effect and should not mask the phenomena which interest us.

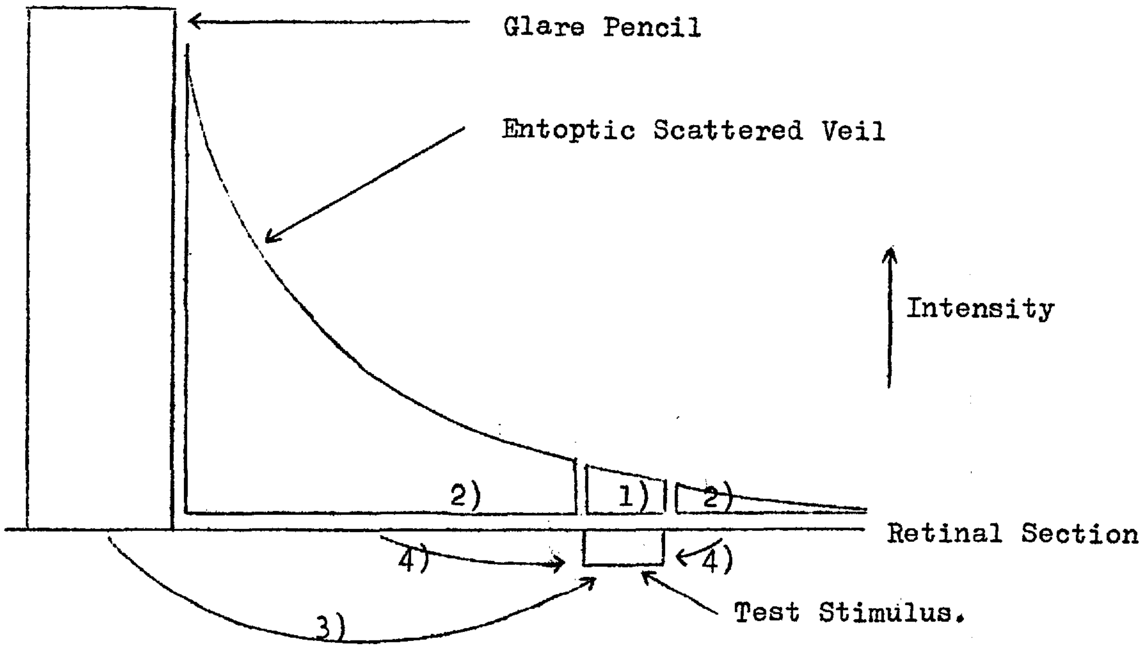
Few workers in the field have dwelt previously at any length on the differences in the glaring effects of lights of high chromatic saturation. Luckiesh, Taylor and Holladay (1925) considered lights whose spectral purity was very low. Le Grand (1937) did valuable work which will be considered in the light of later findings. Ivanoff (1943) found significant differences between the glaring effects of different colours, but his method of comparison makes consideration of his results very difficult. Vos (1963) failed to find any significant differences.

Method.

We wished to derive as much information as possible from our observations and to separate the causes of glare into different mechanisms (see Fig. 19) and accordingly an initial examination of the effects to be observed with glare of various colours was conducted by arranging that in the binocular comparator the right eye could be subjected to different stimuli. These were A, a glare source, B, a uniform background field on which the test patch was superimposed, and C, a uniform surround field to this test patch. The left eye viewed only the test patch in the equivalent system.

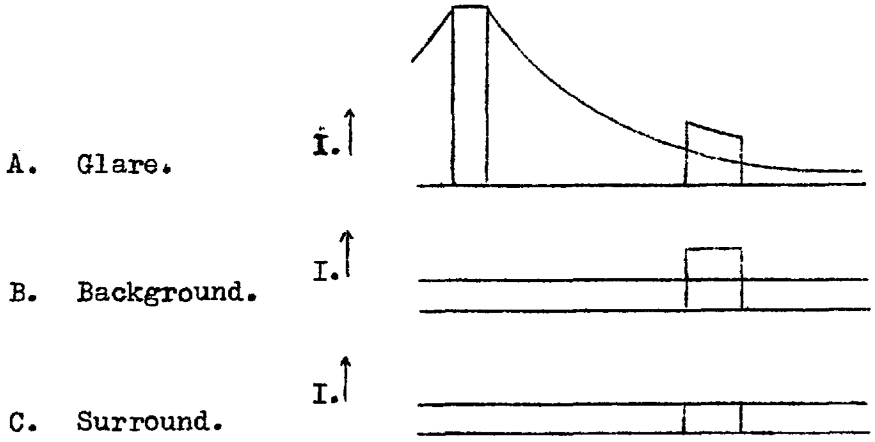
Colour filters, Wratten No. 47B (blue), No. 61 (green) and No. 29 (red), were used for convenient selection of colours. The transmission ranges of these filters do not overlap and each has a sufficiently large band-pass to preserve a reasonable luminance when used with an incandescent lamp (transmission curves are given, see Fig. 22). A rough attempt to equalise the luminances of these

Influences Acting on the Test Patch.



1) Local Adaptation in the region of the test patch caused by coincident part of entoptic veil.
2) Contrast with surround consisting of entoptic veil.
3) Neural Inhibition (Lateral) caused by bright region of impingement of glare pencil.
4) Neural Inhibition (Lateral) from surround.

Three conditions of performance of qualitative experiment.



A. — 1) + 2) + 3) + 4) .
B. — 1) + 2) + 4) .
C. — 2) + 4) .

FIG. 19.

by adding neutral filters in series was made by binocular heterochromatic brightness matching using the same apparatus. Whilst these values were subsequently found to be not far in error (see next section) little or no quantitative conclusion may be drawn with confidence because of the crude equalisation of luminances.

Results.

Comparison of the appearance of the right test patch under conditions of glare, background and surround with that of the left test patch under constant conditions was made and the results tabulated in Fig. 20 (Table 6), with the test patches and conditioning stimuli filtered to the colours tabulated. Prolonged exposures were used.

Extracting important features from Table 6 we find that the test patch luminosity (right eye) is depressed somewhat in the presence of other stimuli, except when the other stimulus is a background of the same colour, when it looks brighter.

Saturation tends to decrease predominantly in A and B , but to increase in C (on average). Colour shifts tend to be in the same direction in A and B, but again different in C (sometimes towards the colour complementary to that change of A and B , but not always). Later changes are not very classifiable but what trend there is goes towards similarity of A and B, to the exclusion of C. Recovery times are only very approximate but are included for completeness.

Discussion.

Fig. 19 illustrates the nature of the situation under discussion and separates the various aspects of the visual stimulation of the eye under test, which may independently affect the perceived change in test stimulus. These influences are tabulated as 1)

TABLE 6

Colour of A,B,C	Colour of Test	A, B, C.	Brightness ↓	Saturation ↓	Colour	Further Change ½-1 min.	Recovery Time (Total).
RED	Red	A	Dimmer		Orange		50
		B	Brighter	Less	Orange		20
		C	Dimmer	Less			12
	Green	A	Dimmer	Less	Orange	Green	27
		B	Dimmer	Less	Orange	Green	20
		C			Violet		10
	Blue	A	Dimmer		Magenta	Blue	55
		B	Dimmer	Less	Magenta	Blue	40
		C	Dimmer	More	Violet		30
GREEN	Red	A	Dimmer		Orange	Red	15
		B	Dimmer	Less	Orange		20
		C	Dimmer	More		Magenta	25
	Blue	A	Dimmer	Less		Magenta	20
		B	Dimmer	Less	Magenta		20
		C	Dimmer	More	Violet		20
BLUE	Red	A	Dimmer	Less	Magenta		20
		B		Less	Magenta		15
		C	Dimmer	More	Red		12
	Green	A	Dimmer	Less	White		40
		B		Less	White		35
		C				Yellow	25
	Blue	A	Brighter	Less	White		70
		B	Brighter	Less	White		35
		C	Dimmer	Less			25

FIG. 20.

to 4). Using the three situations here the difference between the test patch appearances in A and B (defined earlier and Fig. 20) showed the contribution likely to be made by the lateral neural transfer of inhibiting effect (Influence 1)) from the point of action on the retina of the glare spot. Inspection of Table 6 shows the similarity of the qualitative effects of glare and uniform overall background as defined. Nowhere is a fundamental trend different in one (A) from the other (B) and what differences exist are of degree only. In the case of red and blue glare and background the recovery from background is faster than that from glare, but in the case of green glare and background recovery times are comparable. Quantitative estimates, however, are uncertain due to the scant rigour in luminance equalisation used here.

In the case of the surround (C) the observations are very different from both glare and background (compared to A or B), and the resulting data seem mostly explicable by contrast phenomena.

We may discuss our postulated four modes of influence of light on the retina on the appearance of a test patch as illustrated in 1) to 4) in Fig. 19. The similarity of A and B made 3) likely to be a very small, or even non-existent, effect. The difference of C from either A or B shows 1) to be a large contributory factor to the change in appearance of the test patch under these conditions and is in the opposite direction to the algebraic sum of the influences 2) and 4).

These tentative conclusions are discussed further as later more precise data become available; here they serve as qualitative verification of established concepts.

3) Calibration of 'V_λ' Curve.

Since so much depended upon the accurate equality of photopic luminance of the various colours of stimuli it was considered necessary to measure the relative spectral luminosity curve (V_λ) of the author, who acted as observer in most of the experiments. A variety of methods were available for measuring the V_λ curve but it was decided to use two; the flicker method and direct comparison. There is reason to suppose that these will give slightly different results from each other and eventually the direct comparison method results were used exclusively,as this situation most nearly corresponded to the conditions of the glare experiments.

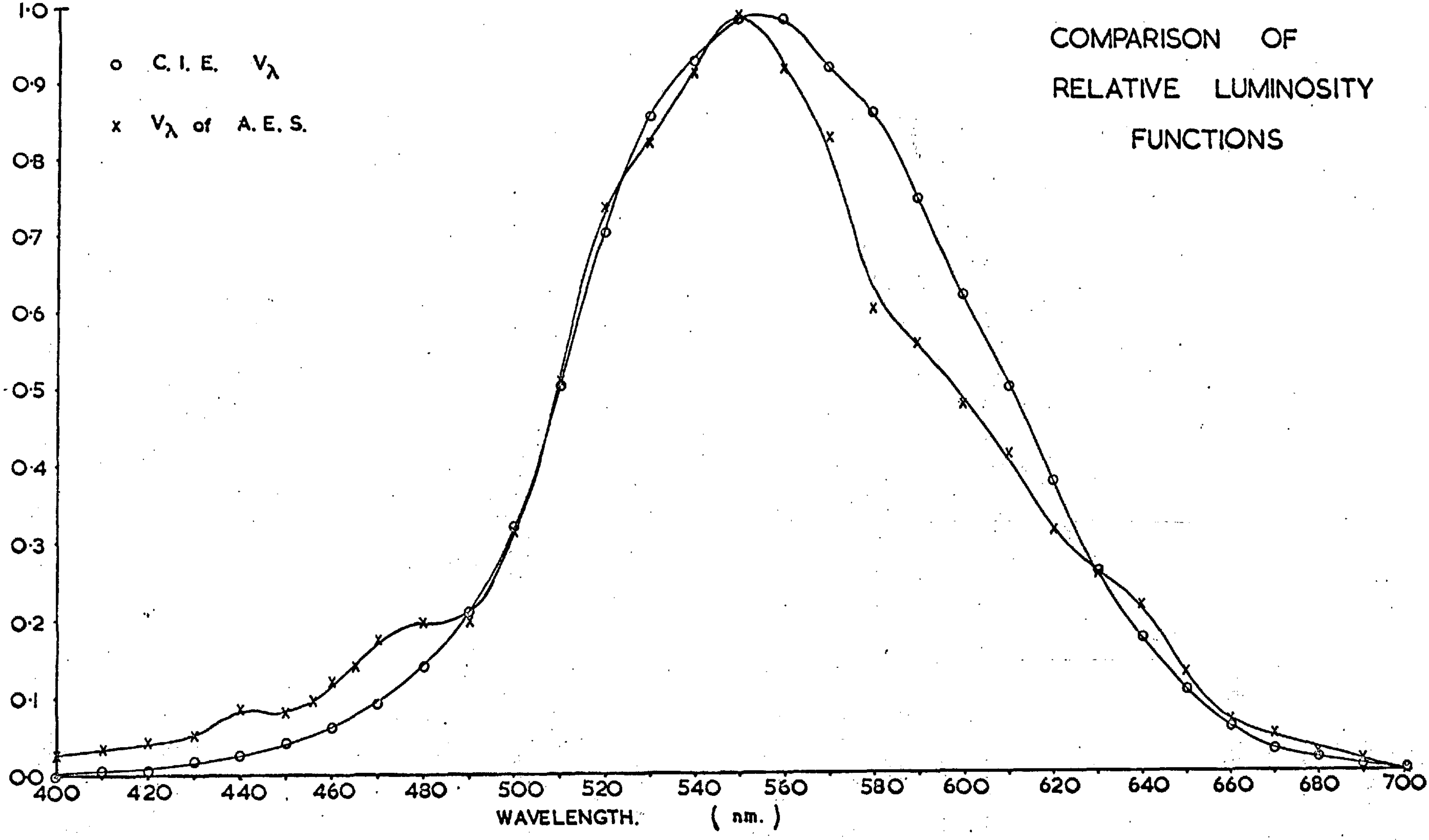
Equipment was the Wright Colorimeter (Wright, 1927-8, 1939, 1946.) but the 108 watt tungsten ribbon filament lamp was replaced by a 650 watt quartz-halogen source run under controlled conditions. This was considered advisable because the blue end of the spectrum was very dim with the former source, and it was of great importance to have the V_λ curve as accurate as possible in the blue. There has always been some suspicion of anomalous effects with high intensity blue light and especially with particular adverse effects in connection with glare.

