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COMPARATIVE STUDIES OF MONOCULAR AND
BINOCULAR VISION

by

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Establishment, Sevenoaks, Kent

for the

DEPARTMENT OF OPHTHALMIC OPTICS AND VISUAL SCIENCE

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CONTENTS

	<u>PAGE</u>
ACKNOWLEDGEMENTS	4
ABSTRACT	5
CHAPTER 1	INTRODUCTION
1.1	The designer's problems 7
1.2	Methods of comparison 8
1.3	Summary of the literature 11
1.4	Form of the proposed experiments 22
1.5	Visual thresholds 23
1.6	Summary 30
CHAPTER 2	DESIGN OF GENERAL EXPERIMENTAL METHOD
2.1	The observers 32
2.2	Presentation of stimuli 33
2.3	Luminance range 34
2.4	Colour of the stimulus and background 35
2.5	Viewing distance of stimuli 37
2.6	Time limits and fatigue effects 38
2.7	Viewing conditions 38
CHAPTER 3	APPARATUS AND GENERAL CALIBRATIONS
3.1	The projection system 41
3.2	Operator's monitor and control system 43
3.3	Production of stimuli 47
3.4	Construction and calibration of the optical filters 48
3.5	Luminance measurements and calibration of the telephotometer 57
3.6	The observer's viewing position 63

	<u>PAGE</u>
CHAPTER 4	THE CONTRAST DETECTION TASK
4.1	Procedure 65
4.2	Subjective results 72
4.3	Numerical results 73
4.4	Control tests 77
4.5	Summary of the contrast detection results 79
CHAPTER 5	THE VISUAL ACUITY TASK
5.1	Procedure 83
5.2	Results 87
5.3	Summary of the acuity results 93
CHAPTER 6	THE VISUAL RECOGNITION TASK
6.1	Procedure 95
6.2	Results 97
6.3	Summary of the recognition results 102
CHAPTER 7	MISCELLANEOUS OBSERVATIONS
7.1	Comparison of results obtained from male and female observers 104
7.2	The effect of changing the threshold probability level 104
7.3	Investigation into possible differences between monocular and binocular viewing when considering fatigue 107
CHAPTER 8	SUMMARY AND GENERAL CONCLUSIONS 120

	<u>PAGE</u>
APPENDICES	
1.1 - 1.4	Detection results 127
1.5	Age distribution of the observers (detection task) 131
2.1 - 2.15	Acuity results 132
2.16	Age distribution of the observers (acuity and recognition tasks) 147
3.1 - 3.4	Recognition results 148
4	Circuit diagram Muirhead D-972-A potentiometer 152
5	Calibration reports on secondary luminance standard 153
6	Example of the prediction of binocular/monocular detection ranges from the contrast detection data 158
LIST OF REFERENCES	160

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R. Home

January, 1976

ABSTRACT

This thesis is concerned with the comparison of monocular and binocular vision. Previous studies are reviewed and the aims and methods of the present investigation have been stated. Psychophysical experiments are described, the aim of which is to quantify the relative merits of monocular and binocular vision by the measurement of visual thresholds. Three tasks are involved: contrast detection, visual acuity and recognition, twenty subjects undergoing each task.

The contrast detection experiment shows that over a range of ambient luminances from 10^{-1} to 4.7×10^{-5} Cd M^{-2} the monocular/binocular threshold ratio can be as high as 1.72 and is not less than 1.35. The ratio is not affected by increasing the stimulus distance from 1.3 metres to infinity nor by changing the shape of the stimulus from circular to square. The results show definite evidence for physiological summation as opposed to simple probability summation as suggested in previous literature.

The comparison of binocular with monocular acuity over a range of luminances from 7.1 to 3.6×10^{-4} Cd M^{-2} shows an increasing binocular superiority as the contrast between stimulus and background is decreased. The binocular to monocular acuity ratio increases from 1.06 for a target to background contrast of 0.70 to 1.54 as the contrast is decreased to 0.01. These ratios are increased if the ambient luminance is decreased.

The recognition experiment involves the comparison of monocular and binocular contrast thresholds for the recognition of letters of the alphabet. The range of luminances considered is from 7.1 to

$3.6 \times 10^{-4} \text{ Cd M}^{-2}$. The results are very similar to those obtained in the detection experiment except that the ratios are significantly lower throughout the luminance range.

A subsidiary experiment indicates that monocular fatigue involved in a prolonged contrast detection task, although causing a subject to have less confidence in his results with increasing time, is not reflected in the actual results obtained.

CHAPTER 1

INTRODUCTION

1.1 The Designer's Problem

Given a free hand to produce a new optical instrument the optical designer has a large number of parameters which he can vary to produce an optimised system. He can generally use a combination of his experience in design and a mathematical weighting of the appropriate design parameters to produce the best solution to the problem at hand. The ultimate design of the system will be a compromise which depends upon the relative importance of optical and mechanical performance. The overriding factor for consideration will be, in general, the cost of the final system. Most of the parameters can be fixed objectively once one has stipulated the task(s) for which the system is to be used and the final cost. For instance, if a hand-held, night surveillance instrument is required, the designer would necessarily think in terms of a low weight, relatively small instrument with large exit pupil(s) to match the pupil of the eye which becomes enlarged at low ambient light levels.

However, an important design feature is whether to produce a monocular or binocular system. The grounds for choosing one system or the other seem, until now, to have been based on very tenuous arguments. Apart from the obvious examples of instruments relying on stereopsis or parallax effects which demand the use of binocular vision, the choice of monocular or binocular instrumentation in the past seems to have been a mixture of simple tradition and subjective assessment of the situation. Hence the seemingly simple

objective of this study is to provide the optical designer with sufficient data to allow him to make the choice between a monocular and a binocular instrument objectively.

1.2 Methods of Comparison

A comparative study of monocular and binocular instruments could be undertaken on the basis of:

- a) Optical Design
- b) Mechanical Construction
- c) Visual Perception.

Let us consider these separately.

a) Optical Design

From a pecuniary point of view the binocular instrument starts at a distinct disadvantage to the monocular with equal optical properties. The binocular requires double the amount of glass, double the amount of assembly and optical alignment, requires an additional collimation procedure between the individual limbs of the instrument and of course contains double the number of optical components which can develop faults and therefore require maintenance.

b) Mechanical Construction

As with the optical design the binocular has certain mechanical disadvantages as compared with the monocular. Assuming equal optical properties the binocular is both heavier and bulkier than its monocular counterpart. The binocular requires more maintenance and is vulnerable to loss of collimation by shock which invariably means that it has to be constructed in a more rugged way. It usually requires an adjustment facility to allow for variation in interocular separation.

c) Visual Perception

In considering the human visual system as a method of comparing binocular with monocular instruments the tacit assumption has been made that the eye is the ultimate detector in the system. This is realistic because in cases where a binocular instrument is under consideration the eye will invariably be involved as the final detection mechanism. It is when the human visual system is considered that the advantages of binocular vision begin to emerge.

Firstly an explanation of what is meant by the term 'binocular vision'. It is defined as two-eyed perception arising from the overlapping regions of the two retinae. In the human visual system the overlap is almost complete. Some advantages of binocular vision are immediately apparent. For example, the second eye acts as a back-up for the first, allowing vision to continue should the use of one eye be lost. Also, one eye can be regarded as being spatially defective due to the existence of a blind spot on the nasal side of each retina. Human binocular viewing overcomes this short-coming insofar as the blind spot due to one eye is overlapped by a 'seeing area' due to the other. Binocular vision also provides an accurate means of locating objects in space, and with this in mind it is interesting to observe that most predatory animals and other primates possess binocular vision, whereas non-predatory creatures tend to have panoramic vision (all round vision with little or no overlap of the visual fields of separate eyes). It would seem that panoramic vision gives the better system for warning of the approach of an enemy, but where evolution has lessened the need for protection, binocular vision provides a more powerful depth cue; stereopsis sometimes enabling a predator to penetrate the camouflage of its prey.

Although stereoscopic vision is not the sole means by which we estimate range (e.g. it is possible to use indirect cues such as the effort needed to focus and converge the eyes, the differences in parallax caused by motion, contrast gradients and angles subtended at the eye by objects of known size) the extent to which we use it only becomes really evident when stereopsis is lost. For example, a tennis player who is used to relying on binocular vision finds that hitting a ball becomes a definite problem when he is obliged to use monocular vision.

Apart from stereopsis there are other advantages in using binocular as opposed to monocular viewing. One of these is that binocular vision is generally the cause of less fatigue than monocular vision. This is especially evident at low ambient light levels. Monocular fatigue can be attributable to a number of factors, the most obvious being that there is a physical effort involved in keeping one eye closed because it goes against the natural tendency for both eyes to be either open or closed at the same time. Another is that, in the absence of stereoscopic cues, the eye is required to make a more conscious effort to maintain a sharp retinal image, due to the lack of range information normally obtained from binocular viewing.

Other advantages associated with binocular vision are lower absolute threshold, higher visual acuity, greater ability to detect contrast differences and larger field of view. These are discussed in the next section.

In designing experiments to compare monocular with binocular vision one has two possible methods of approach, namely the psychophysical and the physiological. Both methods have their limitations but

should not be regarded as completely independent especially as both techniques are generally mutually consistent in the results which they yield.

1.3 Summary of the Literature

a) Physiology of the Visual System

It would seem unnecessary to include a section on the structure of the eye at this point. If necessary, good accounts of the optical properties and basic structure of the eye can be found in the published literature (e.g. Davson, 1962; Cornsweet, 1970; Westheimer, 1970). A more important consideration in the context of binocular vision is the neural mechanism between the retinal receptor cells and the visual cortex.

Basically there are six types of nerve cell in the visual chain, three at retinal level, one in the geniculate body and two in the cortex. Fig. 1.1 depicts the human brain as viewed from below and fig. 1.2 shows the visual pathways in schematic form. Additionally within the retina there are interneurons called amacrine and horizontal cells which are responsible for lateral interaction at retinal level. Modification and analysis of neural impulses takes place at the synapses (junctions between nerve cells), the nature of the analysis depending upon the type of synapse involved and the number of nerve fibres converging on a single cell.

From fig. 1.2 it is evident that one receptor cell (rod or cone) may influence a number of bipolar cells and conversely one bipolar cell may receive impulses from several receptor cells. The only proviso is that there exist rod bipolar cells and cone bipolar cells, and these synapse only with their associated kind of photoreceptor. The next stage involves the ganglion cells which

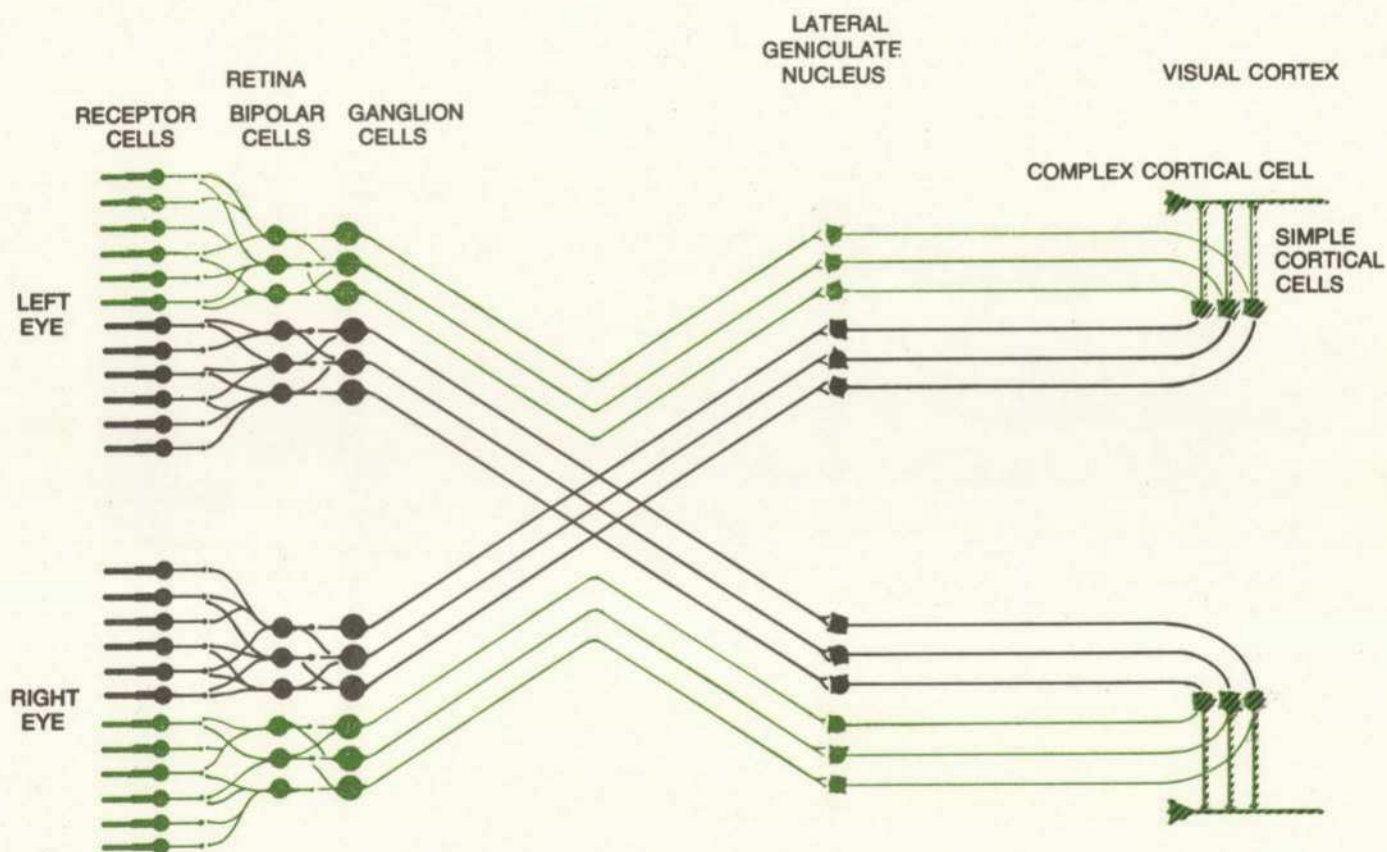


FIG. 1.2 SCHEMATIC REPRESENTATION OF THE VISUAL PATHWAYS
(From Pettigrew, 1972)