Since the flicker measurements were not used they are not quoted here, but served as a practice run for the measurements to follow and gave some familiarity with the instrument. For the direct comparison method a 2° square bipartite field (two contiguous rectangles) was used. The 'white' test area was derived from two 'monochromatic' wavelengths (650 nm. and 503.5 nm. mean) modified by suitable neutral filters to approximate to the C.I.E. Standard Illuminant A. The retinal illumination derived from this patch was about 20 photopic Trolands. Whilst this level could be matched over most of the spectrum the extreme blue (450 nm. and shorter) was too dim, even with the new bluer light source. The test stimulus was therefore reduced in this region by a rapidly rotating sector (well in excess of the critical fusion frequency) to a retinal illumination level of about 1 photopic Troland. This sector reduced the intensity uniformly throughout the spectrum, whereas a 'neutral' filter is not truly neutral and would have introduced error by changing the test stimulus colour.

The comparison patch was illuminated 'monochromatically' and its intensity varied by means of a precalibrated neutral wedge. In the centre of the spectrum (green-high luminosity) this patch looked too bright to make a match using the wedge in question, and was accordingly reduced by a neutral filter. Any variation from neutrality was accounted for by measuring the intensity of the comparison stimulus at each wavelength used throughout the spectrum, thus calibrating the instrument plus filter combination at each relevant point. This calibration was executed with an N.P.L. calibrated photocell and a null-reading (balanced bridge) galvanometer system with decade potentiometers.

For each point at 10 nm. wavelength intervals three or four matches were made. Knowing the calibration of the wedge, and that of the instrument 'in toto' it was possible to evaluate the relative luminous efficiency curve (V_λ) of the right eye of the observer. Towards the blue end the two graphs, corresponding to high and low levels of retinal illumination, were taken over a common region and interleaved to give a continuous smooth curve. The experiment was performed three times and the results (normalised at the point of maximum luminous efficiency) were averaged to produce the curve shown in Fig. 21., (the C.I.E. Standard Observer 'V_λ' Curve is shown

FIG. 21.



COMPARISON OF RELATIVE LUMINOSITY FUNCTIONS for comparison (Wyszecki and Stiles, 1967)).

The 'V_λ' curve quoted was obtained at the fovea centralis of the right eye of the observer (all measurements were made monocularly) over the cone region, where rod intrusion is reduced to a minimum. This assured a good approximation to a truly photopic 'V_λ' curve which was required for reasons discussed at greater length later, and because subsequent data for glare behaviour referred primarily to the fovea.

There are significant differences to be noted in these two curves, but this is not surprising considering the different methods of assessment and differences to be commonly observed between persons. That the blue should be very different is not a cause for alarm, but rather a justification of the need to know this curve accurately in these specific circumstances.

4) Equalisation of Luminances.

In order to make valid comparison between different coloured stimuli the equalisation of luminances is an essential. This was achieved with the formula of Chap. II, sect 1,

$$L = Km \int V_\lambda . L_{e\lambda} . t_\lambda . \, d\lambda .$$

in which section was also discussed the inappropriateness of equating luminosity. The $L_{e\lambda}$ (spectral radiance at wavelength λ) was measured for the light source (Chap. III.)(run at a colour temperature of 3,000° K,)by means of a spectrophotometer, the dispersion characteristics of which were known, and an N.P.L. calibrated photocell.

The finite sum approximation to this luminance integral used data,at 10 nm. intervals, on the spectral radiance of the light source, photopic V_λ of the observer and the spectral transmission of each filter (t_λ) (Fig. 22). This calculation, performed on the three Wratten colour filters and also the white and yellow discussed in previous chapters yielded value which could be associated with the overall foveal photopic luminance.

There are approximations in this method in that for these equated luminances to be correct over several orders of magnitude of stimulation level, heterochromatic additivity is assumed. It is not therefore valid to say that if the colours have the same luminance at one illumination level then this will be true at all levels, since additivity is know to break down at glare levels.

The equalisation of stimulus luminance at the fovea using a particular illumination level is permissible and satisfactory only if all subsequent measurements are made using the fovea and only the fovea, near that illumination level. If it is necessary to assess the relative effects of influences acting at the fovea, but derived from stimulation of other regions (lateral inhibition) then the stimuli should be equated at the region from which these effects are supposed to act. If, however, these relative effects are considered to be due to light falling on the fovea alone (Straylight Hypothesis) then the former equalisation is valid. Ergo, there is a danger of anticipating the result by the method of approach. This appears to be the principle objection to recent work by Reading (1968), which we may now consider. She equated white and yellow stimuli for luminance using Wright and Walters (1946) 10° data. This did not rely explicitly on the photopic, or cone response, curve, but included an unknown and possibly large amount of rod intrusion. Hence she was equating the receptoral response where the glare source was presented, some way off the fovea, and was therefore innately assuming that effects 3) and 4) were greatly in excess of 1) and 2) (Defined Fig. 19).

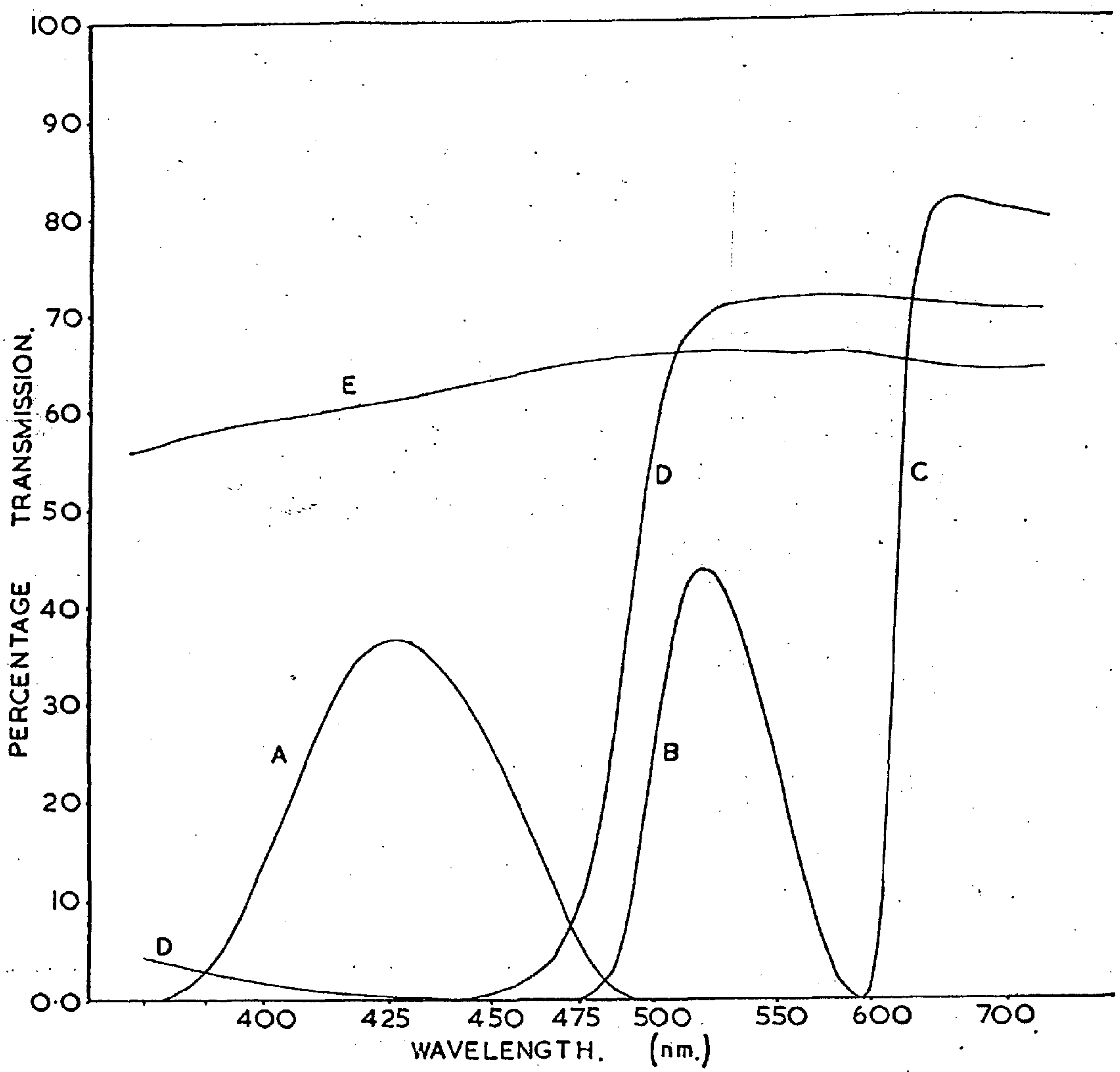
The present author is of the opinion that this is unlikely. If there were no scattered straylight component her argument would be valid, but as it is widely accepted that there is significant scattered light, her argument becomes suspect. Thus, two stimuli, one yellow and one white, could be equated using either 10° (mixed V_{λ} & V'_{λ} functions) or pure photopic (V_{λ}). If the former were used it would result in the two stimuli having equal luminance at 10° from the fovea, but at the fovea the white would be dimmer than the yellow. Thus, if it is the light scattered from the glare source over the foveal test field which is the significant factor the use of 10° luminosity functions should yield a lower threshold of luminance difference for white than yellow — exactly her reported conclusion (qualitatively) ; and this is assuming that white and yellow give rise to equal percentages of entoptic scatter from the incident beam. If white had scattered more than yellow this would have tended to minimise the observed effect, and if large enough difference had been present the observation could have been reversed, hence her results must of necessity be inconclusive.

From the above it would appear unjustified to say that white and yellow controlled in this way have been 'equated for luminance'. At glare levels a difference such as was of relevant magnitude would have been visually indetectable, and if extrapolated from comparison at lower luminance levels the assumption of independence of colour perception and illumination was involved.

In this work it has been possible to draw on the experience of others and equate foveal photopic luminance, with the following justification ;— We have assumed that straylight plays a large part in producing the equivalent veil and that 1) and 2) are large compared with 3) and to a lesser extent 4) (Fig. 19.). In the light of past work this seems a more satisfactory assumption than that of neural lateral inhibition being the sole agent in glare.

Since all measurements were made using the fovea for observation, we required that the glare stimuli should be equated in such a way as to give the same magnitude of effect at the fovea regardless of colour if, and only if, the parameters of the visual system, which are effective in glare, had been colour independent. That is to say, that with this method of equalisation any differences were due to reaction of the visual system to different colours only, the luminance effect having been entirely eliminated.

The implied extrapolation to glare levels was unnecessary since it was the luminance level of the equivalent veil that set the order of illumination for which equality was desired.



A – No. 47B BLUE.

B – No. 61 GREEN.

C – No. 29 RED.

D – 'CAMIUM SULPHIDE' YELLOW.

E – NEUTRAL.

TRANSMISSION CHARACTERISTICS.

FIG. 22.

5) Recovery during, and after, Chromatic Glare

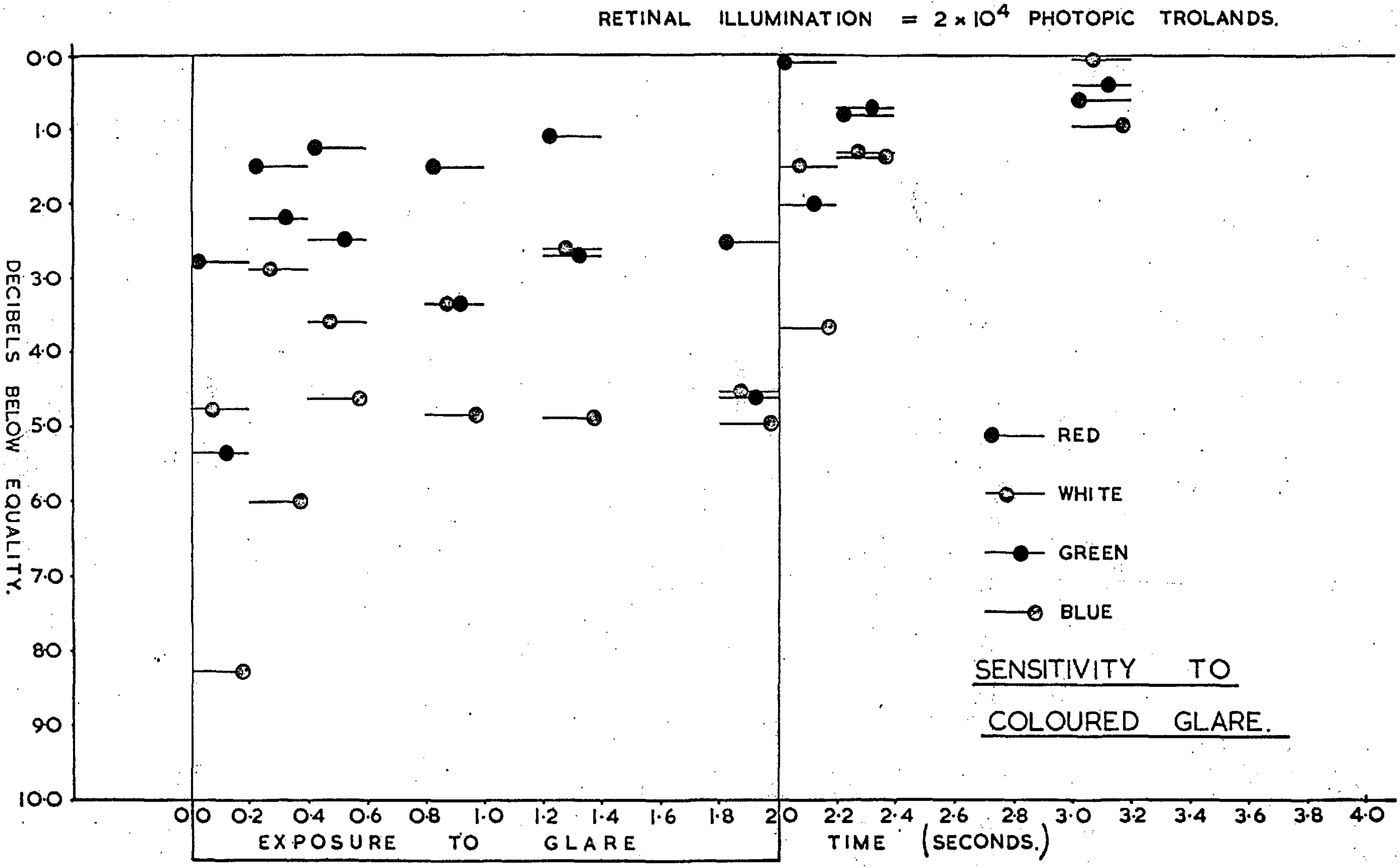
From the preceding section, a workable equalisation of the photopic luminances at the fovea of different coloured stimuli was derived, thus enabling the author to repeat earlier curves for lights of various colours, and observe the nature of the recovery characteristics.