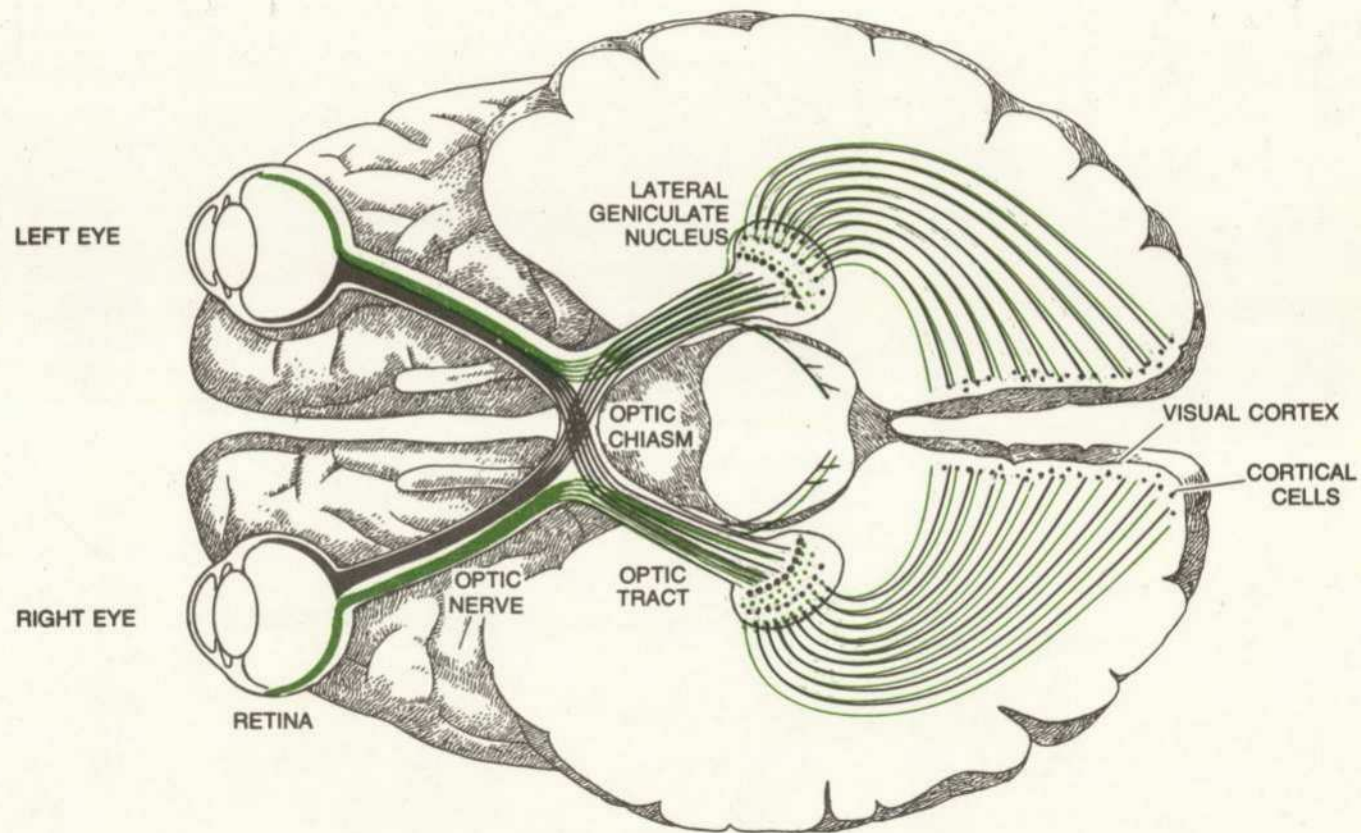


FIG. 1.1 THE HUMAN BRAIN AS VIEWED FROM BELOW (From Pettigrew, 1972)

synapse directly with the bipolars. The ganglion cells fire at a fairly steady rate, even in the absence of any stimulation. (N.B. Ganglions give action potentials or spikes as opposed to the slowly changing potentials of the receptors.) Some synaptic connections are excitatory and others are inhibitory with the result that a single cell responds according to the net effect of all the neural inputs to it. A signal via an excitatory synapse increases the firing rate and one via an inhibitory synapse reduces the rate. Beyond the ganglions the optic nerve fibres leave the eyeball and intersect at what is called the optic chiasma where decussation takes place. Approximately half the fibres from each eye remain uncrossed at the optic chiasma. These ipsilateral (uncrossed) fibres from the outer part of the retina of one eye join with the contralateral (crossed) fibres from the inner part of the retina of the other eye before connecting with the lateral geniculate nucleus (LGN). This means that after intersection at the optic chiasma the optic tract connecting with the right hemisphere of the brain contains nerve fibres coming from the right half of each retina, whilst that connecting to the left hemisphere contains fibres from the left half of each retina.

Each geniculate cell is driven from a circumscribed retinal region (the receptive field) and the retina, as a whole, is mapped in a regular manner on to the LGN in the sense that fibres arising close to one another in the retina generally end close together in the LGN. The role of the LGN would appear to be the enhancement of the disparity, already present in retinal ganglion cells, between responses to small centered spots and to diffuse light. Binocular interaction at this level appears to be almost non-existent in primates.

From the LGN information is relayed to the striate cortex. This is organised into columns which measure about 0.5 mm in diameter and extend from the surface to the white matter. Holmes (1918) studying field defects caused by war wounds affecting the occipital cortex and Brindley and Lewin (1968) examining sensations caused by direct electrical stimulation of the visual cortex, have investigated the projection of the retina on to the cortex.

The most successful method of investigating responses from single cells seems to be the microelectrode technique where electrical responses are recorded using electrodes having tip diameters measuring less than a micron. Considerable differences have been found between the receptive field organisation of cells in the visual cortex and that of the cells in the LGN. Although at the LGN the optimum stimuli seem to be circular spots, at the cortex the most efficient stimuli are composed of straight edges at specific orientations.

Recording responses to patterned stimuli from single cortical cells of the cat and rhesus monkey Hubel and Wiesel (1959, 1962, 1968) found four types of receptive fields which they called circular-concentric, simple, complex and hypercomplex. Circular-concentric receptive fields respond in a similar way to the ganglion and LGN cells whereas the simple receptive fields respond to straight edges, slits and dark bars. Each unit seems to respond best to a particular orientation, other orientations producing less vigorous responses, the orientation perpendicular to the optimum generally evoking no response at all. For moving stimuli, certain directions of movement tend to be more effective in producing a response than others.

The complex fields are similar to the simple ones insofar as they respond most readily to straight edges, slits and dark bars but the position of optimally orientated stimuli can vary considerably, the response remaining constant. Further to these, even more specialised cells (hypercomplex) have been observed in the cat and monkey cortex by Hubel and Wiesel (1965, 1968). These show optimum response to stimuli limited in length in one or both directions and also to properly orientated "corners" anywhere in their field.

There seems to be a divergence of opinion about how colour coding takes place. Motokawa, Taira and Okuda (1962) suggested that to some extent shape and colour information are transmitted together. However, Andersen, Buchmann and Lennox-Buchthal (1962) concluded that most responses from cortical cells are of narrow spectral band non-opponent type. More recent work by Boles (1971), Poggio, Mansfield and Sillito (1971), Couras (1972) and Dow and Gouras (1973) suggests that about 28 per cent of cortical cells are colour-coded.

Studying the receptive fields of the cat and the monkey, Hubel and Wiesel (1962, 1968) concluded that most of the cells in the visual cortex are binocularly activated. The receptive fields of these cells have positional correspondence on the two retinae. Barlow, Blakemore and Pettigrew (1967) found that for the cat's visual cortex, stimuli correctly located in the visual fields of both eyes were more effective at driving these cells than monocular stimuli and much more effective than a binocular stimulus which was correctly positioned in one eye only. Some binocular cells were found to have an optimum response to stimuli orientated in such a way that their projections on to the retinae were at some specific disparity. Support was given by Nikara, Bishop and Pettigrew (1968).

The optimum disparity was found to vary from cell to cell, indicating a mechanism for encoding objects at different distances (Blakemore, 1969, 1970) and different tilts (Blakemore, Fiorentini and Maffei, 1972). Also, there is evidence to support the idea that there are intercortical fibres in the human corpus callosum which are necessary for binocular integration in the centre of the visual field (Mitchell and Blakemore, 1970; Blakemore, 1970).

In summary, the visual system of the primate appears to possess an inherent preference for binocular stimulation. It uses disparity between the images formed in each eye to give depth perception. Also, if the visually evoked responses to flashes of light are measured (Ciganek, 1970) the increase in size from monocular to binocular response can be as much as 100 per cent. This idea is reinforced by psychophysical experiments, an outline of which is given in the following section.

b) Psychophysical Experiments in Visual Perception

Investigation into the phenomenon of binocular summation (and the absence of binocular summation) has been studied mainly by consideration of a visual threshold. Various conclusions have been reached by different experimenters about the nature and degree of binocular summation. Graham (1930, 1931) studied the summation effect in the fovea and the periphery of the eye, reporting that monocular thresholds were consistently as low as binocular thresholds in both cases. Bartlett and Gagne (1939) found no evidence to suggest foveal binocular summation at threshold and four years later Pirenne (1943), in attempting to rationalise the results, produced an equation which assumed the two eyes to be acting as independent channels at absolute threshold. The equation was $P_X = 1 - (1 - P_L)(1 - P_R)$ where P_X is the probability of detection by one or both eyes when

both are stimulated and P_L and P_R are the probabilities of monocular detection by the left and right eyes respectively. Also, Lyman and Mote (1956), in comparing monocular and binocular thresholds during dark adaptation, found very little evidence for concluding that the binocular thresholds were significantly lower.

However, Collier (1945), in attempting to replicate and extend Pirenne's experiment, found that the empirical P_B (binocular probability of seeing) was significantly higher than P_X (from Pirenne's equation). The thoroughness of Collier's work is enough to cast considerable doubt on Pirenne's results and also on his contention that the eyes act independently at threshold. Thorn and Boynton (1974) have recently extended and modified Pirenne's equation and after experimentation have concluded that when two stimuli are presented simultaneously to corresponding retinal areas a physiological summation takes place, lowering the visual threshold. Further to this, they found that the summation was not detectable for stimuli which were separated by more than 100 milliseconds, or were presented to non-corresponding retinal areas.

Earlier work had suggested differing amounts of summation. Laird (1924) found summation under scotopic conditions but not under photopic conditions. Shaad (1935) supported the idea of scotopic summation and Lythgoe and Phillips (1938), studying dark adaptation, found binocular summation throughout the adaptation period for both central and peripheral vision and also produced a mathematical expression which described the monocular to binocular relationship throughout the adaptation period for all observers. The expression was $1.4 Th_B = \frac{1}{2}(Th_R + Th_L)$ where Th_B was the binocular threshold and Th_R and Th_L the monocular thresholds for the right and left eye

respectively. Lythgoe and Phillips also showed that the binocular threshold was approximately the same as the monocular threshold for a test patch of twice the area. This compares with earlier work by Piper (1903) in which square stimuli subtending angles between 2 and 14 degrees at the eye were used. He found that the binocular threshold was approximately half the monocular threshold.

In 1940 Crawford compared monocular and binocular brightness thresholds and found that for foveal vision at all adaptation levels and parafoveal vision at very low levels the difference was small. However for parafoveal vision at medium and high levels the binocular threshold was approximately 30 per cent lower than the monocular threshold. Another interesting result obtained by Crawford was that exposure of the non-observing eye to field luminances up to about 1300 CdM^{-2} did not affect the measured threshold of the other eye. This conclusion is supported by others, including Bouman (1955) who extended the result to include coloured light. Support for Crawford's low level parafoveal result was confirmed when Zigler and Wolf (1958) found differences between monocular and binocular parafoveal sensitivity for the scotopic eye.

Results suggest that Pirenne's method of treating the two eyes as independent channels (i.e. no summation) does not represent the true mechanism within the visual system, especially with regard to the peripheral eye. Thorn and Boynton (1974) have suggested that Pirenne was studying a situation in which the two stimuli were not actually on corresponding retinal areas, in which case simple probability summation could have been expected. Martin (1962), supported by Thorn and Boynton, expressed the difficulty in maintaining stimuli situated only 7 degrees from the fovea on precisely corresponding retinal areas.

On the basis of physiological evidence it seems reasonable to assume a binocular summation of information at the cortical level, although on the information available at the present time it is impossible to decide upon the magnitude of the effect with any degree of certainty. In attempting to account for the discrepancies in the results obtained by different individuals in the past one has only to consider the large number of variables involved in any experiment of this kind to realise that each variable introduces another possible source of variation in the final result. For example, changing the duration of the stimulus or the angular subtense of the stimulus could have the effect of bringing into action different visual mechanisms within the system. Many experiments have used artificial pupils in front of the observer's eyes in order to be able to specify accurately the amount of light entering the eye. This can have the effect of decreasing the aberration introduced by the optics of the eye at low light levels, the natural mesopic or scotopic state of the eye involving inherently more aberration than the photopic state by virtue of the fact that the iris is allowing the system to operate at a larger aperture. An artificial pupil enables the experimenter to eliminate the effect of fluctuation of pupil diameter at low light levels (Crawford, 1936) and also allows the experimenter to neglect the Stiles-Crawford effect (Stiles and Crawford, 1933). Although it makes specification of the experimental conditions more precise, each control of this nature which is imposed on the experiment, makes the results further removed from reality.

Although most of the comparative studies of monocular and binocular vision in the past have involved the measurement of the minimum amount of light required to evoke a response from the observer, a

few studies have departed from this principle. Comparisons have been made by Crozier and Holway (1939) who measured ΔI (illumination of object - illumination of background) at threshold for different areas, intensities and wavelengths of stimuli. The mean monocular value of ΔI was found to be 38 per cent higher than the binocular value. The result is, to some extent, supported by Campbell and Green (1965) who, in comparing binocular with monocular acuity at high luminances, found a ratio of 1.42 in contrast sensitivity (reciprocal threshold contrast) for a range of spatial frequencies. In addition they found that in measuring visual acuity using high contrast targets there was about a 7 per cent improvement in acuity for binocular as compared with monocular viewing. Support for the acuity result had already been published by Horowitz (1949) who compared binocular with monocular acuity using both grating stimuli and Landolt rings. He also repeated the experiments using both natural and artificial pupils for a range of luminance conditions. Binocular acuity was found to be superior in all the cases considered.

An extensive study of the relative merits of monocular and binocular field-glasses was carried out by Hyde, Cobb, Johnson and Weniger (1920). It was concluded that binocular vision gives a distinct improvement when one is attempting to detect a contrast gradient, but the field trials involving the use of actual optical instruments, although interesting, are applicable solely to those instruments used in the tests.

In summary, the designer can conclude that there seems to be some advantage, perceptually, in using binocular vision. The actual magnitude of this advantage would seem to depend upon the task involved and the adaptive state of the eye.

1.4 Form of the Proposed Experiments

There are inherent difficulties involved in both the physiological and the psychophysical approaches. Neurophysiological experiments on the human visual system are hampered by the microscopic size of the neural units and also the difficulty in studying living neural circuits without interfering with the mechanisms themselves. As the results are required to be applicable to the human visual system, the psychophysical approach would seem to be the more practicable, although it too presents certain difficulties.

- a) There are a large number of extraneous variables which influence the state of the visual system.
- b) The state of the visual system is very difficult to define in an absolute way.
- c) The response to a given stimulus varies from one observer to another.

Chapter 2 describes how factors a) and b) were dealt with, in an attempt to make the experiments as repeatable as possible. To allow for factor c) a sample of 20 observers was used in the experiments and statistical methods were used to produce an estimation of the population mean and variance. Also, control tests were used to increase the generality of the results.

The actual experiments involved the measurement of visual thresholds for particular tasks. The measurement of a subject's threshold, apart from defining a performance limit for a particular subject performing a specific task, also allows the possibility of isolating effects due to basic mechanisms. As threshold measurement forms the basis of the experiments which follow, it is pertinent at this point to describe some of the previous work associated with visual thresholds generally.

1.5 Visual Thresholds

A visual threshold is defined as the point at which a stimulus becomes just detectable, or as the difference between two stimuli necessary for them to be just noticeably different. The visual threshold for a particular task will vary from observer to observer but in general a threshold for a given observer will depend on:

- (i) the luminance of the stimulus or stimuli,
- (ii) the contrast between the stimulus and its background,
- (iii) the spectral composition of both stimulus and background,
- (iv) the duration of the stimulus,
- (v) the angular size of the stimulus and its surrounding field,
- (vi) the shape of the stimulus,
- (vii) the region of the retina stimulated,
- (viii) the state of adaptation of the observer, and
- (ix) the observer's response criteria.

The measured threshold is also affected by any motion of the stimulus against its background (this particularly applies to peripheral rod vision) and variation of the viewing distance. Even for normal subjects tested under the same physical conditions, Hecht and Mandelbaum (1939) found that scatter of about $1 \log_{10}$ unit occurred in the measured absolute thresholds of different individuals. Also, the results obtained from one individual can show significant variation with time (Ronchi and Brancato, 1971). (N.B. The absolute threshold is taken to mean the brightness of a just detectable stimulus against a black background.)

Actual threshold measurements made under nominally constant conditions show an uncertainty of response which makes the value

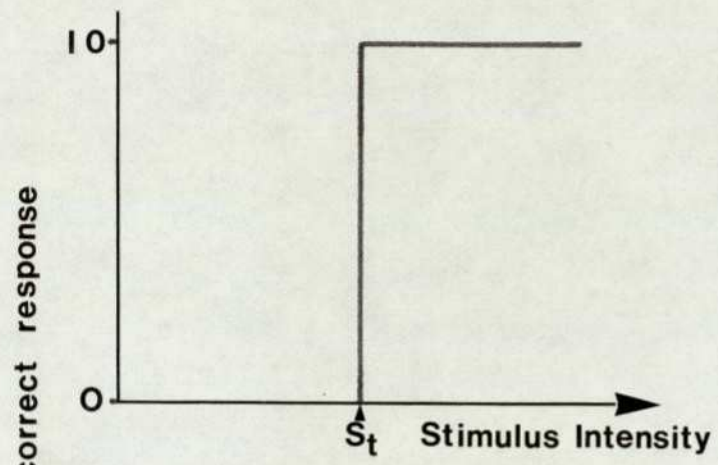
of the threshold ill-defined. Fig. 1.3(a) shows the response curve associated with a perfectly defined absolute threshold, i.e. no response to stimulus values less than S_t and a positive response to any values greater than S_t . Fig. 1.3(b) shows a typical response curve associated with the eye-brain system. It is sigmoid in shape and the uncertainty of response extends typically over an intensity range of $1 \log_{10}$ unit when the curve applies to an intensity threshold (Hecht, Shlaer and Pirenne, 1942).

The sigmoid shape of the frequency-of-seeing curve applies also to the other processes such as the contrast threshold (Blackwell, 1946; Vos, Lazet and Bouman, 1956). The uncertainty in the measurement of the absolute threshold is attributable to biological and psychological effects and also to the very nature of electromagnetic radiation. Light not only has wave properties giving rise to diffraction effects but is also quantised (Hecht, 1942; Pirenne, 1955). This quantisation effect becomes especially noticeable at low intensities where the rate of emission of quanta from a source is relatively small.

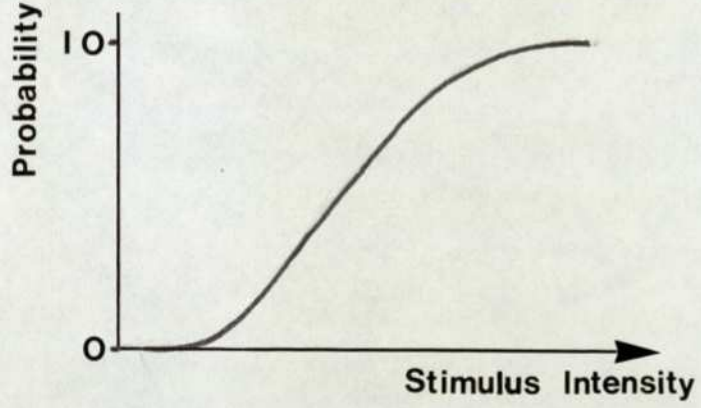
In order to produce a chemical reaction in the retina a quantum of light must be absorbed by it (Grothaus-Draper law) and as a quantum is, by definition, the smallest quantity of light of a given frequency which can exist, it must be absorbed totally by one receptor. The wave nature of electromagnetic radiation results in the fact that a specific quantum of light entering the eye cannot be localised until it has been absorbed. Hence it is impossible to devise an experiment where the stimulus is restricted to one particular rod or cone. Although a retinal rod is capable of being stimulated by the absorption of a single quantum (Hecht, Shlaer and Pirenne, 1942),

FIG. 1·3

(a)



(b)



this does not imply that each quantum absorbed causes effective stimulation of the rod. Further to this, it appears that the stimulation of a rod by one quantum of light energy is not sufficient to allow a human subject to "see" the effect.

Barlow (1956) and Bouman and van der Velden (1947) suggested that at least two and probably more quanta have to be absorbed in order to give the sensation of seeing. Barlow suggests that noise in the optic pathway is the limiting factor, and certainly Piper's (1903) area-threshold law suggests a signal to noise discrimination mechanism. Hecht, Schlaer and Pirenne (1942) found that 5 to 8 fold coincidence of quanta was needed to evoke a visual response. Allowing for absorption and reflection of quanta as they pass through the eyeball to the retina, about 100 quanta incident on the front surface of the cornea would be sufficient for 10 to reach the photosensitive retina. It is when considering such small numbers of quanta that the full implications of the quantum nature of light become evident. A Poissonian distribution of the quanta emitted from a light source gives good agreement with the resultant frequency-of-seeing curves obtained experimentally at the absolute threshold of intensity (Hecht, Schlaer and Pirenne, 1942; Pirenne and Marriott, 1955).

For other thresholds the frequency-of-seeing curve appears to have the same basic sigmoid shape and can be represented theoretically by a normal ogive (Blackwell, 1952). However, this is only an approximate mathematical representation of what is fundamentally an experimental result. So many factors contribute to the shape of the resultant curve that no simple theory can predict the results of experiment.

Mathematical descriptions of the visual thresholds have been sought by many experimentalists in the hope that basic mechanisms could be understood. A particular example is the luminance difference threshold. Bouguer, in 1760, discovered that the difference threshold could be described approximately by the relationship $\frac{\Delta L}{L} = \text{constant}$ where ΔL is the luminance difference just perceptible at ambient luminance L . Weber (1834) extended the same relationship to the other senses, and the relationship is generally referred to as Weber's Law. Fechner (1860) took the basic relationship a little further, defined ΔS as the change of sensation associated with a change in luminance, ΔL , and produced an equation

$$\Delta S = K \frac{\Delta L}{L} \quad \text{where } K \text{ is a constant}$$

which after integration leads to

$$S = K \log_e L + \text{constant}.$$

This seemingly logarithmic relationship between stimulus and sensation has caused controversy and a more realistic description of the operating characteristics of a sensory system would involve a power function rather than a simple logarithmic function. For example:

$$\Psi(\text{subjective magnitude}) = K(\phi - \phi_0)^n$$

Stevens (1961).

ϕ = stimulus magnitude

ϕ_0 = effective threshold

K = constant.

There are many methods used to measure visual thresholds and the results are as varied as the methods used. In fact, it has been suggested by Swets (1961) that when the effects due to an observer's

response criterion are isolated, that sensory limitation is not evident. Although this may be true for stimuli involving luminance differences it is not true in the measurement of spatial resolution limits. Although the same uncertainty occurs at the acuity threshold, there are fundamental physical limitations on the spatial resolving power of the eye. For the human eye the receptor size taken with the saccadic eye movements and also the diffraction effect at the pupil impose an upper limit to the measured acuity.

The organisation of both the retina and the cortex results in certain types of object being more resolvable than others. In general acuity varies with

- a) ambient luminance (Pirenne and Denton, 1952)
- b) colour of test field (Shlaer, Smith and Chase, 1942)
- c) retinal position (Mandelbaum and Sloan, 1947)
- d) orientation of the stimulus (Campbell, Kulikowski and Levinson, 1966; Leibowitz, 1953), and
- e) state of adaptation of the observer (Maudarbocus and Ruddock, 1973).

It has also been shown that a change in the distance of a test object from the observer's eye does not bring about an exactly corresponding change in the retinal image (Shlaer, Smith and Chase, 1942). This is because the posterior nodal distance of the eye alters during accommodation and increases the size of the retinal image as the object is brought closer to the eye. However, it appears after calculation that the effect is only appreciable at very close range (Hartridge, 1950).

Visual acuity is not a universally definable quantity in so far as there are as many different acuities as there are test objects.

It is basically a measure of the eye's ability to detect detail, and is usually expressed as the reciprocal of the angular subtense, in minutes of arc, of the separation which can just be detected between two objects. It is also necessary to define the actual stimuli used in any measurement of acuity.

For very small stimuli where the eye is effectively looking at point sources the sizes of the retinal images are nominally those of the Airy discs, allowance being made for optical aberration in the eye. As the pupil size grows so the effect of diffraction decreases and the effect of aberration increases. So diffractive effects together with the limitations imposed by the retinal receptor sizes give a general limit to normal visual acuity. An average value of monocular acuity under daylight conditions can be taken as $1.0 \text{ (minutes of arc)}^{-1}$. This value is slightly higher for binocular vision (Campbell and Green, 1965). Visual acuity is usually measured using objects having unit contrast (or very close to unit contrast) and could be expected to fall if the contrast of the test object against its background were reduced considerably from unity.

In general, methods of measuring visual thresholds can be divided into three groups, i.e.

- a) the adjustment method,
- b) the yes/no (forced choice) method, and
- c) the rating method.

The adjustment method involves the subject varying a particular quality of the stimulus until it is either just discernible or just not discernible. This method highlights the quite considerable 'hysteresis' effect in the eye. For example, when measuring an

intensity threshold it is found that there is a difference between the threshold measured as the intensity is increasing and that measured as the intensity is decreasing. That is, the threshold intensity is higher when approached from below threshold than it is when approached from above.

The yes/no type of experiment involves a subject in making a choice between yes, he can detect a given stimulus or no, he cannot. This method involves the subject in less complex criteria than other methods, and as such, introduces less subjective effects into the measurement of a particular threshold.

The rating method has many variations but generally involves the subject in rating a particular stimulus, A, as greater or less than another stimulus, B. It may also require the subject to say that although A is less than B it is not as small as C, and this can be extended to a number of stimuli, the subject being required to place them in order of ascending magnitude. This method is, for example, sometimes used in defining the extent of a subject's colour-defectiveness. Although the analysis of rating experiments can become very complex unless very strictly controlled, such experiments do have the advantage of giving a measure of a subject's response criteria.

Because of the uncertainty of the visual threshold it must be defined statistically and for this reason a yes/no type of experiment gives results which are easiest to analyse.

1.6 Summary

A psychophysical experiment was chosen in which a number of basically normal individuals underwent threshold-determining tasks both

monocularly and binocularly. The method chosen was the basic yes/no experiment with slight additions as proof that a stimulus had been detected. Tasks were repeated for a range of ambient luminance conditions.

Initially three tasks were chosen. They were:

- (i) Contrast detection threshold
- (ii) Visual acuity
- (iii) Contrast threshold for recognition.

Control tests were performed in addition to the main experiments in an attempt to make the results more generally applicable.

CHAPTER 2

DESIGN OF GENERAL EXPERIMENTAL METHOD

Three tasks were chosen as a basis upon which to compare monocular with binocular vision, namely

- a) Detection
- b) Acuity
- c) Recognition.

All three tasks were carried out in basically the same manner, a stimulus being projected on to a white screen in front of the observer. The design of the method involved the control and specification of a number of variables, some of which applied only to a single task, and others which applied throughout the experiments. This chapter is concerned with those applying generally throughout the experiments, whilst those relating to particular tasks will be dealt with in the appropriate chapters.

2.1 The Observers

A large number of subjects undertaking each task would have been statistically desirable but with the number of results required and the time available a total of 20 individuals for each task was found to be the number most suitable. Two main requirements were demanded of the observers:

- (i) the results of any one subject must be consistent within themselves, and
- (ii) the results from one subject must be applicable, within certain limits, to the mean of the population to which these results will be applied.