The experiment detailed in section 1) of this chapter was repeated with some differences in technique. The sampling time was taken down to 1/5 second to increase the temporal resolution. In order to minimise the otherwise lengthy experimentation time, the glare duration was reduced to 2 seconds.

Initially a fairly low level of glare was used (2×10^4 photopic trolands) with the test patches at a level of 10 photopic trolands, and controlled by colour and neutral density filters to the same criterion of equal foveal luminance, independent of colour. The resultant sensitivity/time curves are shown in Fig. 23 for the four different chromatic compositions, white, red, green and blue. It will be immediately noted that the sensitivity depression caused by blue is significantly in excess of that caused by red, with green and white lying between these two extremes. The overall depressions are relatively small (red 1.5 db. blue 5 db.) and a certain amount of error is to be expected, causing scatter about a mean curve.

To verify that similar behaviour was to be found at higher glare levels, the glare source retinal illumination was raised to 2×10^7 photopic trolands. Curves in Fig. 24 show the course of sensitivity followed under these much more severe conditions. These curves do not include blue, because it was impossible to get to the required intensity using the light source as defined earlier.

FIG. 23.

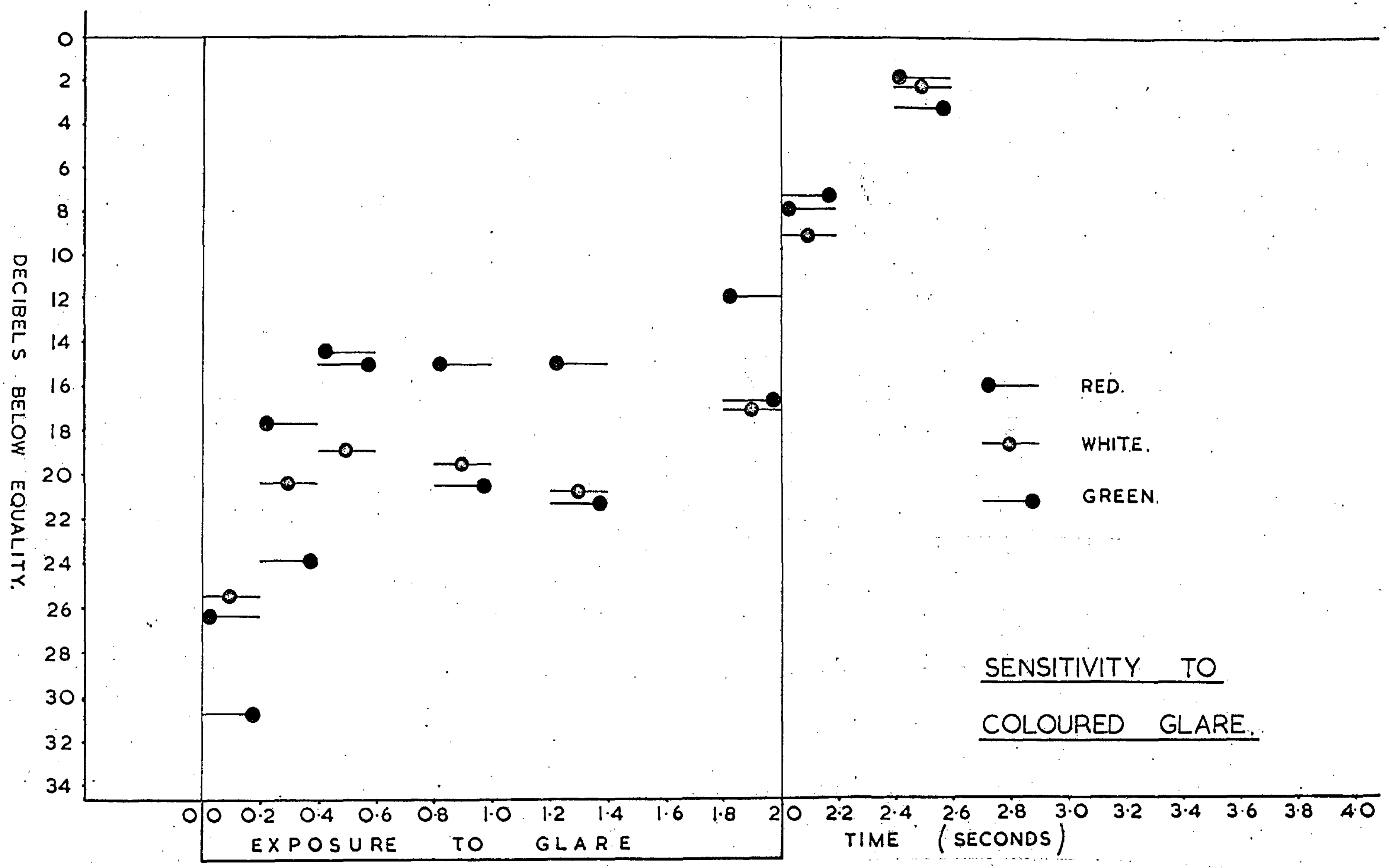


RETINAL ILLUMINATION = 2×10^4 PHOTOPIC TROLANDS.

SENSITIVITY TO COLOURED GLARE.

FIG. 24.

RETINAL ILLUMINATION = 2×10^7 PHOTOPIC TROLANDS.



SENSITIVITY TO COLOURED GLARE.

(That is without raising the running voltage, hence the colour temperature, and invalidating the stated equalisation of stimuli.)

It appears that the form of these recovery curves is very much the same, both during and, to a lesser extent, after removal of glare for all colours. (There is the odd spurious point, vis. Fig. 23, red recovery after termination of glare, but the error necessary to produce this is not large considering the generally small lowering of sensitivity that takes place — the effect is not to be found in Fig. 24.) There is a consistent displacement of the curves towards increase of the lowering of sensitivity as the predominant wavelength is shortened, illustrating, at least in this arrangement, that the blue glare has more effect on the perceived brightness of a stimulus than does red glare of the same luminance.

Finally it should be noted that although the parafoveal rods would be saturated at these glare levels,the reduced macula pigment in the parafovea would produce a higher relative blue cone response than at the fovea. The consequences of this are to be discussed more fully in the next chapter.

CHAPTER V

Chromatic Glare.

1) Qualitative Simultaneous Comparison of Different Glare Haloes.

Introduction

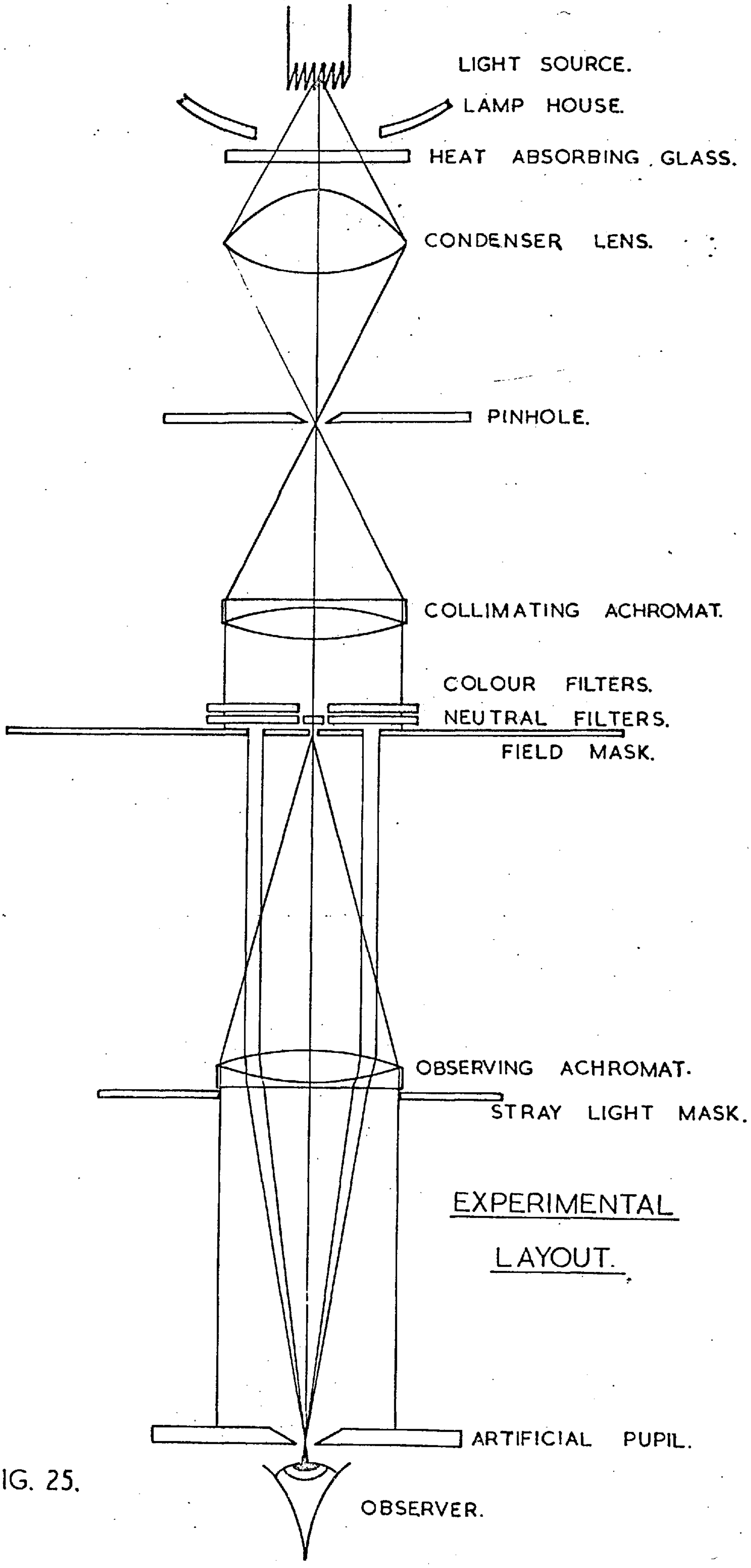
Certain consistent differences between glare of different colours were noticed when these were used in the experiments of the previous chapter. In order to verify these apparent differences, it was thought necessary to construct a simple system to compare the various colours simultaneously.

Experimental.

Fig. 25 shows a sketch of the layout. A 2 mm. artificial pupil was used and the coloured glare spots were seen at infinity in Maxwellian view.

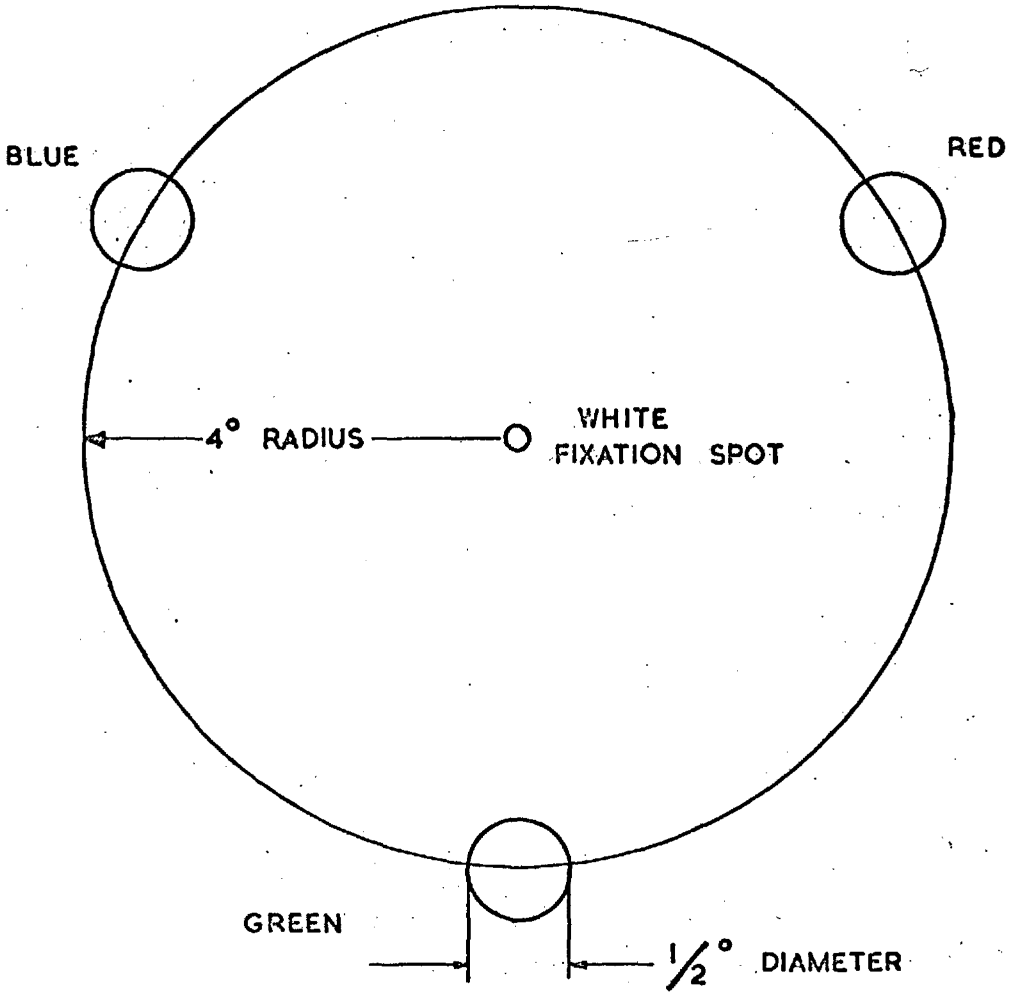
The lamp which provided glare for the previous binocular experiments was used in the same running conditions, and equality of luminance between the three sources was established in the same way as before. A very small white fixation point was presented in the centre of the array of lights (Fig. 26) which were symmetrically disposed around a 4^{o} radius circle, each seen as a featureless disc subtending an angle of $1/2^{o}$ at the eye.