In attempting to achieve condition (i) it was found to be better to use subjects with a scientific background or at least have some basic interest in the results of the experiments. To this end, most of the observers were scientists of one kind or another.

As the work was carried out under the auspices of the Ministry of Defence and the results were to be applied to military personnel in active service, it was decided to choose subjects of 40 years or less, with average or better than average eyesight in both eyes. Colour defective individuals were excluded from the main tests, however, two deuteranopes were employed as control observers to test for any significant differences due to their colour defectiveness. A quick visual acuity test was undergone by each subject before he or she was allowed to take part in the main experiment. Average eyesight was defined in this case as having at least 6/6 acuity in each eye. A test chart conforming to British Standard 4274: 1968 was used for this purpose.

Previous measurement of threshold contrast (Vos, Lazet and Bouman, 1956) has demonstrated that there is very little difference in the results obtained from trained and untrained personnel. All the subjects used in these experiments were untrained to the extent that they were not familiar with tests of the kind involved in the experiment. However, the subjects were informed about various aspects of the human visual system, especially the method of looking away from an object for better detection at low ambient light levels. Also, practice runs were included so that the observer could familiarise himself with the task at hand.

2.2 Presentation of Stimuli

It was required to present the stimulus against a background of

sufficient size to define the state of adaptation of the eye.

Defining the contrast between stimulus and background as

$$C = \frac{L_s - L_o}{L_o}$$

where L_s = luminance of stimulus

L_o = luminance of background

it has been found that there is very little difference in the detectability of objects having the same numerical value of contrast, but opposite sign (Blackwell, 1946; Vos, Lazet and Bouman, 1956).

A wide angle, front-projection system was chosen, back-projection being rejected through lack of space. A field of view of 50 degrees at the observer's eye was taken to be representative of a real-life situation (most optical instruments having an apparent field of 45-55 degrees). As the stimulus itself subtended much smaller angles than this (5 degrees or less), edge effects were minimised.

The projection system had to include facilities for varying both the background luminance and the contrast between the stimulus and its surround. A system which projected a single photographic slide was chosen, the overall luminance being fixed by positioning neutral density filters in front of the projector lens and the contrast being varied by simply changing the slide. A remotely-controllable slide changer was used to allow the experimentalist to change slides and write results at a table slightly removed from the main projection system.

2.3 Luminance Range

A range of background luminances from 7 Cd M^{-2} to $5 \times 10^{-5} \text{ Cd M}^{-2}$

was chosen. From Table 2.1 it can be seen that this represents a range of ambient light levels from a dark day to overcast starlight.

Support for the figures in Table 2.1 is given elsewhere (e.g. Middleton, 1962). If the visual system is operating with an unrestricted pupil, this range involves the photopic, mesopic and scotopic states of the eye. Higher luminances were not considered, partly because of practical difficulties (the projection lamp would have had to have been run at a higher current level, causing more rapid aging of the lamp) but mainly because of the fact that a levelling-off of the eye's response mechanism occurs at higher light levels. For example, there is a plateau effect for visual acuity (Lythgoe, 1932; Foxwell and Stevens, 1955) where acuity becomes substantially independent of luminance at about $50-100 \text{ Cd M}^{-2}$. Also, in the contrast domain, liminal contrast becomes effectively independent of adaptation luminance at levels above 10 Cd M^{-2} (Blackwell, 1946; Vos, Lazet and Bouman, 1956).

A telephotometer, calibrated with respect to a standard light source, was used to measure and to monitor the luminance level at the screen. A regulated voltage supply to the projector was used to eliminate mains fluctuations.

2.4 Colour of the stimulus and Background

A white projection screen was used throughout and this is to some extent justified by the fact that Blackwell (1952) found that threshold contrast changes very little with change in background colour. Coloured stimuli were not included mainly because of the amount of extra work which would have been involved, and the inherent difficulty of adequately specifying colour contrast.

Description	Luminance (Cd M ⁻²)
Full daylight	3×10^3
Overcast day	3×10^2
Very dark day	30
Twilight	3
Deep twilight	3×10^{-1}
Full moon	3×10^{-2}
Quarter moon	3×10^{-3}
Starlight	3×10^{-4}
Overcast starlight	3×10^{-5}

Range of horizon sky luminances encountered during
an average period of 24 hours, (Duntley, 1946)

TABLE 2.1

Although only white light was used to project stimuli, it was considered important to specify the colour temperature of the light for two reasons. Firstly, the experiments should be made as repeatable as possible and secondly, Levi (1974) shows that colour temperature of an incandescent body can influence its threshold visibility. After consideration of naturally occurring sky colour temperatures, it seemed realistic to choose a colour temperature between 5000 °k and 10000 °k (LeGrand, 1968). As an example, an overcast sky has an average colour temperature of 6400 °k (Taylor and Kerr, 1941; Moon, 1947). Standard illuminant C was chosen as a practical level at which to work ($S_c = 6740$ °k) and a colour correction filter was used to raise the colour temperature of the projected light to this level. So that this value was not changed significantly as the screen luminance was decreased, neutral density filters with a very flat spectral response were used to attenuate the light.

2.5 Viewing Distance of Stimuli

Tests have been performed by the Ministry of Defence to decide upon which preferred position of focus of an eyepiece on a binocular instrument (Poole, 1967). It was discovered that the preferred focus was at -0.75 dioptre at daylight levels of illumination, and this agrees with the state of the eye for minimum spherical aberration (Davson, 1962). This means that the eye prefers an object at 1.3 metres range at high light levels. At low levels the eye becomes myopic due to the increased pupil size. It was decided to choose a viewing range of 1.3 metres for the main tests, with control tests included to determine the effect of varying this distance.

2.6 Time Limits and Fatigue Effects

The time allowed for detecting detail in a test object has a marked effect on the performance of the observer (Foxwell and Stevens, 1955). Also Ikeda (1964) suggests that, when measuring the visual threshold, sometimes a simple change in the duration of the test stimulus may entail a change in the mechanism responsible for the increment threshold. Therefore, to assist in obtaining consistent results and to relieve the stress of "working against time", the observer was allowed as much time as he wished to make a judgement on a given stimulus.

In order to minimise the fatigue effects due to prolonged working at threshold levels of the eye, the observer was allowed to rest when he felt it necessary, and was encouraged to make any remarks about the appearance of the stimulus or condition of his eyes throughout the experiment; (sometimes when fatigued, an observer mentioned bright spots of light on the screen at the very lowest luminances).

2.7 Viewing Conditions

Before commencing any of the tests, the subject was required to adapt to the ambient luminance. In support of the data in fig. 2.1, which gives an indication of the number of minutes required to adapt to a given light level, it was found that a subject required a period of up to 25 minutes to adapt to a given level.

In an attempt to give the observer a realistic (real-life) task, the natural pupil was used, i.e. no artificial pupils were placed in front of the eye. Also, when the subject was viewing monocularly, the non-viewing eye was occluded. This approximates to the general case, where an individual, viewing monocularly, would close the non-viewing eye. Campbell and Green (1965) measuring acuity,

COURSE OF DARK ADAPTATION IN THE HUMAN EYE

The eye was initially adapted to an ambient luminance of 2400 Cd M^{-2} (After Walsh 1958)

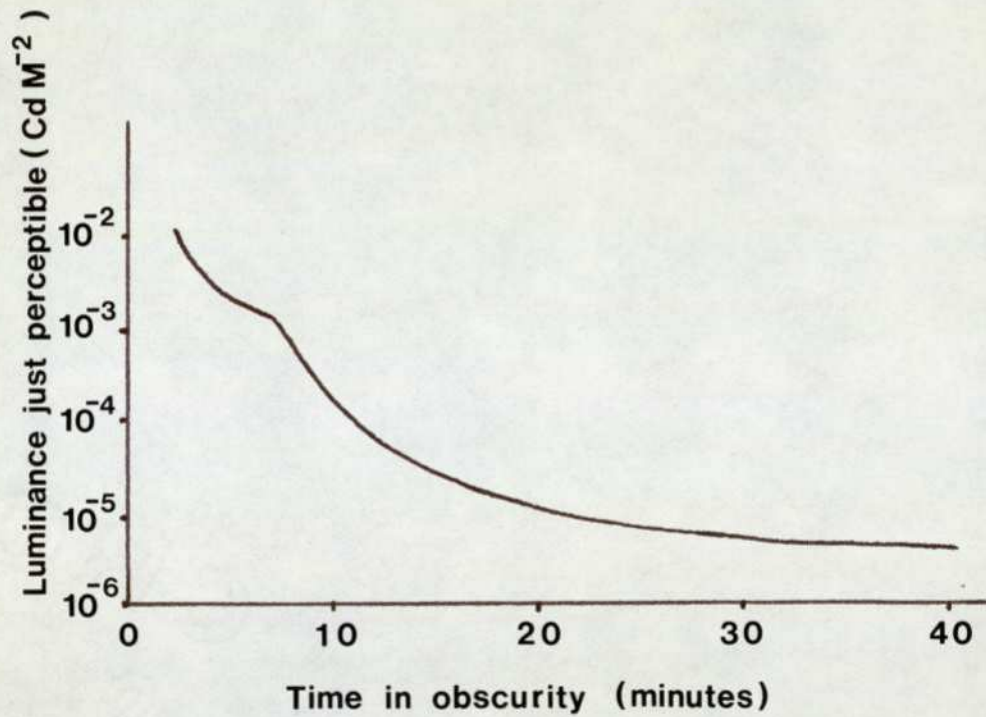


FIG. 2·1

Kristofferson (1958) measuring detection threshold and Crawford (1940) measuring thresholds foveally and parafoveally found that when making measurements monocularly, no significantly different results were obtained by blanking out the unused eye completely or presenting it with diffuse illumination of the same level as that of the test field.

Test runs were made as short as possible, with frequent changes from right eye viewing to left eye viewing, and from monocular to binocular vision. It was generally found also, that if a subject were given an adequate explanation of why the tests were necessary and the general reasoning behind the experiment as a whole, he could sustain quite a high level of concentration, and hence a good degree of reliability.

A small red lamp was fixed to the centre of the projection screen to give the observer a reference point - this was especially important at lower light levels as it gave the observer a point upon which to focus. Red was chosen so that the light would have a minimal effect on the subject's state of adaptation. The intensity of the light was variable so that it did not present a distraction to the observer.

CHAPTER 3

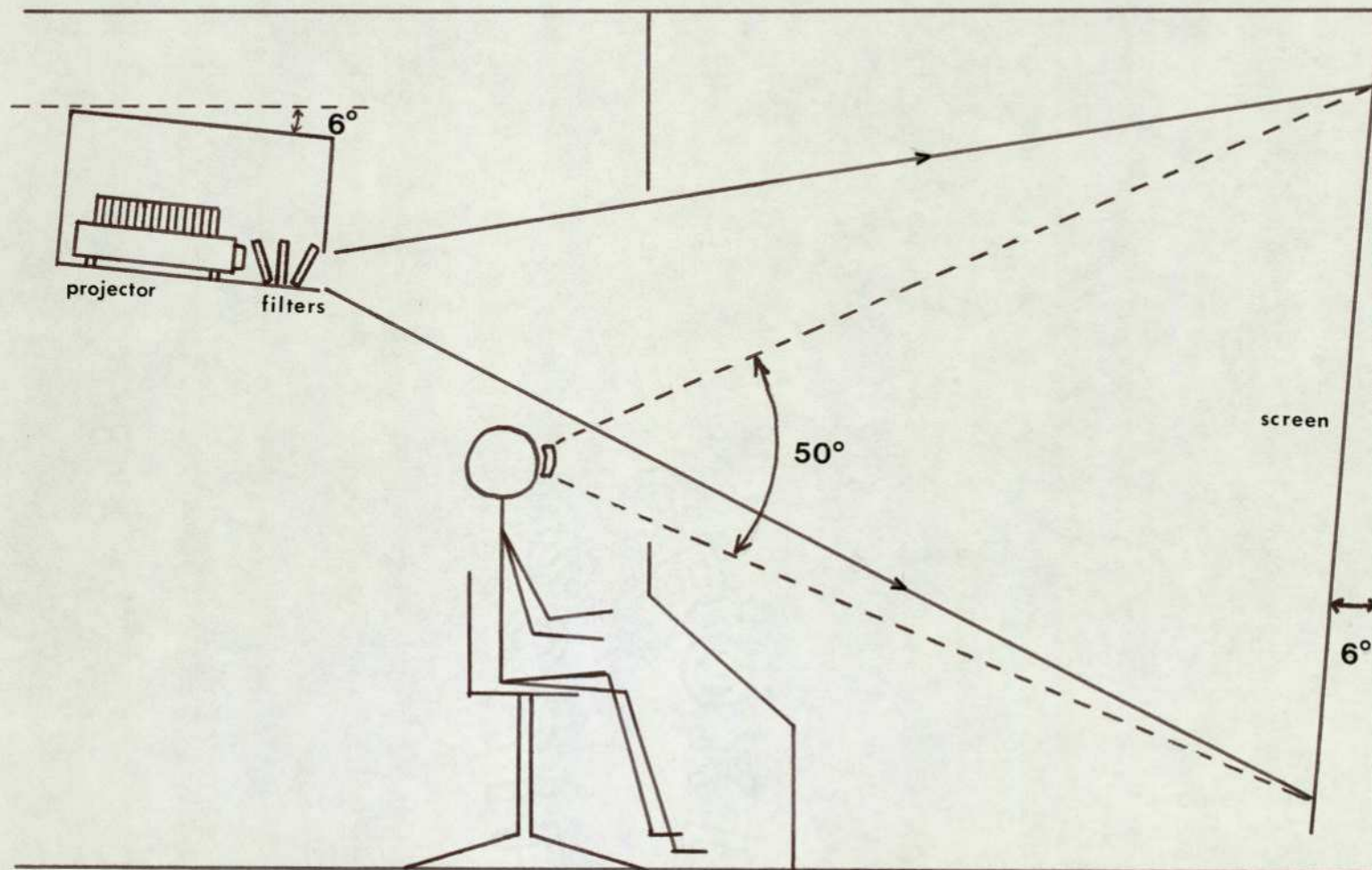
APPARATUS AND GENERAL CALIBRATIONS

All experiments were carried out inside a dark room. The general layout was basically quite simple. A Kodak Carousel slide projector was used to project the stimulus onto a white screen and the subject sat in front of the screen and viewed the stimulus directly, as in fig. 3.1. Neutral density filters were used to vary the luminance at the screen, and a colour filter raised the colour temperature of the projected light to standard illuminant C. Measurement of luminance and contrast were made by means of a Gamma telephotometer, the contrast between the stimulus and its background being measured at the screen directly. The projector was supported on a steel lifting-table at a distance of 6 feet from the screen, the optical axis of the projection system being inclined at 6 degrees to the horizontal so that the subject's head did not interrupt the projected beam. The screen was positioned at 6 degrees to the vertical (as shown) so that a sharp image of the slide was obtained over the total area of the screen. The subject viewed the screen using a brow pad (plate 1) to maintain a distance of 1.3 metres from the centre of the screen to the subject's eyes. The illuminated area of the screen subtended 50 degrees at the brow pad. The reasons for the 1.3 metre range and 50 degrees field of view were explained in chapter 2.

3.1 The Projection System

The slide projector and filter system were housed within a black box to prevent extraneous light from reaching the screen either directly

FIG.3-1



SCHEMATIC LAYOUT OF PROJECTION SYSTEM

or from surrounding walls. An extractor fan was fitted into one side of the black box to allow movement of air from the projector. This was necessary because of the large amount of heat produced by the high power lamp. The projection lamp was a tungsten-halogen type (nominally 24 volts, 250 watts) and was under-run so that a longer life (~ 100 hours) could be obtained from the lamp and also a slower fall-off of luminous intensity with age was achieved.

A Kodak Carousel S-AV remote-controlled slide projector was used to project the stimuli from 50mm x 50mm slides onto the screen.

Provided that all the slides were constructed in the same way, the spring loading of each slide against a backplate ensured that if one slide was in focus at the screen, all the other slides would be in focus also. The circular slide magazine held up to 80 transparencies, and the remote controlling mechanism enabled the operator to move the slide tray either forwards or backwards, and it also included a remote focussing facility.

3.2 Operator's Monitor and Control System

Plate 2 shows the operator's view of the remote control and monitoring apparatus. This apparatus was housed within a small cubicle situated just behind the projector. The main control panel allowed control of overhead lights (white and red), electric fans, the projector lamp and certain digital displays. These displays indicated the following:

- (i) mains voltage to the projector,
- (ii) reference number of the slide magazine in use,
- (iii) attenuation factor of neutral filters in use,
- (iv) slide number.

The operator could move the slide carrier either backwards or forwards and could also focus the slide by remote control. A flexible red

PLATE 1

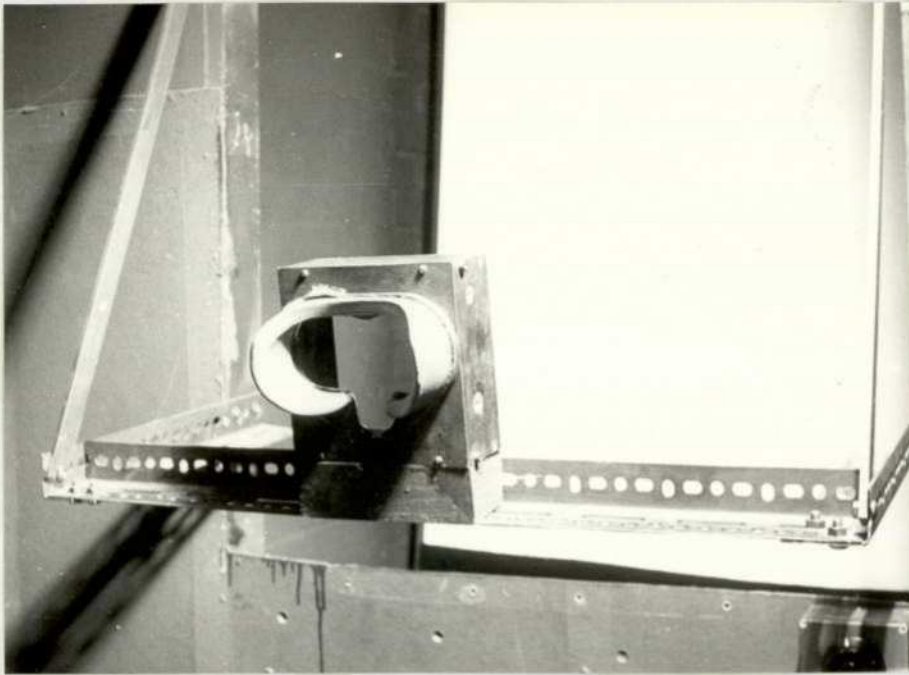


PLATE 2



light was provided so that the operator could see enough to be able to write results without introducing any distracting light to the system. The telephotometer was permanently pointed towards the screen from a position just beside the operator, and regular checks were made on the screen luminance.

It was necessary to move the slide magazine both backwards and forwards, sometimes missing out certain slides. To provide a constant check on which slide was in use at any moment, a digital readout system was constructed and this displayed the number of the slide being projected.

Basically, the slide number display system consisted of a resistor chain with a regulated voltage across the ends of the chain. All the resistors were chosen to have accurately equal resistances and when 8 volts were maintained across the ends of the chain, the potential difference between the end of the chain and each link point was $8 \times n/80$ volts, where n was the number of resistors between the link point in question and the end (fig. 3.2). The resistors were 0.5 watt, metal oxide type, each with 100 ohms nominal resistance.

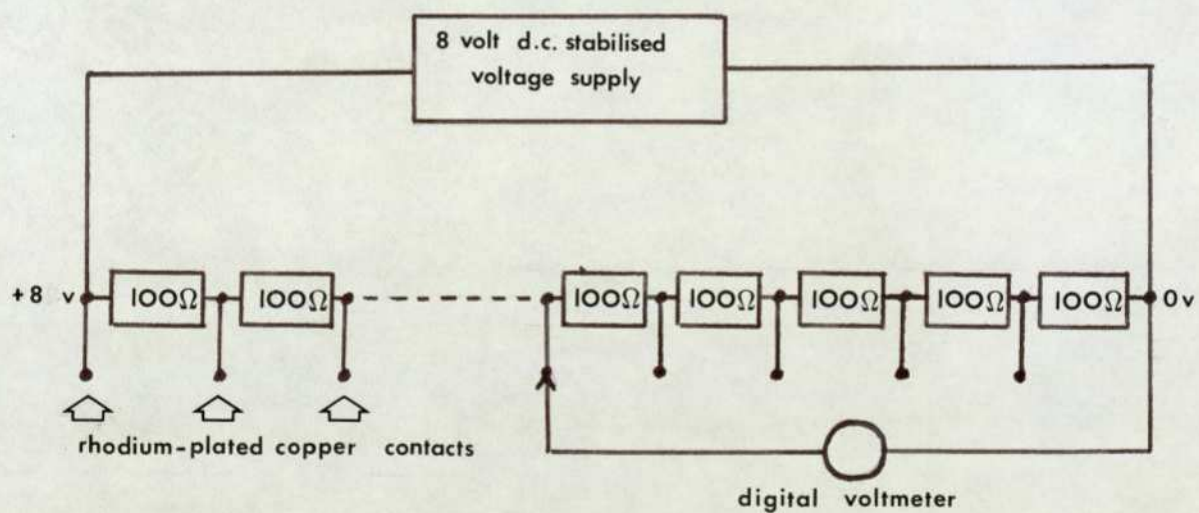
Plate 3 shows the construction of the readout system. Contact was made through rollers running over etched copper strips on printed circuit board. The copper strips were all rhodium plated to provide a hard-wearing surface. The complete disc was attached to a magazine cover and this was fixed so that when the digital readout was $0.1 \times n$ volts, slide number n was being projected.

Initially, an attempt was made to stabilise the mains voltage to the projector by using a voltage stabilising transformer, and indeed it was found that this controlled the voltage to within ± 1 volt.

PLATE 3



FIG. 3.2



SLIDE COUNTING SYSTEM

However, the noise (transformer hum) was found to cause a distraction to the observer so the regulation of the mains voltage was achieved by wiring in a heavy duty rheostat between the mains output and the projector, and leaving the operator to ensure that mains drift was kept to within specified limits (discussed in section 3.5).

Finally, the operator had a tape recorder at his disposal so that incidental remarks from the observer could be easily recorded throughout the experiment.

3.3 Production of Stimuli

All stimuli were projected from transparencies and in every case a black (or grey) object was projected on a lighter background, i.e. negative contrast. The method of production of all the slides was the same. The object was drawn on a large sheet (24 x 24 inches) of white card, photographed to produce a high contrast (50mm x 50mm) negative, and then prints were made on lantern plates (50mm x 50mm). A clean cover plate was then bound to the emulsion side of the lantern plate with metallic adhesive tape.

The initial photographing of the object on white card was carried out using a Linhoff Technical camera, enabling an accurate reduction of size from 24 x 24 inches to 50 x 50mm to be achieved. The very small Landolt ring slides were made by carrying out a double reduction process so that the rings could be drawn at a reasonable size in the first place. The lantern plate prints were made by a simple contact process, the exposure time being constant at five seconds and the development time being varied to give the necessary range of contrasts. It was found that only an approximate calibration curve of development time versus final contrast (defined in chapter 2)

could be produced for any negative (fig. 3.3) and that a number of prints had to be made to ensure a final slide having the required contrast. The plates were washed thoroughly after fixing and wetting agent was used to eliminate drying marks. The final slide was bound with metalised tape because it was found that a binding tape of this type was affected less by the heat from the projection lamp than any other kind.

As a number of slides was produced with an object to background contrast of 0.005 - 0.01, and this was very difficult to distinguish, using the naked eye, a microdensitometer was used to check on edge sharpness and uniformity. A 5 per cent variation across a given object was taken as the maximum allowable change in density.

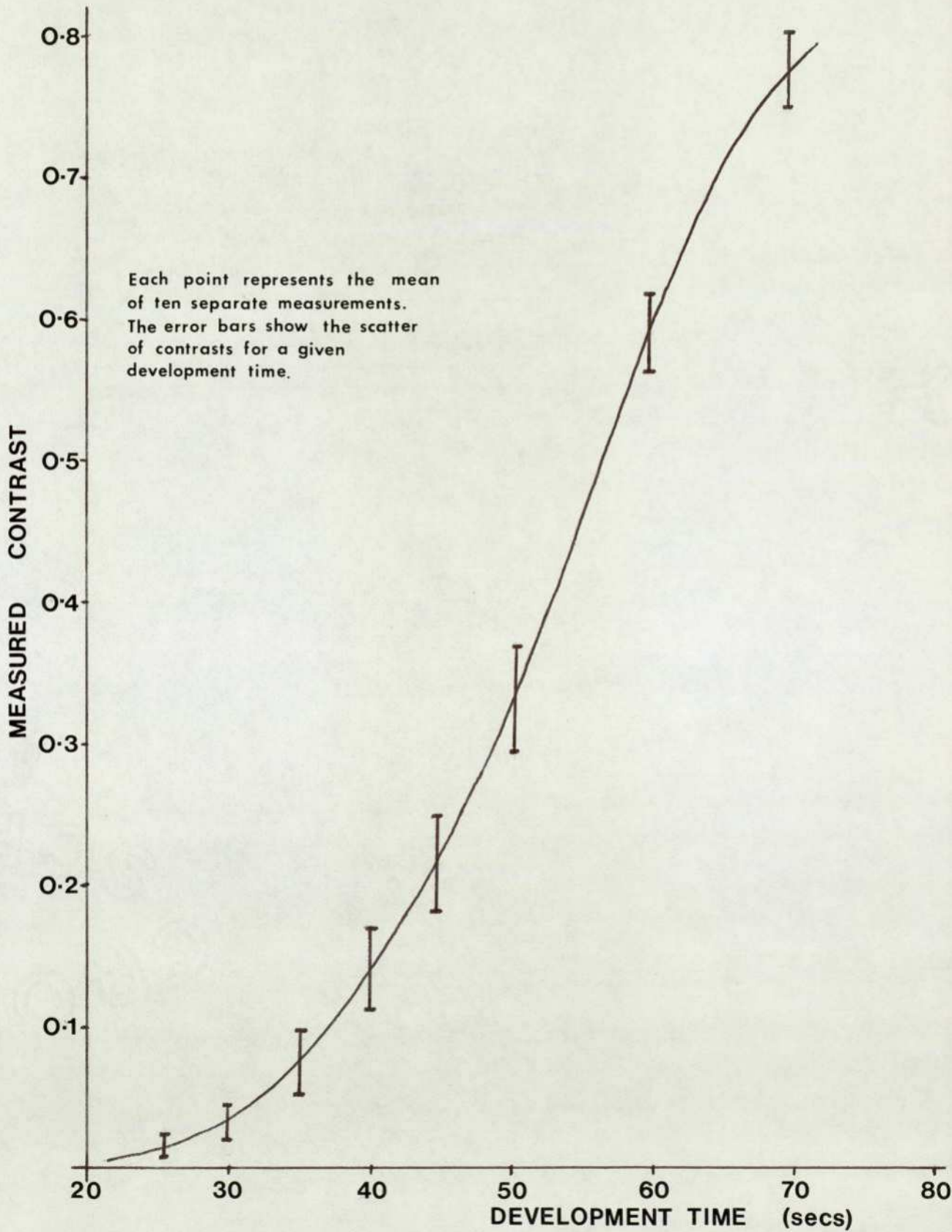
Dust on the slides was kept to a minimum by cleaning them with anti-static cleaner.

3.4 Construction and Calibration of the Optical Filters

(a) Neutral density filters.

Neutral density filters were required to attenuate the screen luminance up to a factor of 10^6 , requiring a total optical density (optical density = $\log_{10}$ attenuation factor) of 6 in front of the projection lens. Because it is very difficult to construct accurately a neutral filter having an optical density greater than 3 (due mainly to monitoring problems), it was decided that a combination of filters would give an adequate solution, and four filters were produced having nominal optical densities 1, 2, 3 and 3. Thus, by a combination of 2 or fewer filters, optical densities of 1, 2, 3, 4, 5 or 6 could be produced.