The observer's head was fixed by means of a dental bite. It might be thought that this was not essential, but in fact the comparative observation relied on perfect centration of the observer's pupil and artificial pupil to preserve the exact equivalence of the three colours displayed. This centration was ensured by making symmetric the chromatic fields derived by replacing the glare filters with purple filters and also by centralising the iris shadow seen in white light (method of pupil centration used by Vos (1963)).



EXPERIMENTAL LAYOUT.

FIG. 25.



VISUAL FIELD.

FIG. 26.

The display was observed at several levels of illumination by many observers, who agreed substantially on what was to be seen. A Holophane Lumeter and standard diffusing surface were used to assess light levels.

Observation.

Since the glare spots were seen some 4° from the fovea, the equality of photopic luminance was no longer exact because rod intrusion made the blue glare spot give rise to a higher retinal illumination than the red. The green suffered in a similar way to the blue, but to a lesser extent. This had a barely noticeable effect on luminosity differences at high illumination levels, but had a considerable effect at lower levels (levels where the spots would no longer be properly considered as glare).

The observation was simply to look at the display and record the field as seen (rather than as it would appear in a photograph).

Results.

At low glare levels misty smudges of light are seen to spill out from the glare spots, but the removal of one or more of these spots does not significantly affect the appearance of the other/s until the level of each spot is some 5×10^{2} photopic trolands. At this level the removal of the green enhances the blue and red haloes slightly. The term 'halo' is used to refer to the bright 'flare' or 'halation' which appears to surround a bright glare source, even though it is not seen as a discrete bright ring.

At a level of 5×10^{3} photopic trolands the effects later described begin to occur, but are in no way, except degree, significantly different. When the glare level used gives rise to a retinal illumination of 5×10^4 photopic trolands from each glare spot, the following effects are to be observed. (Rough estimates of angular extent can be judged knowing that the separation between glare spot and fixation point is 4°.)

With steady fixation the appearance of the haloes from blue and red were larger than that for green. There was, however, an important difference between blue and red haloes, in that the former exhibited a gradual falling off from $1/4^\circ$ or so to about 3° out from the edge of the glare spot. The red halo, while of similar luminosity and overall extent, seemed to be brighter near the glare source ($1/2^\circ$ to 1° from the edge of the glare spot), and thereafter to fall off in luminosity more rapidly. The green halo was of smaller extent (1.5° radius) and perhaps somewhat less bright.

When one of the glare spots was removed the change in appearance of the rest was of note. If the blue was removed, then the apparent brightness of red and especially green increased very much. The change in green was particularly dramatic, as it became as large in extent as the red, which changed only slightly in dimension. The green halo showed the diffuse and gradual reduction of intensity formerly characteristic of the blue. Removal of green enhanced the luminosity of the blue and red, but did not otherwise change the characteristics. Removal of red glare did very little to alter the blue or green, the latter being very slightly enhanced.

It will be noted that for the extrafoveal region the luminance of the haloes will partially depend on the scotopic V_λ'. Particularly, the red halo would tend to go below the rod threshold at a higher intensity than the corresponding blue. To check that this was not causing the effects noted, fixation was moved to various parts of the visual field (excluding the glare sources, of course) with no substantial modification of the observed phenomena.

Discussion.

The above, rather qualitative, results require that the mechanisms involved in glare depend on the chromaticity of the glare source. One postulate is that the various entoptic media scatter different colours to different extents. Expanding this hypothesis we assume that the pre-retinal elements scatter mainly blue and some green light (Rayleigh type scatter, or perhaps even stronger wavelength dependence) and that the retina scatters all wavelengths to some extent. The retina, however, together with its pigment epithelium anti-halation backing and choroid supported by whitish sclera, contains much blood, and more particularly haemoglobin, whose absorption bands are in the blue and green spectral regions. Light which impinges on receptors outside the optical image, having been scattered within the retina, will be red rich, since some of its blue and green components will have been absorbed by haemoglobin.

Support for this is offered by the fact that the ophthalmoscopic fundus image, for all races, especially Caucasoid, is reddish orange.

Iris Shadow.

The first aspect of this hypothesis was tested using the projection of iris shadow technique. White light entering the eye as a narrow pencil scatters at various places within the pre-retinal elements (slit lamp observation) and that which scatters in the cornea acts as a point source at that place which casts a shadow of the iris on the retina. (It was only possible, by this method, to attempt a verification of our hypothesis for the action of the cornea.) This method has been used previously as a method of pupil centration, where the luminance step appears many degrees off axis where,acuity is low (Vos, 1963).

Better quality of observation of this phenomenon was obtained by reducing the size of the artificial pupil (defining the light pencil) to 0.8 mm. and viewing the system obliquely in such a way that the iris shadow is permitted to fall across the fovea. The pupil size variations (natural pupil) were a source of frustration but with care the observation was quite possible without miotics (Boynton and Clarke, 1954).

The pencil producing the iris shadow was made blue, green and red in turn. The limb of the shadow had a rather curious appearance; neither a blurred edge nor a sharp continuous luminance step, but rather it appeared as a series of short overlapping arcs, each with a fairly sharp luminance step but together covering a region about $\frac{1}{2}^{\circ}$ wide at the shadow's edge.

The shadow was clearly visible in blue light, the region within the shadow being quite brightly illuminated by corneal scattered light. There was little sensation of blueness from this scattered light. This shadow was less clearly marked in green light, but still quite obviously a luminance step caused by scattering. With red stimulation there was no suggestion of an iris shadow.

This was taken to imply that very little red light is scattered at the cornea.

This set of qualitatively based observations was subsequently repeated by several tens of subjects, many of whom had been trained in this type of observation, with the same results outlined above.

Some few percent. of persons found the iris shadow indetectable even when the ambient lighting was raised briefly causing an iridial spasm, which moved the shadow's limb, thus drawing the attention to it; but most observers experienced no difficulty and produced, without any prompting, the observations which amplified our data. This extra wealth of observational information further justified the acceptance of the material from which our inferences had been made.

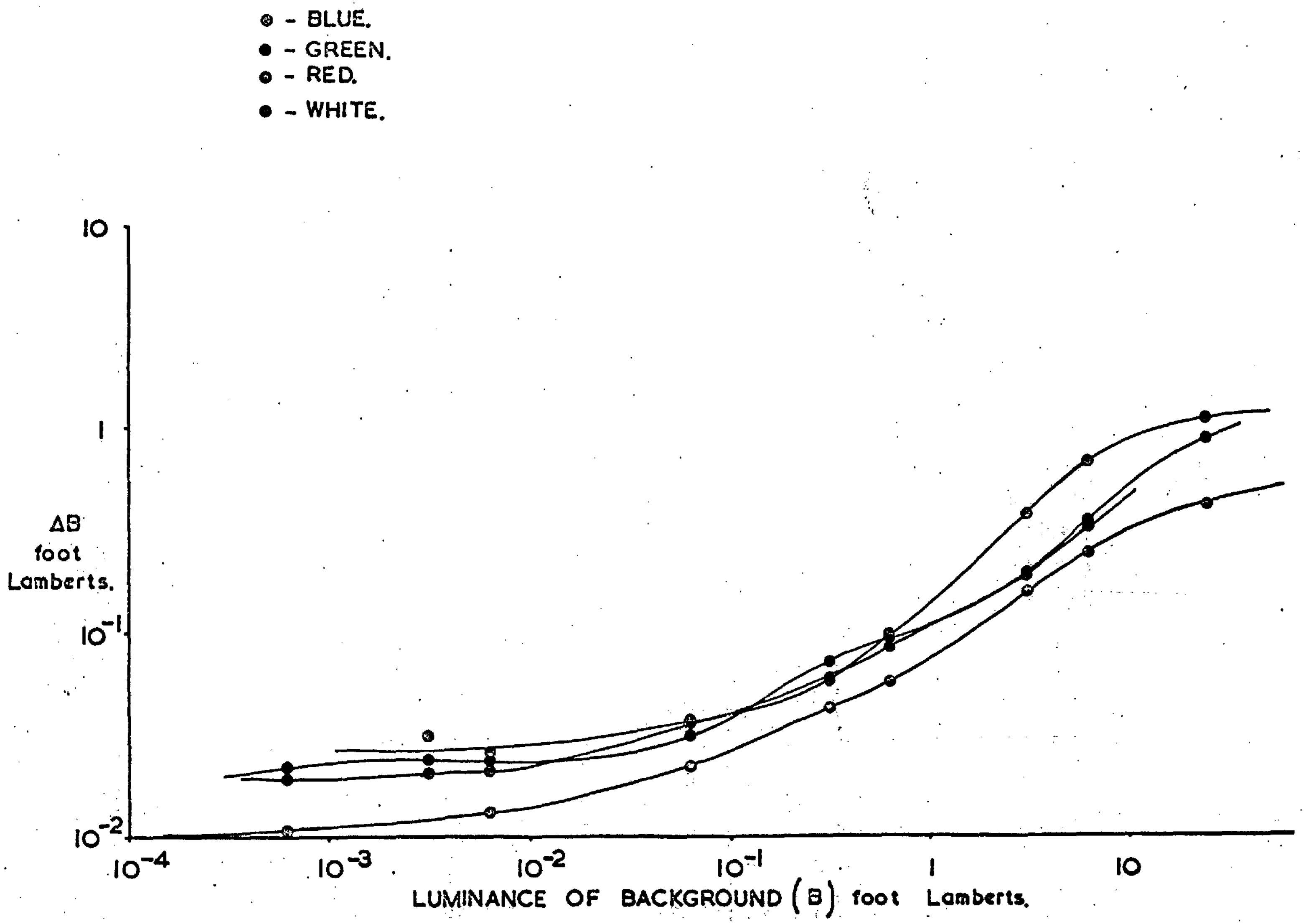
2) Calibration of Fechner-fraction.

The hypothesis of the last section, whilst not contradicted by experimental data can hardly be considered justified on the basis of the rather flimsy corroboration offered so far. More unambiguous information was required and it was thought that measurement of luminance distribution in the haloes would yield valuable information about the functional dependance on angle of the equivalent veiling luminance obtained from each colour. The Stiles-Holladay Formula (Holladay, 1927, Stiles, 1936, et.al.) has been taken to describe the change in equivalent veiling luminance with angular distance from the glare source for white light, and a summary of past results of this measurement is to be found in the Thesis of Vos(1964) and later here (Fig. 30).

To obtain similar measurements for different colours it was decided to use a threshold method whereby a small test spot was presented at a certain variable angular distance from the glare source and the luminance of that spot varied until it was only just visible against the equivalent veil, (produced either as real scattered light or as the neural suppression of sensitivity). We were not yet justified in taking the neural component to be zero, even though it has been shown earlier that the neural inhibition derived from a retinal glare spot itself is probably small (Chap IV, section 2). In order to associate these measurements of threshold with real equivalent veiling luminance in objective units it was necessary to measure the Fechner-fraction ($\Delta B/B$) for threshold luminance increment at all the luminance values and colours likely to be encountered (ΔB was the excess luminance needed for liminal perception above a uniform background field of luminance B).

The basic equipment was that of Fig. 12 and monocular (right

FIG. 27.



FECHNER-FRACTION CALIBRATION.

eye) observation was used. The infinitely variable stimulus (formerly presented to the left eye) was moved over by means of two penta-prisms to be coincident with the right system which it blocked off. In the case of measurement of Fechner-fraction the half-mirror was replaced by a very thin cover slip acting as a semi-reflector to provide a uniform background field from the glare system, (suitably reduced in intensity). The former test patch mask was replaced by a moveable mask containing a small circular hole (subtending 20' arc at the eye). This provided a small test region seen against a background some 6° across.

The luminance of the background field was calibrated at a high level using the Holophane Lumeter technique described earlier and reduced by calibrated neutral filters to suitable values. The test spot luminance was assessed similarly and both the background field and test spot were filtered with colour filters compensated for equivalent photopic luminance. The Fechner-fraction was measured for red, green, blue and white between background luminances of 10^{-4} and 10^{2} foot Lamberts. The results appeared as shown in Fig. 27, where ΔB is graphed against B since the value of B was required when ΔB was known, for the experiment to measure equivalent veiling luminance. To obtain the required accuracy from Fig. 27 the original results were graphed on 6 x 3 cycle log.-log. graph paper of large size.

Information derived from the Fechner-fractions made it possible to associate each luminance threshold increment with a specific background luminance and hence an equivalent veiling luminance.

3) Equivalent Veiling Luminance from Chromatic Glare.

The equipment was further modified to replace the original mirror and calibrate the position of the mask which defined the position of the test spot. The mask could be adjusted very accurately and its position read off a pointer and ivory scale. This was calibrated so that the angular separation of the centres of the glare and test spots was known. The glare spot subtended 40' arc at the eye and the test spot 20' arc. The threshold observations were made with fixation on the place where the test spot was last seen or would appear. This gave very consistent results. (When the technique of forced choice was used and the test spot flashed the results were very erratic! — possibly the psychological influence of the glare was itself sufficient to disturb the observer's ability in the latter situation?)

The measurements were made by the same steady state (continuous exposure) technique in both this and the Fechner-fraction determination and the observer varied the luminance of the test spot in both cases. Readings of luminance difference threshold were taken, at least ten values for each point, in two batches of five at different times. If these showed a substantial discrepancy then the series was rejected and repeated in full on another occasion. The readings were taken over a period of days and in random order, with extreme care being taken to ensure constancy of stimuli from one time to the next.

The equality of foveal photopic luminance of the chromatically different test and glare stimuli (both the same colour) was assured in this experiment as before and measurements were made with the angular separation of the test and glare spot centres between 50' arc and 3^{o} arc for red, green and white and as far as 6^{o} arc for blue.

This threshold method became difficult and liable to wide variations outside this region as the luminance of the veil had fallen to a very low level, and the apparatus became less appropriate. The photopic luminance of the glare spot was again 5×10^4 photopic trolands and only one observer was used (the author, since it was he for whom the luminance equivalence was valid).

The values of threshold were used to find the equivalent veiling luminance from the pre-calibrated Fechner-fraction graph. (Fig. 27). Fig. 28 shows the values of the equivalent veiling luminance (in $\log_{10}$ foot Lamberts) as functions of angle ($\log_{10}$) for the four stimuli, red, green, blue and white. It will be seen that the measured values of light in the equivalent veil for blue are higher than those for other colours, also the tendency to diminish with increasing angle is less marked than that for red. Applying the principle of the Stiles-Holladay formula an attempt was made to fit the curves to

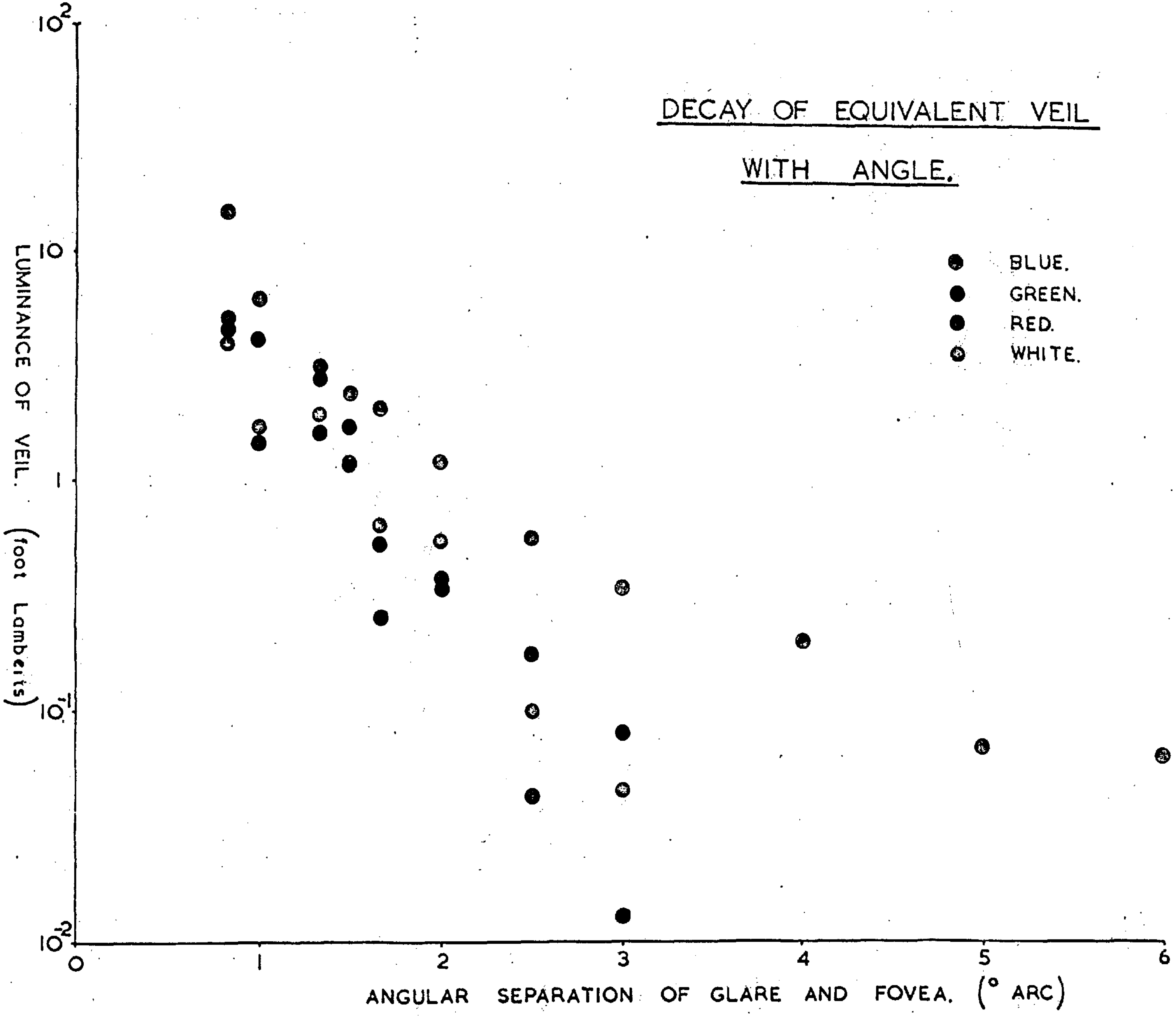
$$B = \frac{k\,E}{\theta^n}$$

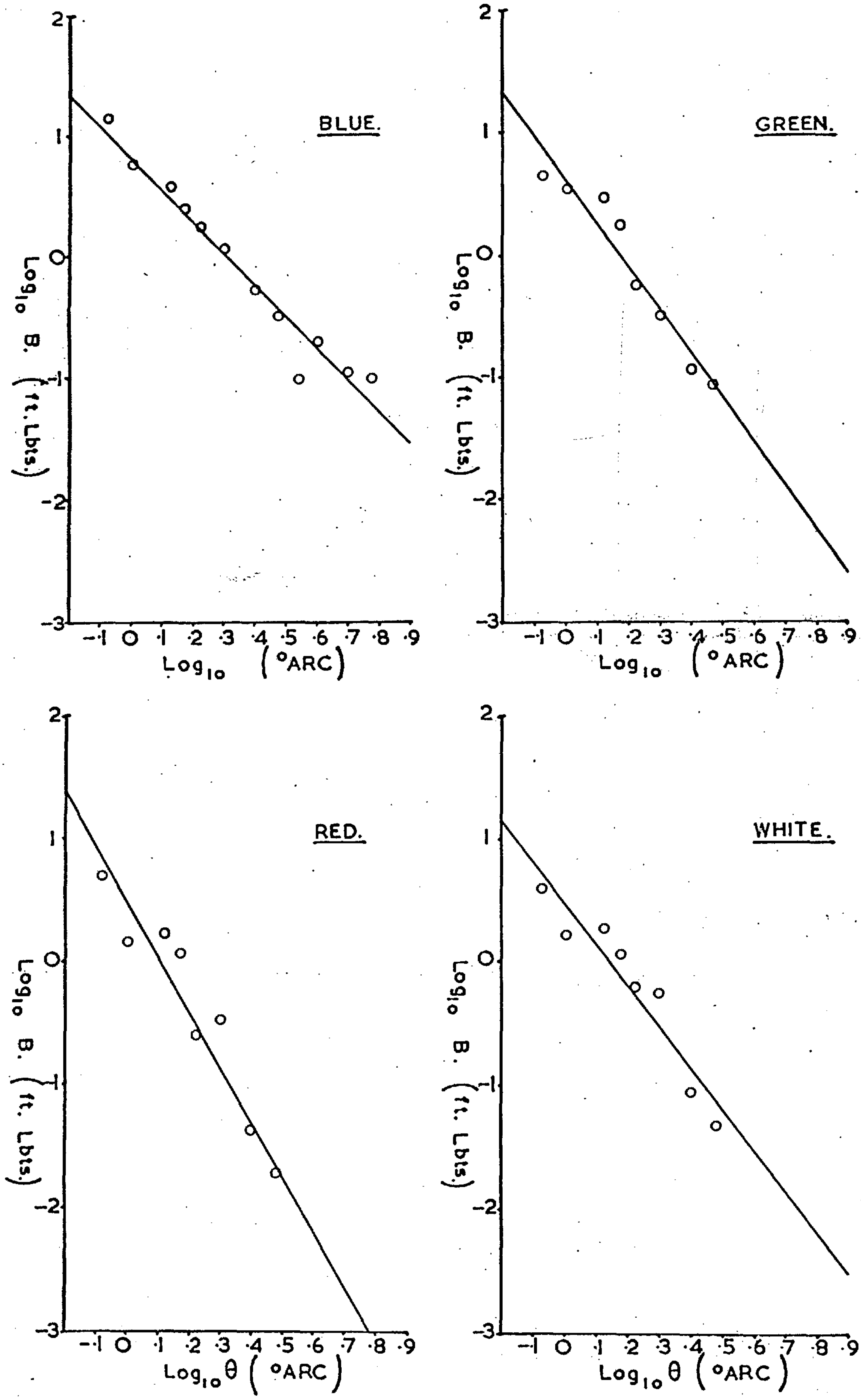
where B is the equivalent veiling luminance and E the illumination produced by the glare source at the plane of the pupil (suitable units).

This was effected by feeding the value of B and θ in a logarithmic form into a computor which fitted a general m^{th} order polynomial with minimised root mean square differences for each colour (set of values). There was no significant improvement in curve fit to be obtained above $m = 1$, and since this gave an acceptable fit (Fig. 29) for all the curves the polynomial which corresponded to

$$\log_{10} B = \log_{10} kE - mn\log_{10} \theta$$

FIG. 28.


DECAY OF EQUIVALENT VEIL WITH ANGLE.
● BLUE.
● GREEN.
● RED.
● WHITE.
LUMINANCE OF VEIL. (foot Lamberts)
10^2
10
1
10^{-1}
10^{-2}
0
1
2
3
4
5
6
ANGULAR SEPARATION OF GLARE AND FOVEA. (° ARC)



APPLICATION OF STILES-HOLLADAY FORMULA.

FIG. 29.

was chosen, where m = 1.

This accords well with the Stiles-Holladay formula and gives fairly reasonable values for k and n for each colour of glare. The reduced formulae constants k and n are shown in Table 7 (Fig. 30) which also illustrates the values obtained by some earlier workers. The results quoted refer to many different methods of assessment of the equivalent veiling luminance and it is likely that the value of k depended to some extent on the method of measurement and the criteria adopted. Most were threshold measurements with various display configurations and times. The experiments of Stiles (1929) corresponded to a continuously displayed test patch whose limen was just detectable against the equivalent veil from a glare source and this was rather closely similar to the method used here. Discrepancies in k are not large but there is a large difference in angular dependence. This latter can be plausibly explained by postulating that at quite small angles the exponent of θ should be larger. This trend was shown in the results of Fry and Alpern (1953 b) and Vos (1963) both of whom worked at somewhat smaller angles. The results of Le Grand (1937) also confirm this trend, but in a slightly modified form as his formula (based on work of high accuracy) allowed for more elaborate variation with θ, but in the past has been occasionally misquoted.

The table published by Vos (1963) summarising earlier work was discovered to contain at least two errors, in the values of k for Le Grand and Fry & Alpern. Working from values appearing in graphs also published by Vos the present author arrived at a figure for k some order of magnitude lower than Vos' stated value, and thus more in accord with that of earlier workers and with the present estimation.

TABLE 7.

Postulated Formula

$$B = \frac{k\,E}{\theta^{n}}$$

where B is equivalent veiling luminance ($cd./m^2$).

E is illumination at plane of pupil (lux).

θ is angular separation of glare source and test patch (° arc).

k & n are constants.

Value obtained by various workers (in standardised unit, as above);—

Investigator.		Date.	θ values.	E values.	n.	k.
Holladay		1926	2.5 - 25	1	2.0	9.3
Stiles		1929	1 - 10	0.5	1.5	4.16
Stiles & Dunbar		1935			2.0	10
Stiles & Crawford		1937	1 - 102	6×10^{-3} & 0.2	2.1	11.5
Le Grand		1937	1 - 30	0.1 - 10	see footnote	
Fry & Alpern		1953	0.75 - 4.5	$5\times10^{-2}-10^{3}$	2.5	7.2
Vos		1963	1 - 8	10^{-1}	2.8	29 @
Smart	(Blue)	1968	1 - 6	5	2.6	4.45
	(Green)		1 - 3	5	3.5	2.6
	(Red)		1 - 3	5	4.4	2.0
	(White)		1 - 3	5	3.4	2.0

@ There is reason to suppose from published graphs that this may be a miscalculation and should be about a factor of 10 lower.

footnote: Whilst Le Grand found colour differences he did not publish in this form. For White he postulated the formula

$$B = k\,E\,(\,13\,\theta^{-3} + 1.1\,\theta^{-1.5} + 0.0002\cos^{4}\theta\,)$$

Fig. 30.

Discussion.

The separation of the components of glare into different colours showing different dependence on angle would seem to verify our tentative hypothesis that different entoptic structures are responsible for scattering different predominant wavelengths.

We can construct an argument against the above conclusion thus;-

In the parafovea the optical density of macularpigment is reduced and the cone population is diluted with rods. We may temporarily assume that the retinal neural inhibition is the dominant factor.

Rods, whilst highly and predominantly sensitive to blue and blue-green wavelengths, would be saturated at glare levels (producing an almost constant response) and in order that the rod contribution should account for the colour dependence of the apparent veil, these rods must be exercising their role very strongly and producing a large signal (neural), and further this must act upon the foveal cones to produce a severe inhibiting reaction. The rod response would be greater for scotopic blue than red but it has been impossible to find any evidence that parafoveal rods should strongly inhibit foveal cones. However the parafoveal cones should yield a larger response than the foveal cones in the blue because of the action of macular pigment. This could possible give rise to the effects found in our curves, but is not likely because even if the macula were completely absent in the parafovea the resultant blue response increase could not be more than 0.2 to 0.3 log. units. Even if this change were completely transferred across the retina as inhibition it would still be too small to account for the observed effects, and even this neural transfer is unlikely when one considers that the summation areas (dependant on lateral information transfer and assumed to have something to do with lateral inhibition) are far too small to be relevant over such angular distances as these. (Brindley, 1954).

If however scatter is the primary cause, neither macular pigment nor rod population changes away from the fovea will cause any change in the foveal perception of scattered light. The macular pigment (the location of which is not exactly known) may affect the response if scatter takes place within the retina and/or macula, and would tend to increase red response close to the glare source (if it were close enough to the fovea to allow significance to the macular contribution).

Considering the preceding argument it seems only to be tenable if inhibition is proven to be a very large factor in glare. Evidence to the contrary is offered in the second part of Chap. VI (if we may be forgiven for anticipation) and on the basis of this the glare mechanism reverts primarily to a scatter phenomenon and as such is strongly wavelength dependent.

Now classical Rayleigh scattering offers too weak a wavelength dependence; vis. The filters used had dominant wavelengths (averaged over the spectral envelope with allowance made for weighting factors based on lamp energy spectrum and observer V_λ) of 645 nm., 540 nm. and 455 nm. . For $1/\lambda^4$ scattering this could introduce only a factor of 4 between blue and red, and should not depend strongly on angle, for small angles, if this were the only effect. The observed difference goes from a factor of 2 (in favour of blue) at 1° centre separation to one of 14 at 3° ; if this trend were continued would probably be very much greater at larger angles.