FIG. 3.3



CURVE OBTAINED FOR ILFORD SPECIAL LANTERN PLATES
DEVELOPED IN ID II AT 20° C

Fig. 3.4a shows the spectral response curves for a dyed-glass type of neutral filter and a metal vapour type. The dyed-glass filter is the ON 10 Chance-Pilkington type, and although other filters of this type are available they all have the same type of spectral response, i.e. much less flat with respect to wavelength than the metal vapour types. The metal vapour filter referred to in fig. 3.4 was constructed by evaporating titanium onto plate glass under vacuum. This was found to be even flatter than an equivalent aluminium filter. The reason for requiring a flat spectral response from the filters becomes evident in fig. 3.4b where the response of a combination of two density 1 filters is shown. As the total density becomes greater, so the humps in the response curve become more pronounced. To keep the colour temperature of the light as close to standard illuminant C as possible throughout the luminance range, four titanium filters were used.

The filters were constructed on pieces of plate glass measuring 4 x 4 inches mounted in brass frames to prevent edge damage. Fig. 3.5 shows a typical microdensitometer trace in two mutually perpendicular directions across a filter with a nominal optical density 0.95. All four filters were measured in this way to confirm uniformity across the filter and to measure the optical density. These measured densities were checked by measurement of the screen luminance using the telephotometer, the photometer measurement being the actual value taken in the experiments. As seen in table 3.1, agreement between the microdensitometer readings and the telephotometer readings was very good.

FIG. 3·4a

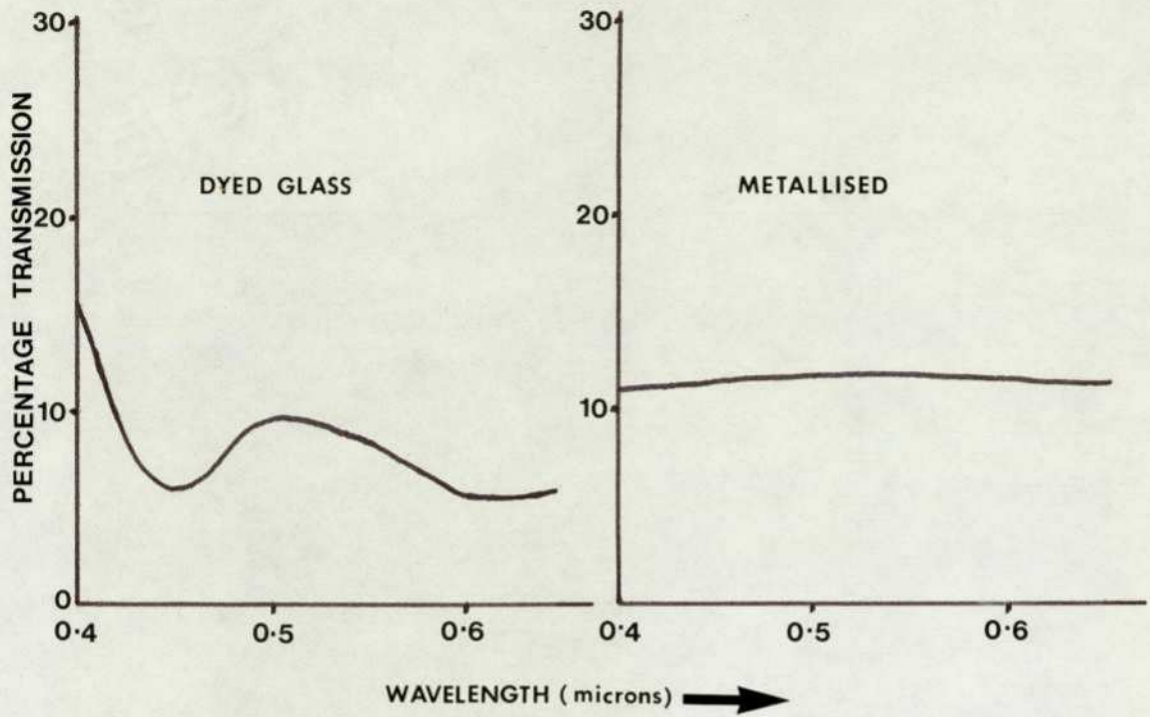
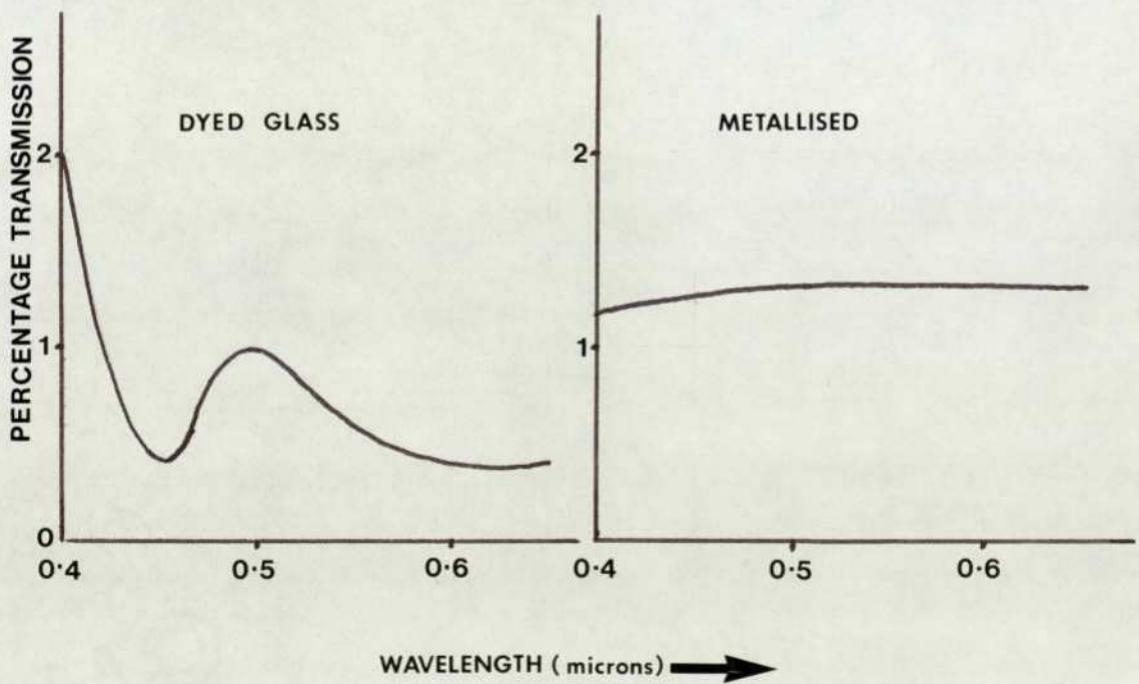
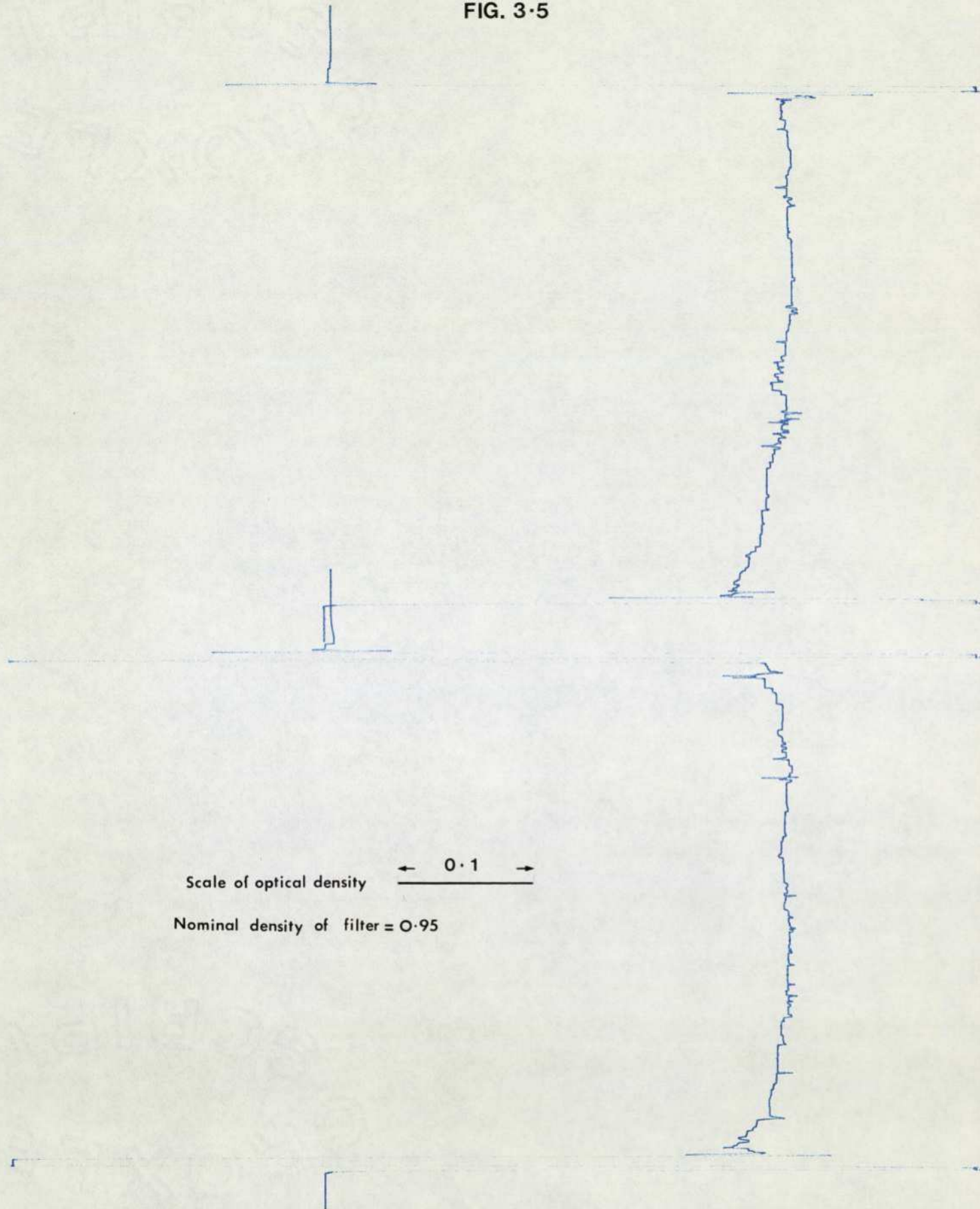


FIG. 3·4b



SPECTRAL RESPONSE CURVES FOR NEUTRAL DENSITY FILTERS

FIG. 3-5



MICRODENSITOMETER TRACES MADE IN MUTUALLY
PERPENDICULAR DIRECTIONS ACROSS A TITANIUM FILTER

Filter	Optical density measured on microdensitometer	Optical density as measured by telephotometer at the screen
A	0.95	0.92
B	1.96	1.91
C	2.94	2.88
D	3.26	3.32
A + B	2.91	2.85
A + C	3.89	3.79
A + D	4.21	4.30
B + C	4.90	4.83
B + D	5.22	5.26
C + D	6.20	6.12

TABLE 3.1

A problem encountered in using metal vapour filters was the fact that such filters act as mirrors and, if positioned parallel to each other, produced secondary images caused by reflections between filters to appear on the screen. To overcome this problem, the filters, when used in a combination, were positioned at small angles to each other (fig. 3.6) so that all reflected images were lost from the system.

(b) Colour temperature conversion filter.

It is not intended to describe the basic principles of colorimetry (a full account appears in LeGrand, 1957). When plotted on the XYZ chromaticity diagram, the locus of a full radiator is shown in fig. 3.7, where

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

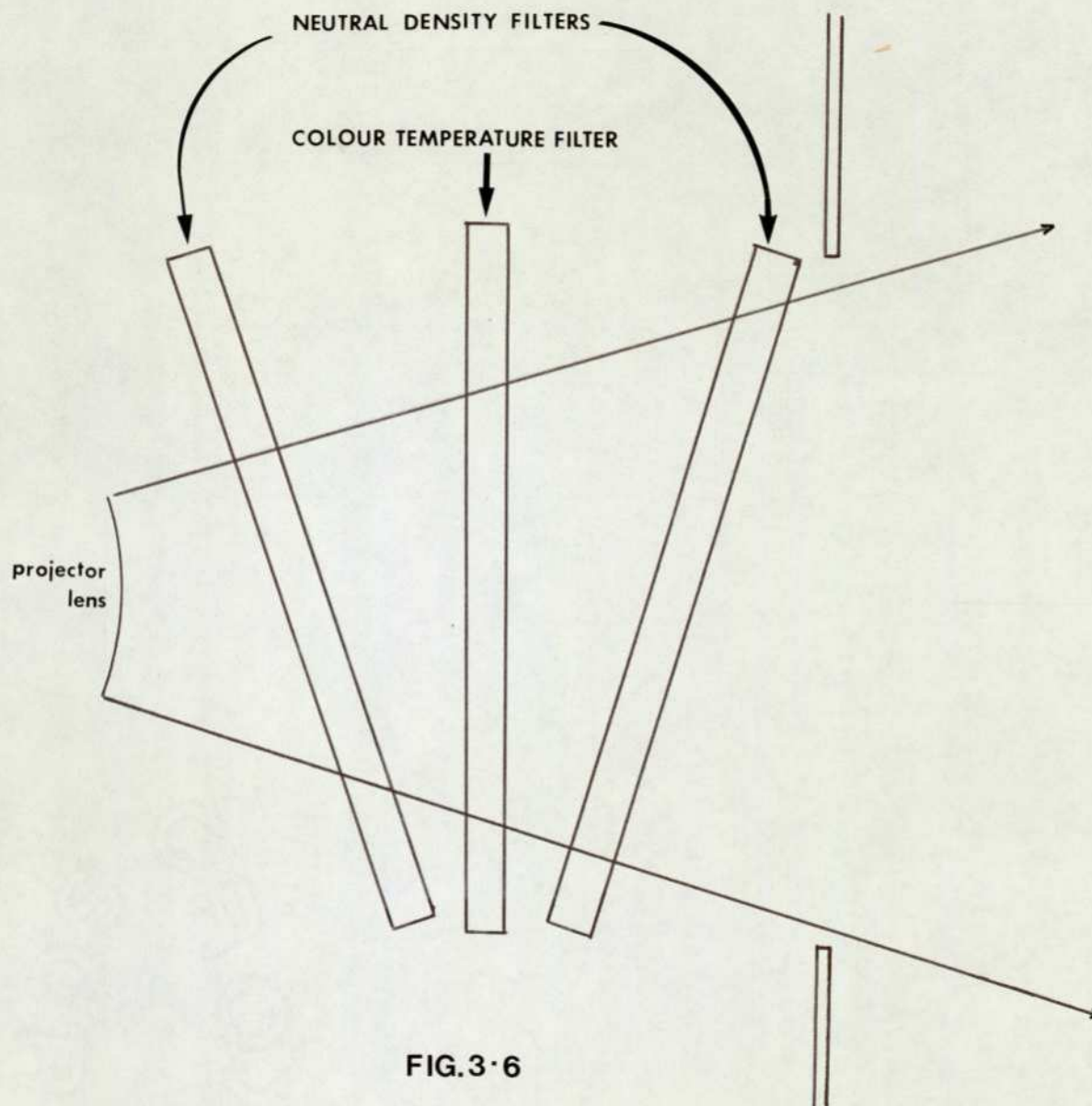
based on the C.I.E. XYZ system (1931). When the representative point of the source lies a little away from this locus, a correlated colour temperature can be defined. Judd (1936) describes how the correlated colour temperature lines are calculated, and the result is shown in fig. 3.7.

Using a Joyce-Loeble telecolorimeter, the colour temperature of the projected light was measured at the screen. The co-ordinates were

$$x = 0.384$$

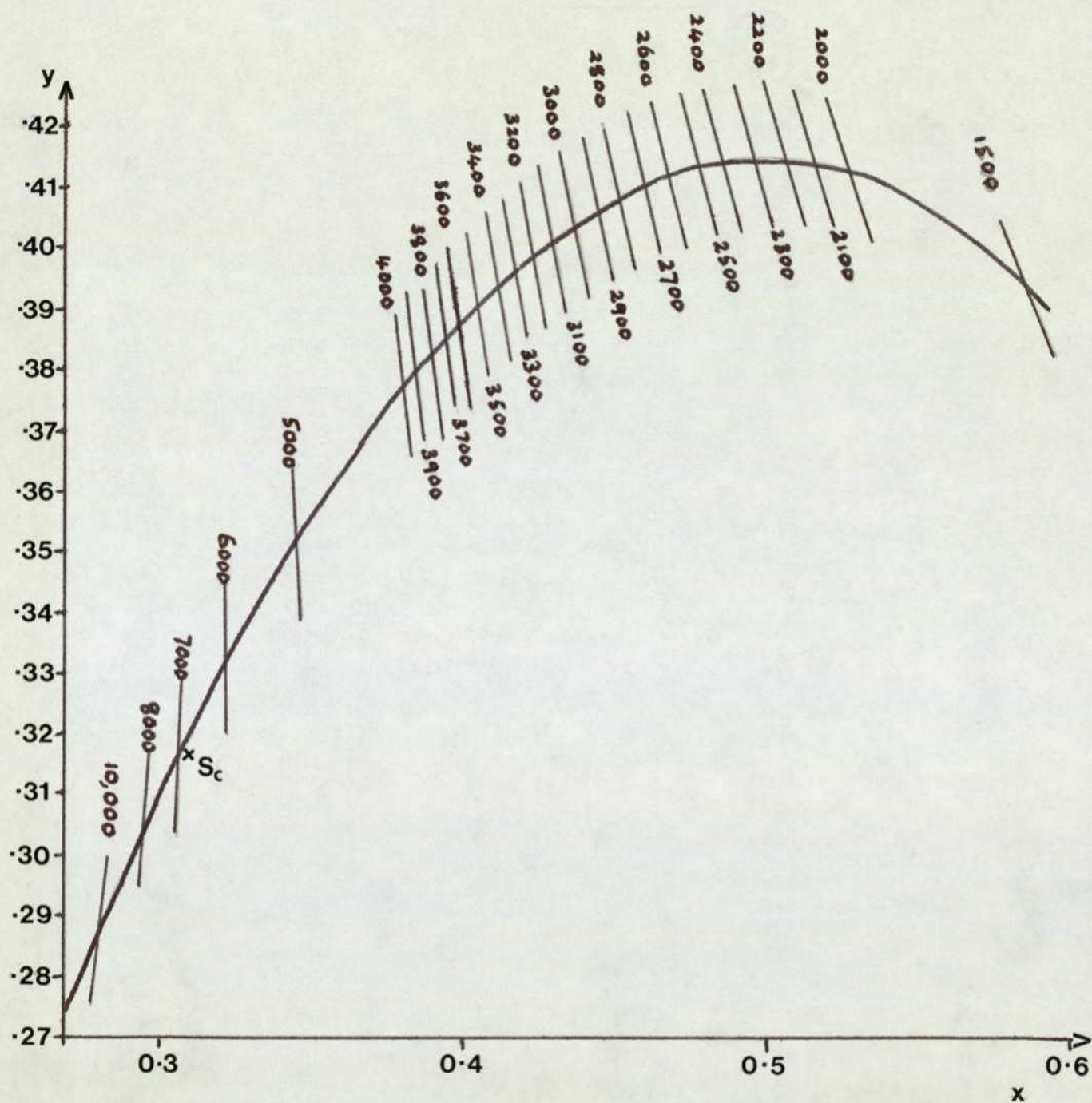
$$y = 0.364$$

giving a correlated colour temperature of 4000°K . A colour temperature correction filter was used to raise this to Standard Illuminant C ($S_c = 6740^{\circ}\text{K}$; $x = 0.3101$, $y = 0.3162$).



POSITION OF FILTERS TO ELIMINATE SECONDARY IMAGES AT THE SCREEN

FIG. 3.7



CHROMATICITY DIAGRAM FOR A FULL RADIATOR WITH
ISO-TEMPERATURE LINES (Judd 1936)

If T_1 represents the colour temperature of the projector system and T_2 represents the colour temperature of filter + projector system, where T_1 and T_2 are expressed in $^{\circ}\text{K}$, then the number of mired units difference is given by N , where

$$\begin{aligned} N &= \frac{10^6}{T_1} - \frac{10^6}{T_2} \\ &= 10^6 \left[\frac{1}{4000} - \frac{1}{6740} \right] \\ &= 102 \text{ mired units.} \end{aligned}$$

A Chance-Pilkington OB8 filter having a correction factor of 45 mireds per millimetre was used. The filter was constructed 2.3mm thick giving a 103.5 mired correction factor. The spectral response curve of the OB8 filter is shown in fig. 3.8.

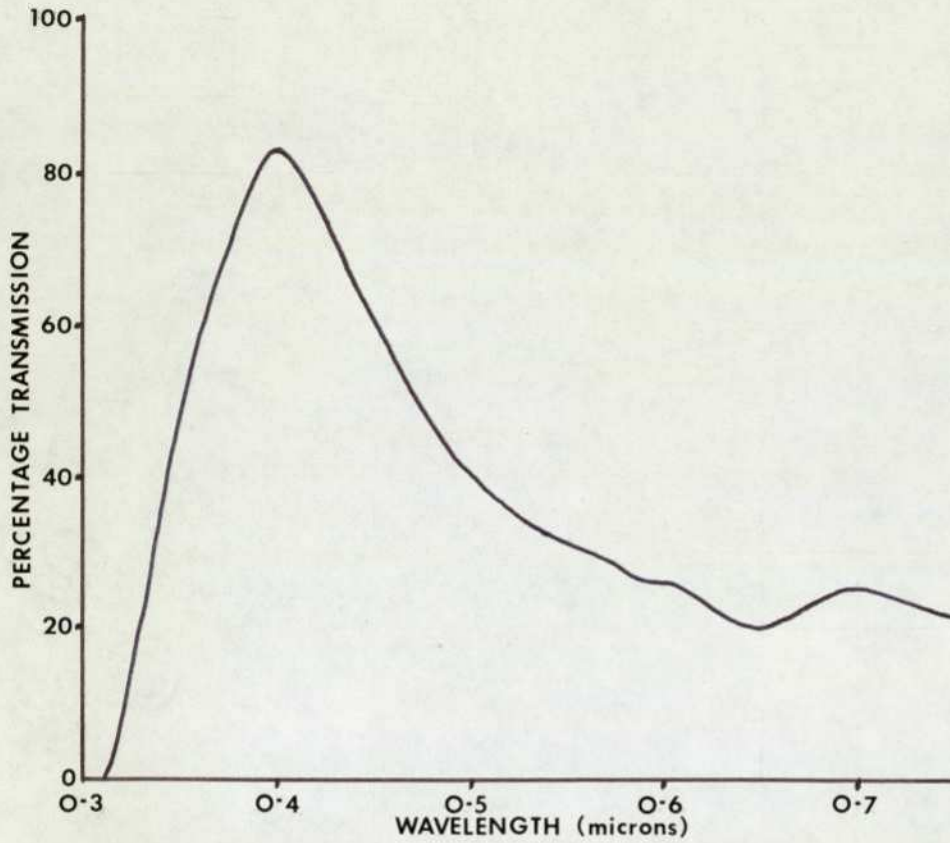
3.5 Luminance Measurement and Calibration of the Telephotometer

All measurements of luminance were made directly at the screen using a Gamma telephotometer. Although the instrument had an internal calibrating lamp, in order to check the linearity of the instrument, a secondary luminance standard was constructed and all luminances quoted in the following experiments have been measured with reference to that standard.

(a) Production of a standard luminance.

A 12 volt automobile lamp was calibrated for luminous intensity by the National Physical Laboratory (N.P.L.) and a standard reflecting surface (Russian MC 20 white opal), also calibrated by N.P.L., was used to provide the standard luminance. The standard lamp was calibrated to run at 10 x Weston Cell voltage, i.e. 10.187 volts, and the current flowing through the lamp was monitored as a check against aging. The basic circuitry is

FIG. 3-8



TRANSMISSION CHARACTERISTICS OF OB8 COLOUR
TEMPERATURE CONVERSION FILTER (thickness = 2 mm)

shown in fig. 3.9, a null method being used in the measurement of both voltage and current. Clearly, when the galvanometer is connected between points c and d and reads zero then the potential difference between points a and b is 10×1.0187 volts. The current through the lamp was monitored by measuring the potential difference across a 0.1Ω standard resistor by means of a very sensitive potentiometer circuit (Appendix 4).

Once the lamp was running at the correct voltage and the opal glass reflector was positioned at a known distance from the lamp, the telephotometer was calibrated using various different ranges. The set-up is shown in fig. 3.11 and a calibration curve (the most linear) is shown as fig. 3.10.

If L = luminance of the opal glass surface (Cd M^{-2})

I = luminous intensity of the lamp (Cd), measured
as specified by N.P.L.

R = reflectance factor of the opal glass at normal
incidence

r = range (M) from the surface of the opal glass to
the filament plane of the lamp

$$\text{then } L = \frac{IR}{\pi r^2} \dots\dots\dots 3(i)$$

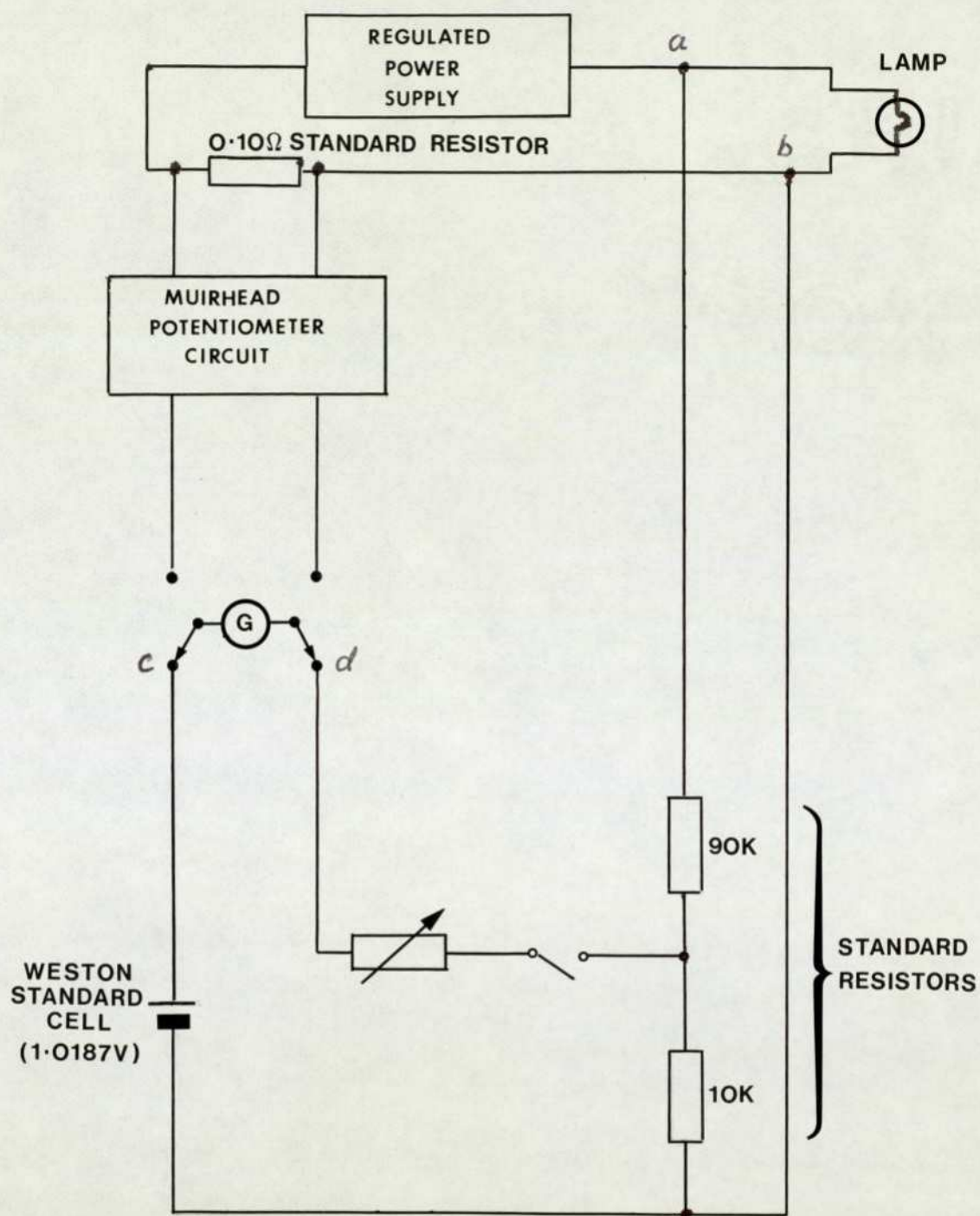
Note: The opal glass was only used in the irradiation and viewing conditions for which it was calibrated.