It therefore seems that Rayleigh type scattering is an insufficient explanation of entoptic scatter, but that chromatic dependence must be much higher than this at small angles (at least). The red scatter differs not only in magnitude but in functional dependence and from its more rapid decay with angle it is not unreasonable to suggest that it arises near, or even within, the retina.

The results do not offer any evidence to violate the hypothesis that various entoptic regions scatter light predominantly according to its wavelength, the pre-retinal structures tending to scatter shorter wavelengths to a degree which is more wavelength dependent than classical Rayleigh type behaviour would allow.

4) Application to Practical Lighting.

The application of these results to the work of De Boer (1959) and Jainski (1962 a,b) is of interest in the less academic sphere of lighting research in the night driving situation. It is easy to suppose that the predominance of the deleterious effects of blue glare over that of other wavelengths would make yellow filtered light a great deal better for avoidance of glare in the night driving circumstance. However, the luminance of lights used by the above workers has not been discussed at any great length and little information was given as to the definition of the physical parameters, particularly spectral distribution and integrated luminance of the various light sources. There is evidence that discharge lamps (particularly, low pressure) are a rather special case in that being primarily monochromatic the visual parameters are different, and should be investigated with the use of a monochromatic glare source. This was impossible to acheive with our apparatus, without reconsidering our foveal photopic luminances. The chief difficulty is obtaining discharge lamps with high standard contant output without elaborate electrical stabilisation which would have to be tailored to suit the required supply of each such lamp type. The data obtained about different colours from our experiments could be applied to such sources but only with carefully considered reservations.

That De Boer should have found shorter recovery time for yellow than for white is a source of some concern since it was not verified by the present author. Reading (1966,1968) is also in disagreement. It is thought, however, that the reason for this lies with the equalisation of luminance and angular parameters that were used.

It seemed likely that, in the light of the present experiments, the relative efficacy of coloured light for producing glare was dependent upon the glare angle. Since it is theoretically impossible to equate luminance at more than one angular distance from the fovea centralis (simultaneously)(because of rod/cone population changes) the terminology seems to be inadequate to define the necessary conditions from which the stated conclusions may be drawn. De Boer may have assessed the luminance of fields in such a way as to allow possible variations which were unsuspected and unmeasured.

It seems that from the practical point of view there is little with which to argue in the works of either De Boer or Jainski — but, again, in the practical situation the simulated environment (controlled only within the specification of the problem (driving at night)) is inadequately specified to ascertain the vagiaries of the immensely complicated retinal behaviour.

It has been shown that behaviour under glare varies with

1) Luminance of Glare Source,
2) Chromaticity of Glare Source,
3) Position and Extent of Glare Source, and
4) Adaptation State.

What is more relevant is that these vary strongly and non-linearly with each other. The relative spectral luminosity function depends on the position of the stimulus on the retina and the adaptation level (from whatever cause) obtaining. The variations to be observed between people are also large and specified only in their broadest outlines. (Weale, 1963. Ruddock, 1964. Reading, 1966,1968.)

For the driving situation we may assume that the system performance which we wish to optimise has certain constraints. That is, the position and extent of a glare source are liable to vary within very wide limits so any advantage to be gained must not depend on either of these explicitly. The luminance has to be high (in the case of motor vehicle headlamps) and again must not appear explicitly in the relevant optimisation of reduction of the disability from glare. Overall adaptation can only be changed by raising the ambient illumination level, a desirable but economically non-viable proposition. We are left with the possibility of selecting a preferred chromaticity which offers the hope of improvement, but this hope is snatched away by the change in retinal behaviour caused by change in luminance, position or extent serving to modify the advantage to be gained from specifying wavelength distribution in a complicated way (even depending on that distribution).

It is meaningless to say that 'all other things being equal' then blue light gives rise to more glare at angles in excess of 1° or so than red or other wavelengths, because the very nature of the visual system precludes 'all other things being equal' .

The best approximation is to note certain basic trends and design accordingly. That is to say, for example, that very blue rich lighting (e.g. high pressure Hg.) (whilst undoubtedly good for seeing things, and giving a psychological impression of luminance in excess of its true value) is rather worse as a glare source than a more mellow (or yellow) light of the 'same' luminance, which may also give the impression of being dimmer.

It is undesirable to have a source which contains widely separated high spectral peaks as this is not only ruinous to acuity but is highly disconcerting (due to chromatic aberration in the eye) — even 'though its luminance and glaring properties would otherwise be acceptable.

The recently produced Osram 'Solarcolour' lamps (high pressure sodium discharge) would seem to approximate to the ideal as far as physiological optics is concerned since they combine several advantages; vis. high luminance, preferential stimulation of the eye at the long wavelength end of the spectrum without losing all the blue (because of their broad spectral envelope), good colour rendering giving psychological acceptability and on a more mundane plane, high efficiency.

CHAPTER VI.

Straylight or Neural Inhibition.

Introduction.

It was thought desirable to perform some experiments to attempt to separate the individual contributions to glare of scattered light and neural inhibition. The first experiment, based on work by Stiles (1929), was aimed at specifying differences in the recovery curves from glare and equivalent background luminance. The equipment already described was found eminently suited to this purpose.

The second, based on an idea by Ruddock (private communication) was an attempt to isolate directly the difference between neural inhibition and scatter and say something about the behaviour of each. The basis of this experiment was the use of the Stiles-Crawford effect (Stiles and Crawford, 1933) to reduce the receptoral response derived from a glare spot when the pencil of light was moved from the centre of the pupil to the limb of the artificially dilated pupil, (whilst the scattered light component changed only slightly). By determining the effect of the glare spot on the threshold level of the test stimulus for different entry positions the effect of the glare could be correlated with the corresponding change in receptoral stimulation.

1) Recovery from Glare and Background.

The first experiment was aimed at obtaining curves of sensitivity, as determined by binocular equalisation of perceived brightness of a standard test patch seen in the right eye and a variable patch seen by the left eye. The course of sensitivity variation was plotted during and after exposure of right eye to a parafoveal white glare source. A similar sensitivity/time graph was drawn for the right eye exposed to a uniform background field overlying the test patch and extending well into the parafovea, and these two graphs were collated.

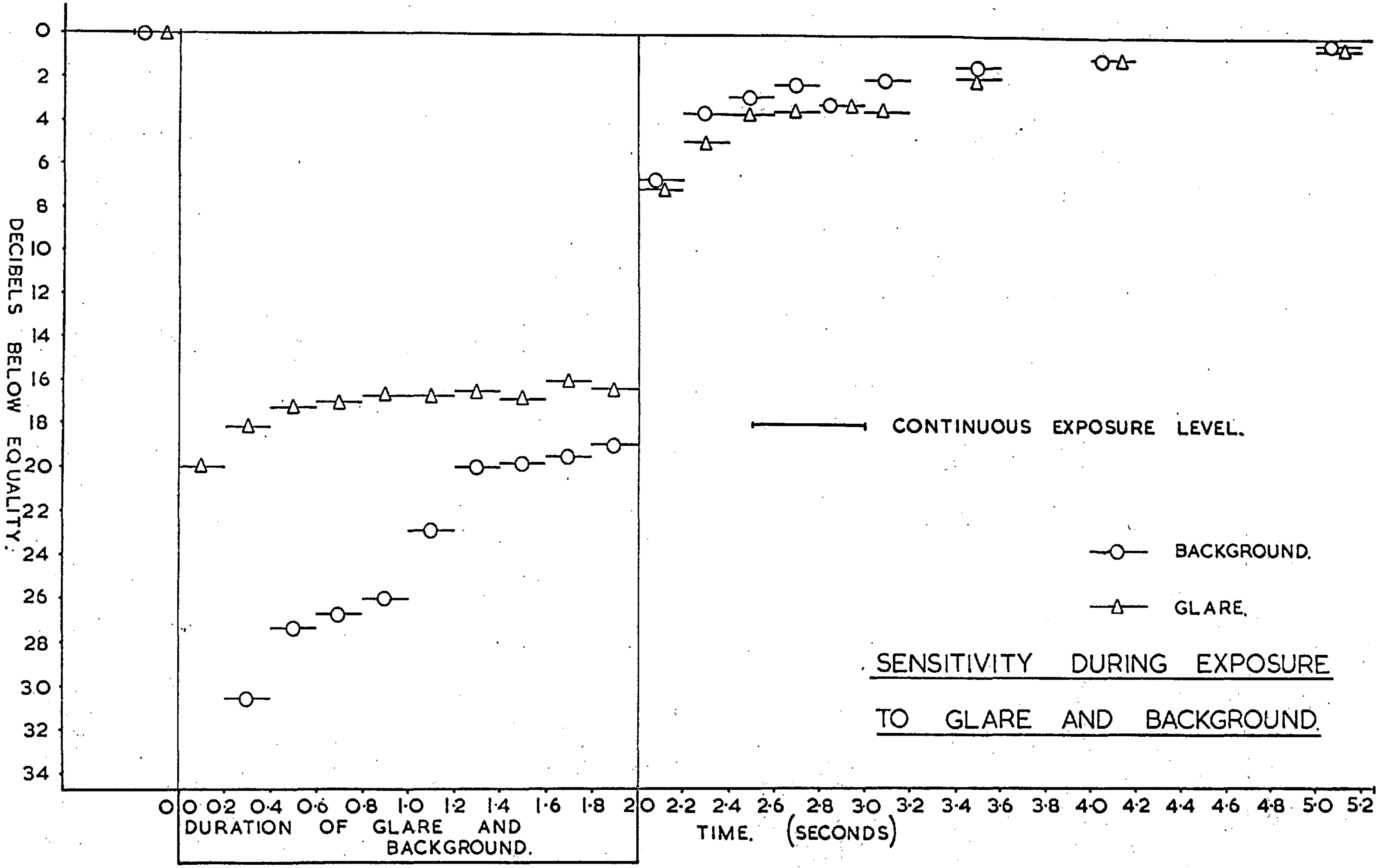
If disability glare were due solely to entoptic scattered light then these two sets of curves obtained under the different conditions would be expected to show the same form, and even the same levels when suitably correlated. Should the curves be different, either in magnitude or functional dependence, then the analysis must explain the deviation. The sensitivity curves were transposed into equivalent veiling luminance at any particular instant since this concept was found to be still valid, but the idea of equivalent veiling luminance (hereafter referred to as e.v.l.) as a time independent correlate with glare halo must be discarded.

The experiment made use of binocular comparison of two stimuli, using the left (quiescent) eye as a standard and subjecting the other to either a uniform background field or to a glare source. All light sources had the same chromatic components and were substantially white at a colour temperature of 3,000° K with a smooth Planckian distribution. Artificial pupils (2 mm.) were used and the intensity of the left eye test patch was varied by a neutral density wedge, the transmission characteristics of which were linear on a logarithmic basis. The observation consisted of equating the luminosity of the two test patches (visual format as inset, Fig. 7) when these were presented. A test and comparison time of 1/5 second was used with a complete re-cycle time of 50 seconds. The conditioning stimuli (glare and background) were each displayed for a 2 second period. The mean separation of the glare source (subtending an angle of 40' arc at the eye) and test patch (1° by 2° rectangle) was about 3° 30' arc. The glare source luminance was 250,000 ft. Lamberts which gave rise to a retinal illumination of 2.5×10^{7} photopic trolands and an illumination at the eye of about 260 lux. This was, therefore, a very high level.

A perceptible time delay occurred between the detection of the stimulus in the right eye and that in the left even though the stimuli were presented simultaneously, but this time lapse was not large and did not seem to make matching any more difficult (c.f. Pulfrich Pendulum effect - Gregory, 1966).

The recovery curve from glare exposure was obtained first. In order to collate the two graphs (glare and background) it was necessary to fix a datum or fiducial level common to both series of measurements. To do this, the level of sensitivity finally reached during continuous exposure to the glare was measured (as decibels below dark adapted equality of sensitivity of the two eyes) as the mean of ten readings (test patch still flashed for 1/5 sec in 50 sec.). This value of sensitivity depression was produced under the same continuous exposure conditions by a uniform background field, the test patch difference being set at the required value and the background smoothly varied to give a match. Again the mean of ten readings was taken and this used to specify the background field used in the remainder of the experiment,, (about 30 ft. Lamberts).

FIG. 31.



SENSITIVITY DURING EXPOSURE TO GLARE AND BACKGROUND.

The curves are presented in Fig. 31.

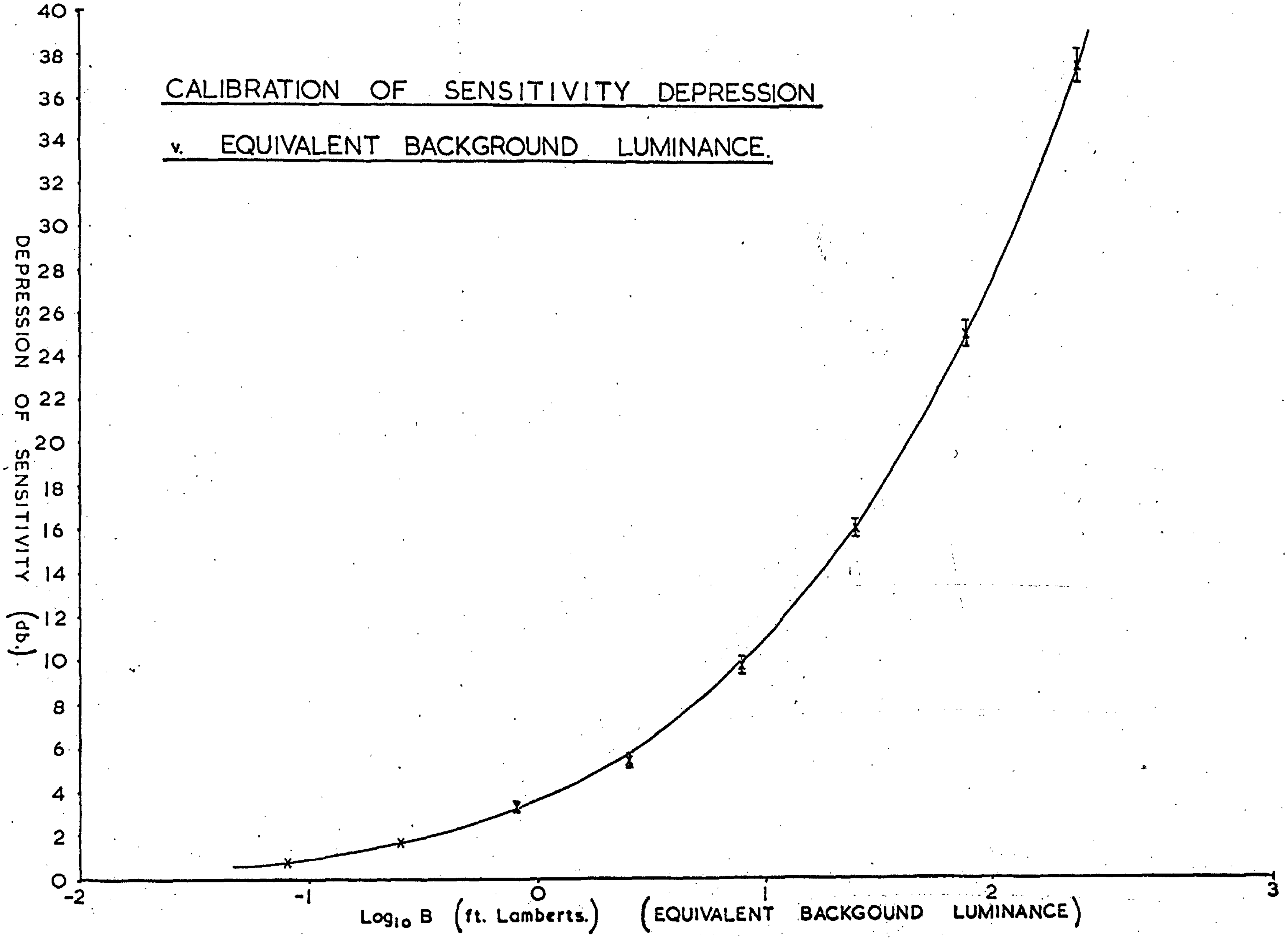
It is immediately apparent that there is a large difference between the recovery from a uniform background and recovery from a glare veil, to which it has previously been assumed 'equivalent', under analogous circumstances. Our e.v.l. was now subjected to harder scrutiny and was not found to be valid for rapidly changing situations. The e.v.l. concept has been shown to work well in the past for configurations where time dependence was not a salient parameter.

Discussion.

Several curious things are noticeable from these curves. The long term exposure levels were equated on the basis of subjective brightness (apparent brightness, perceived luminance, luminosity) of the test patch seen with the same eye as the glare or background. If we calculated on the basis of the results of the previous chapter, there was a serious anomaly between the background and the glare induced e.v.l. in the region of the test patch. The background was some 30 ft. Lamberts whilst the calculated e.v.l. was c. 2 ft. Lamberts (a discrepancy of a factor of 15 !). The relevance of this latter value (for e.v.l.) might be questioned since it was obtained by extrapolating linearly from the value observed at a glare level (retinal illumination therefrom) of 5×10^4 photopic trolands to the higher level used here (which was 2.5×10^6 photopic trolands). Also, and perhaps more importantly, it was assessed using threshold measurements whereas here we are concerned with the apparent brightness relying to and unknown extent on real contrast. It seems that this difference is not an error of calculation but is born out by the behaviour of the curves (Fig. 31).

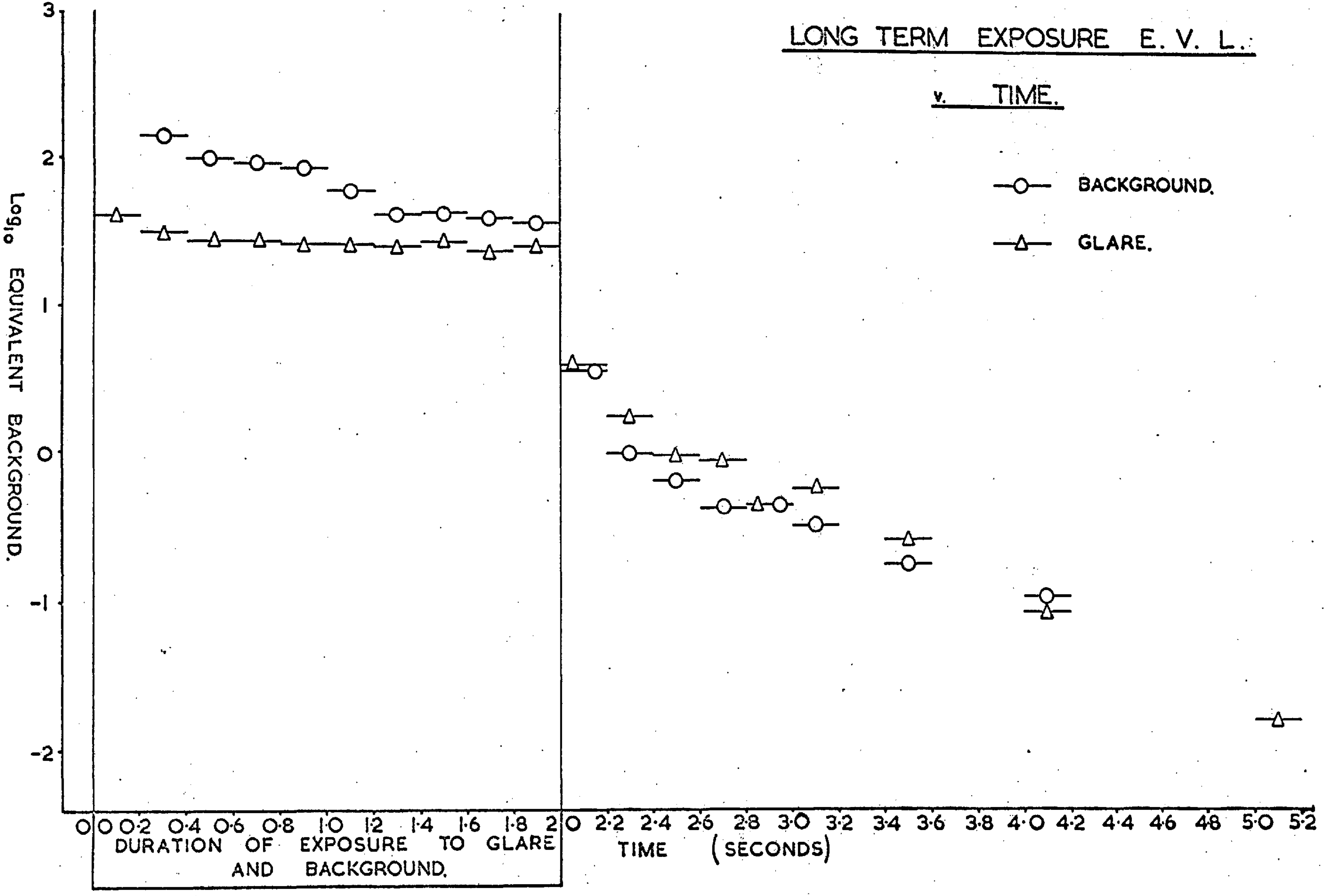
So we had a glare source which gave an e.v.l. of 2 ft. Lamberts

FIG. 32.



CALIBRATION OF SENSITIVITY DEPRESSION v. EQUIVALENT BACKGROUND LUMINANCE.

FIG. 33.



LONG TERM EXPOSURE E. V. L. v. TIME.

at the point in question and produced the same retinal sensitivity reduction on a long term exposure as a uniform background field of 30 ft. Lamberts, although up to an exposure duration of 2 seconds they produced significant differences, initially as large as might simply have been expected from their nominal magnitudes.

The data were transformed into equivalent background on long term exposure for each point in time by plotting Fig. 32, the graph of sensitivity reduction against background field, which, on long term exposure, produced it. Fig. 33 shows the transformed recovery curves. Time is plotted against $\log_{10}$ background luminance (long term exposure) which would be necessary to produce the sensitivity depression (measured instantaneously) which was characterised above.

We may conclude that the binocular comparison of apparent brightness relies on more than was hitherto supposed. In short, it would appear that the presence of a glare source in the field of view affects the perceived luminance of a dimmer patch to a greater extent than might be suspected from the e.v.l. derived from threshold measurements.

This might be due to lateral inhibition but other estimates (Chap. IV,section 2 , and Chap.VI, section 2) do not suggest that its effect could be as large as implied. Perhaps the presence of a glare source alters the perceived luminance by contrast with the very bright source more than by contrast with the dimmer background. — a kind of non-linear simultaneous contrast, based neither on scattered light nor lateral inhibition, but on the psychological attempt to judge one stimulus regardless of a much brighter one in the same eye as being equal to one seen by the other eye. If this psychological error is possible then it offers a new effect of glare which reduces the apparent brightness of objects to a large extent, but reduces their luminance difference thresholds by a much smaller amount, measured by the scattered light veil plus neural component. This would also account for the visual impression of being blinded when experiment shows that luminance difference thresholds are reduced to quite a small extent. (Chap. II, section 3.)

Explanation of the Graph (Fig. 33) during the exposure period follows immediately, where adaptation to the large background field takes place over 2 seconds and the adaptation to glare (the much smaller e.v.l.) is complete within 0.4 seconds. That the two should reach a similar level is due to non-linear reduction of apparent brightness of the test patch in the presence of glare.

On this hypothesis the recovery from the background exposure should proceed more slowly than that from glare. This is found not to be so, leaving only neural lateral inhibition to explain the slower recovery from glare. Recovery from both systems under this comparison is very rapid, but it is thought unlikely that the differences detected on removal of the stimuli are completely insignificant.

From these graphs it seems necessary to invoke three glare mechanisms :-

1) Scattered light within the eye,
2) Neural lateral inhibition, and
3) Reduction of apparent brightness in the presence of glare by simultaneous contrast comparison of the two (glare and test) sources serving to further reduce the apparent brightness of the dimmer one.

Effect 3) may not be present in experiments which rely purely on measurement of thresholds, but only when the assessment of subjective brightness is desired.

That the recovery from glare should proceed slowly and have a different time dependence from the background seemed to demonstrate that there is some effect due to lateral inhibition. If we assume that it is only scattered light that constitutes the veil then, since the background was 30 ft. Lamberts. and the equivalent veil only 2 ft. Lamberts (factor 15 difference), the recovery from the latter would have been more rapid, had it not been for some weighting factor. Simultaneous contrast is excluded because only the two test patches (one in each eye) were in the field of view during recovery. Lateral inhibition is then this weighting factor which apparently cannot always be ignored.

2) Stiles–Crawford Effect.

Introduction.

The second experiment was conceived to try to distinguish between the effects of entoptic scattered light and retinal neural inhibition. The neural component is considered to derive from effect 3) of Fig. 19, and it was the magnitude of this influence which we wished to reduce without altering the other effects, 1),2) & 4). (Fig. 19). We wished also to obtain quantitative data where experiment 2) of Chap. IV gave only qualitative.

Method.

The measurements consisted of finding the luminance difference threshold at various angular distances from the glare source in three conditions of observation;–

A. With the glare pencil incident through the centre of the pupil of the eye.

B. With the glare pencil of the same intensity incident through the limb of the dilated pupil.

C. With the glare pencil incident through the centre of the pupil but with reduced intensity such that its apparent brightness in C was equal to its apparent brightness in B.

Case A, the conventional case, will have the glare pencil more or less perpendicular to the receptors and hence the Stiles–Crawford Effect will allow maximum response to the glare, but tend to reduce response to light which has been scattered out of the principal ray and is no longer normally incident on the receptors (The entoptic veil).

Case B utilises the Stiles–Crawford Effect to reduce the glare response whereas that same effect now has a somewhat more complex

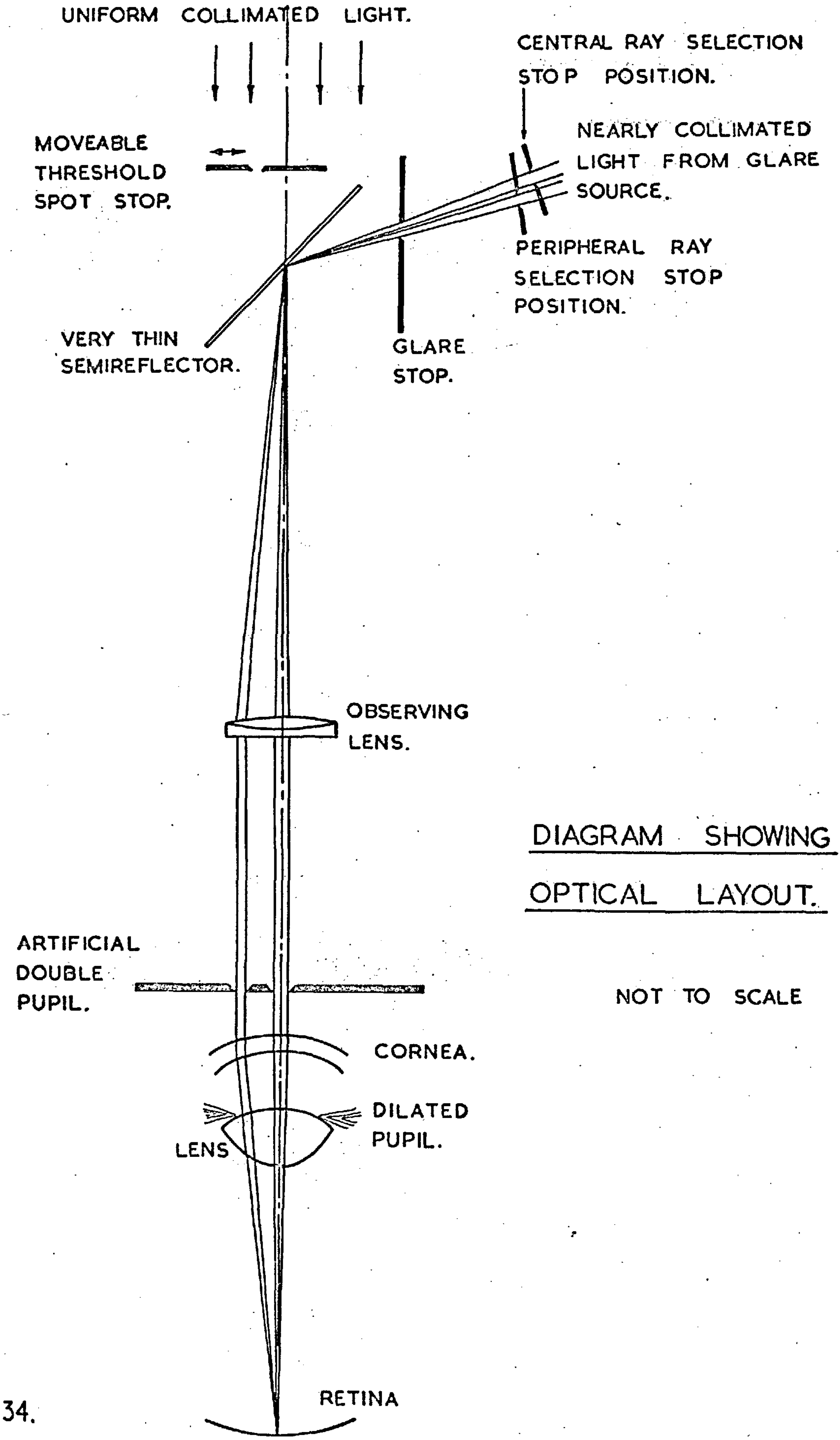


DIAGRAM SHOWING OPTICAL LAYOUT.

NOT TO SCALE

FIG. 34.

effect on the scattered light according to its point of origin. i.e. Light scattered once out of the main beam suffers the same reduction as the glare pencil, but light scattered more than once (secondary scatter) will give rise to a further reduction of response due to the Stiles-Crawford Effect at even greater obliquity. The entoptic scattering media are located discretely (i.e. cornea (scatter), anterior chamber (no scatter), lens (scatter), etc.) making this multiple scattering a significant contributor.

The effects of retinal scatter are likely to be similar in both cases A and B.

Experimental.

The experimental layout is shown in Fig. 34 (not to scale) and illustrates how the glare pencil was admitted to the eye, either centrally or peripherally through one of two identical artificial pupils (in the same metal mask) each of 1.3 mm. in diameter and with a centre separation of 3.2 mm. The exclusive use of one or other of these pupils was arranged by moving the glare selection stop, which was placed behind the glare stop itself, in a slightly convergent beam of light. Equality of glare intensity in each position was assured by use of 'through the lens metering' by photocell and galvanometer. The test spot was always supplied through the central pupil and its angular distance from the glare spot was set accurately on a small finely divided ivory scale, at values between 1^o and 4^o from the glare spot centre. Other conditions were as in previous experiments except where stated. The luminance of the glare spot was 2.24×10^4 ft. Lamberts giving a retinal illumination of 5×10^5 photopic trolands and an illumination at the plane of the pupil of 28 lux. All sources were white. The right eye was used throughout and its pupil dilated using one drop (c. 0.02 cc.) of 0.5% Mydrilate.

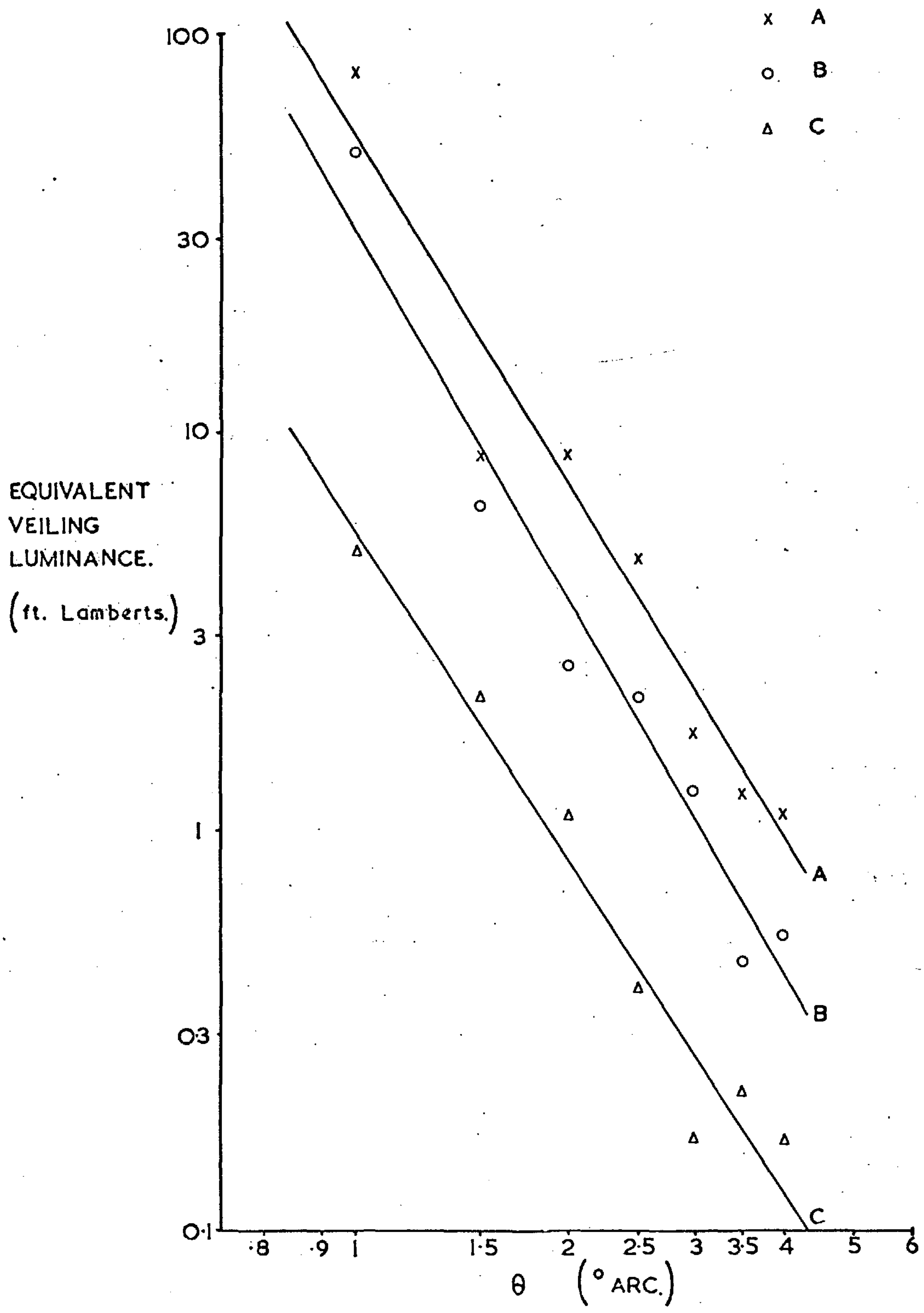
The Stiles-Crawford Effect reduced the apparent brightness of the glare source by about a factor of 5 when the glare pencil was incident peripherally. This assessment was made by lowering the luminance of the glare source with neutral filters until it could be matched by the somewhat brightened test spot, moved to be almost contiguous with the glare spot. This match was made in central and peripheral positions and the reduction in receptoral effect thus measured. The reduction of intensity resulted in the selection of a level of 2×10^4 photopic trolands for curve C. It was considered justified to extend this to glare levels at which measurement was impossibly inaccurate due to reduced luminance discrimination at very high levels. Rod intrusion was thought not to be a problem here at these glare levels where the rods would have been producing saturation response, and the low level match was performed on the rod-free fovea.

Luminance difference threshold measurements were made under continuous exposure conditions with fixation on the test spot (a 20' arc diameter field). Values of this threshold were transformed using the Fechner-fraction graph (Fig. 27) to give e.v.l. derived from the glare, and this is plotted in each condition (A, B, & C.) in Fig. 35.

Results and Discussion.

Computor fitted curves (minimisation of the least squares fit on a log-log plot) showed a mean difference between A and B of a factor of 2 (B/A = 0.52) and a difference between A and C of a factor of 10 (C/A = 0.12).

Derived mean values of k and n are given overleaf in a short table.



LOG-LOG PLOT OF E.V.L. v. θ.

FIG. 35.

Values of k and n ;-

	A	B	C
k	7.0	4.2	13.8
n	3.0	3.2	2.7

when the units are the same as, and defined in, Chap. V (table 7). Once again it transpires that k is substantially dependent upon the conditions and illumination levels of measurement. It would have been expected on a purely linear basis that k should have been found to be the same for A and C. In fact it seems to differ by a factor of 2, a discrepancy which seems large considering that the retinal illumination from the glare source was reduced by a factor of 5 from A to C (resulting in a reduction of the measured equivalent veil by a factor of 10). That this type of discrepancy can occur without explanation unless new and less quantizeable parameters (such as general well-being of the observer, fatigue, willingness to cooperate, etc.) is of some concern. Many repetitions of the experiment and statistical analysis of subsequent data could improve this, but time has not permitted.

The values of n are considered to be constant within the limits of the experiment. A real difference between 'n' for A and C would be disquieting indeed and a difference between 'n' for A or C and B (which is not only plausible but quite likely considering the intraocular optics of the experiment) would only be worthy of discussion if its measurement were made with very much higher accuracy than was feasible with this experimental technique, without many repetitions.

Facts that remain are that B lies much closer to A than it does to C and is more or less parallel to both. Now if the reduction in visual sensitivity due to the presence of a glare source were wholly caused by lateral neural inhibition (no scatter) (not very likely for slit lamp examination shows that there is entoptic scatter to a significant degree) we should expect that curves B and C should be very closely similar (allowing for experimental error),since we have defined the levels of B and C as giving the same apparent receptoral response (at a lower level, but there is no reason to suppose that this particular linear extrapolation to higher levels might be invalid). If glare were due to scatter (exclusively) the B would be expected to overlie A,approximately. To qualify the 'approximately' we must take into account the intraocular optics and structure, and consider that the glare pencil through the pupil centre traverses a path which is very different from that through the limb. The supposedly scattering elements present different thicknesses in the two cases. Even these optic elements are not homogeneous (Weale, 1963) so one should not consider that the amount of introduced scatter is in any way proportional to the mere thickness traversed.

From considerations of ocular anatomy and measurements of corneal and lenticular structures (Salzmann, 1912, Tscherning, 1898.) the extra thickness of the cornea traversed by the peripheral rather than the central ray is some 0.2 mm. or 25% of the corneal thickness at the anterior pole (central position), whereas the lens contributes a rather shorter path to the peripheral ray of some 3.2 mm. compared with and axial transit of 4 mm. on average with the eye accommodated for infinite conjugates. The lens is not optically uniform, the core and outer region scattering more than the intermediate zone. It is thus possible to say little about the optical equivalence (from scattering considerations) of the two paths.

We are able to say that the separation of A and B (Fig. 35) is plausible without the need to invoke neural lateral inhibition across the retina, so this is one more piece of evidence that scatter rather than neural behaviour is the overwhelmingly important parameter in disability glare.

It seems that this type of experiment might yield far more conclusive results if it were performed with different colours and many more times. Also a fourth type of measurement with the peripheral glare pencil at the same intensity as in C might yield interesting results. Time has not permitted the devotion of more experimentation to this end, but it is felt that the possible outcome might throw further light on that which has been already postulated.

Conclusions.

White v. Yellow.

With respect to the controversy of white and yellow headlighting for motor vehicles and the relative advantages to be gained from the point of view of disability glare, the following conclusions have emerged from our researches. The four aspects of glare we considered were;-

1) Reduction of apparent brightness of environment with attendant reduction in perceived contrast.
2) Reduction of luminance difference threshold.
3) Recovery during first few seconds after glare removal.
4) Total recovery on removal of glare.

With the adopted criteria of luminance equality, discussed at some length earlier, the above aspects are all marginally better in white light than the equivalent yellow for the driving situation. It is to be stressed that this difference is very small and it is the considered opinion of the author that the use of such a small difference to make categorical and dogmatic statements is unwise.

The glare aspect of fixed highway lighting can be considered on a rather broader base, because the types of light sources available are somewhat different. Whereas for moving vehicles the choice of light source is usually incandescent tungsten of one or other type, discharge lamps have been generally favoured for fixed installations and in the immediate past these have tended to be, low pressure sodium, high pressure mercury or coated fluorescent tubes. On the basis of this research work it would appear that high pressure sodium (now readily available) is superior to all of these and should be employed wherever possible, since this last type of lamp combines many of the good points and excludes many of the bad from the formerly popular sources. This statement is based on the work on white and yellow glare and amplified by results of research into glare of different chromatic constituents.

Chromatic Glare.

On a more academic level the results from investigation of chromatic glare mechanisms are rather interesting. The idea that some chromatic spectral distributions have a different glare effect from others has been widely held, but not investigated adequately. From experiments outlined in this thesis the hypothesis that the anterior ocular elements give rise to the short wavelength scatter and that long wavelength scatter tends to predominate within the retina has been constructed. Neither qualitative nor quantitative estimates designed to test this have shown it to be obviously in error and with the customary inferential (rather than logically rigorous - rarely available in science) argument we may place more faith in the hypothesis, perhaps even such as to call it a theory.

Glare.

The equivalent veiling luminance concept for defining glare situations has been found not to be generally valid unless specified both spatially and temporally rather than merely spatially as has been accepted in the past. The large difference to be observed in the temporal behaviour of the retina exposed to a uniform brightness or a glare source, synonymous with what was hitherto referred to as an equivalent veil was large and probably very significant for assessment in short exposure situations (e.g. real life).

About mechanisms of glare our investigations have led us to believe that entoptic scattered light is the prime cause of glare. Not entirely insignificant is the effect of neural inhibition which most probably acts to a greater extent over small distances. We found a simultaneous contrast phenomenon which seemed to reduce apparent brightness – and presumably apparent contrast – without reducing the luminance difference threshold. It is more likely that this is a psychological phenomenon rather than physiological or physical with respect to its perceptual effect, but it does help to explain the anomaly between disability and discomfort glare assessment; i.e. How a subject's visual performance is really affected and how he says it affects him.

Acknowledgements.

The author wishes to thank Prof. W. D. Wright for suggesting the topic and giving helpful guidance, Dr. K. H. Ruddock for many suggestions and discussions and for proof reading the manuscript, the Road Research Laboratory who provided money for invaluable equipment and the Science Research Council who sponsered the research.

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