The standardisation figures for both the lamp and the opal glass reflector are given in Appendix 5.

(b) Possible errors involved.

The luminous intensity of the lamp was known to an accuracy

FIG. 3·9



STANDARD LAMP POWER SUPPLY AND MONITOR CIRCUIT

FIG. 3-10

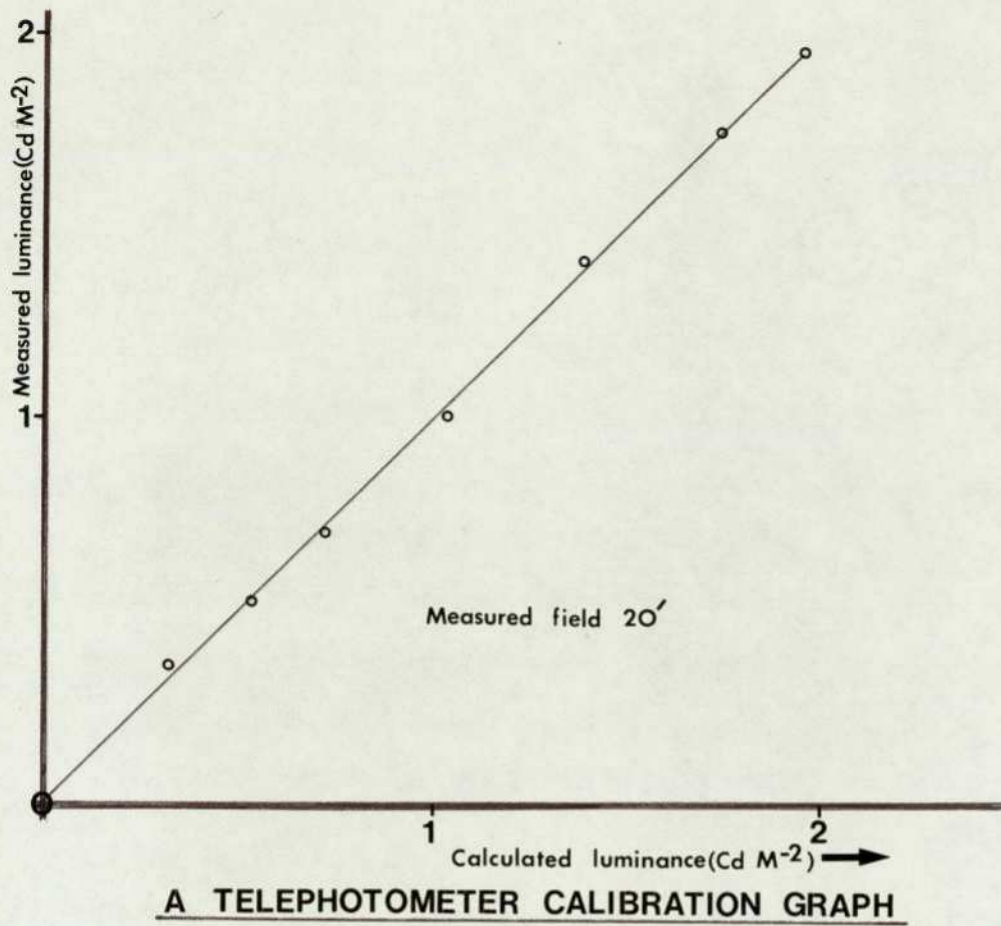
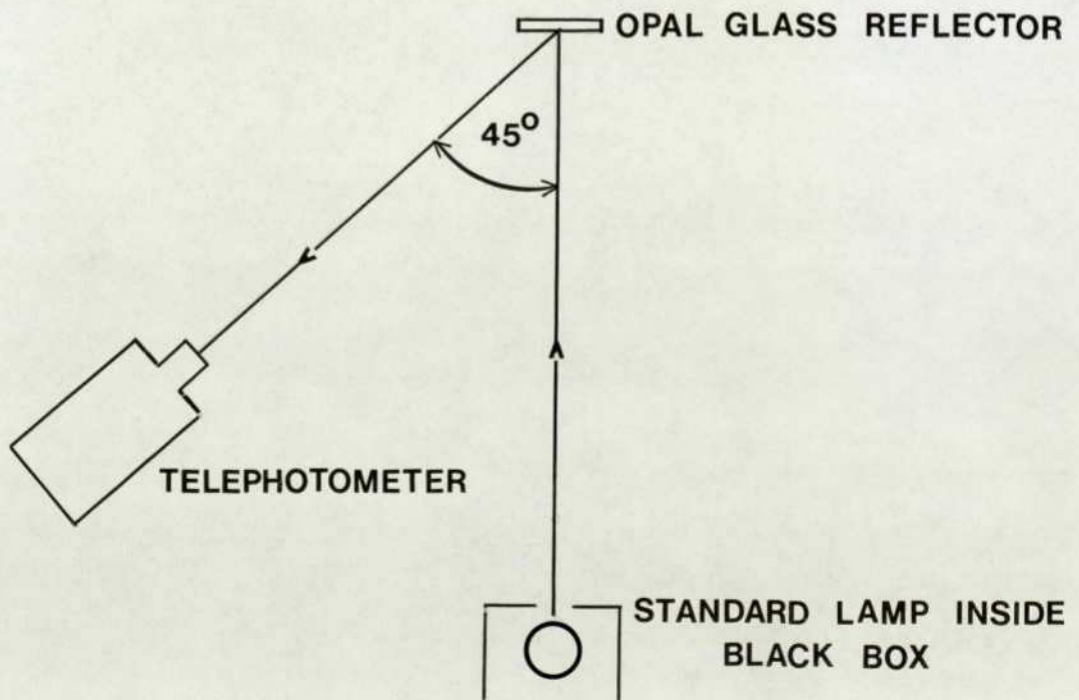


FIG. 3-11



ARRANGEMENT FOR CALIBRATION OF TELEPHOTOMETER

of ± 2 per cent. The reflectance factor, R , was calibrated to within ± 0.5 per cent and the range, r , could be specified to within ± 0.5 per cent, assuming $r \geq 10$ cms. From equation 3(i), the possible error in the calculated value of L is ± 3.5 per cent. This gives a limit on the absolute accuracy of luminance measurements and also means that there is a possible 7 per cent error in the measurement of contrast using the calibrated telephotometer.

(c) Variation of luminance at the screen.

Variation of luminance occurred both spatially and temporally. Fluctuation of luminance with time was due almost entirely to the mains variation. Other changes were negligible in comparison. It was found that a variation of ± 2 volts in the mains voltage (230 volts) led to a change of less than ± 2.5 per cent in the luminance at a given point on the screen. By use of a rheostat, the fluctuation in mains voltage could be kept to within ± 1 volt, i.e. less than ± 1.25 per cent change in screen luminance.

Spatial variation of luminance was measured across the screen, and it was found that there was a variation of just greater than 25 per cent between the centre of the screen and the extreme outer edge. However, within the middle 20° (as measured at the eye) the variation was less than 10 per cent and the mean variation of luminance round the edge of a given stimulus was less than $3\frac{1}{2}$ per cent, i.e. less than the absolute accuracy obtainable in measuring luminance with the telephotometer.

3.6 The Observer's Viewing Position

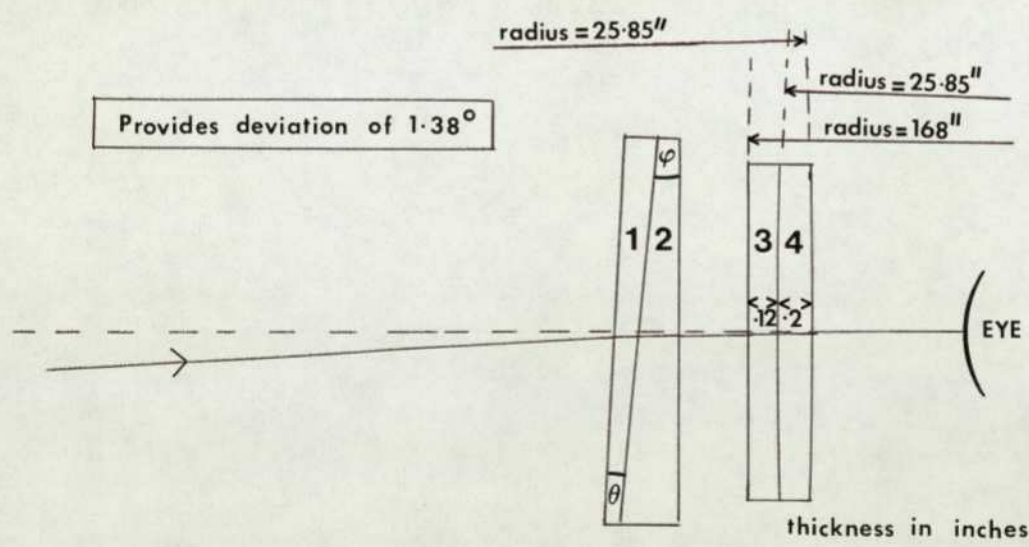
The observer sat in an adjustable chair, i.e. adjustable for height, and his eyes were maintained in a position 1.3 metres from the centre of the screen by the use of a brow pad (plate 1). A control test was performed in a number of cases to discover the effects of varying the distance between the observer and the screen. This was achieved by the use of two 0.75 diopetre, achromatic lenses which were fixed in position just behind the brow pad. They had the effect of producing an image at infinity, i.e. the eye was completely relaxed. Two achromatic prisms were positioned behind the lenses to nullify any convergence effect, i.e. the subject saw the stimulus as though it were at infinity with no convergence to suggest that the object was any closer. The optical design parameters relating to the lenses and prisms are shown in fig. 3.12. Plate 4 shows the brow pad with lenses and prisms in position. They produced no magnification and the inter-ocular separation was adjustable.

The observer was provided with a control for the red reference light which was fixed to the centre of the screen. The light was produced by a red light-emitting diode subtending approximately 4 minutes of arc at the subject's eye. The control enabled the observer to adjust the intensity of the lamp to a non-distracting level.

Finally, it should be mentioned that in the interests of hygiene the brow pad, which was made of soft rubber, was cleaned with an odourless disinfectant after each experiment.



FIG.3-12



1 & 3 SF2 (flint glass)

2 & 4 BK7 (crown glass)

Full apertures: prism 2"
lens 1.75"

φ = 5.64°
θ = 2.37°

PLAN VIEW OF LENS AND PRISM SYSTEM (FULL SIZE)

CHAPTER 4

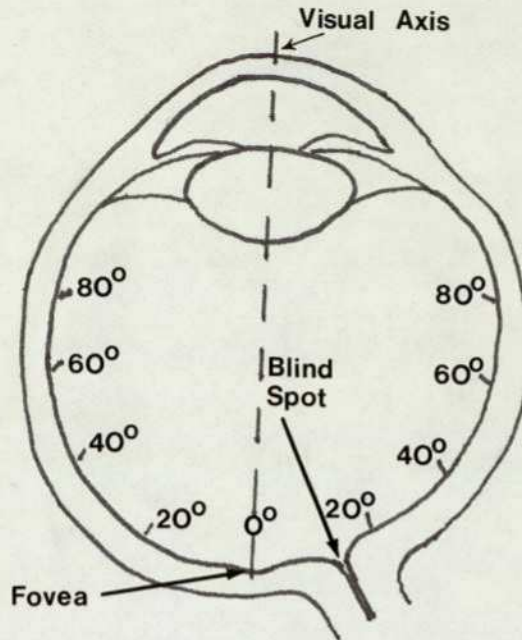
THE CONTRAST DETECTION TASK

Before undergoing any of the tests each subject was required to demonstrate that he or she possessed at least 6/6 acuity in each eye. This was achieved by the use of a distance chart conforming to BS 4274:1968. In certain cases this was achieved by allowing a subject to wear spectacles. The 20 subjects were aged between 18 and 40 years, the majority having ages between 20 and 25. Appendix 1.5 shows the distribution.

4.1 Procedure

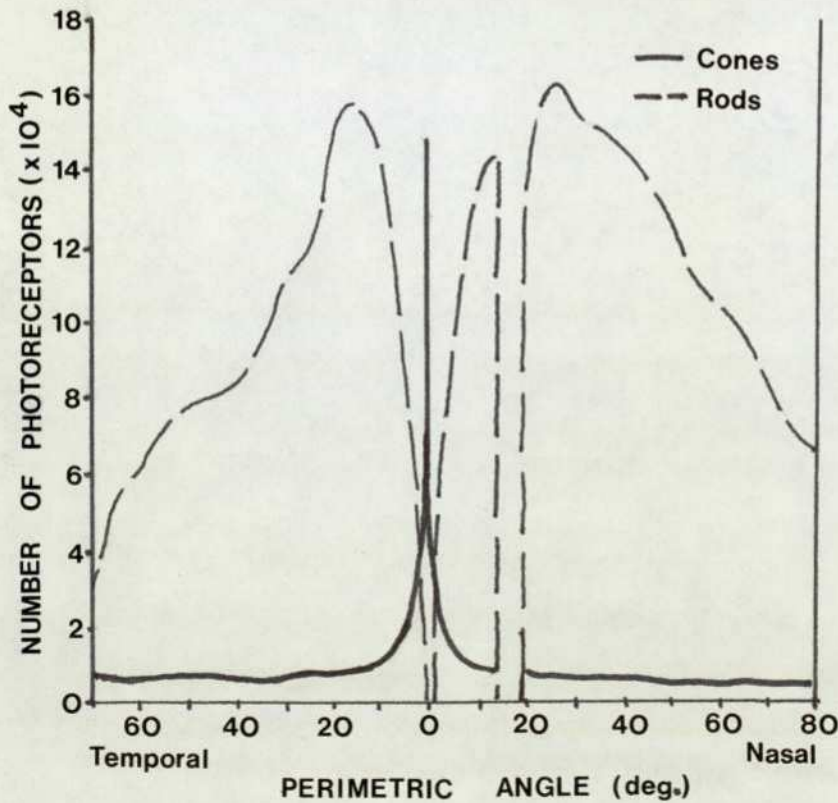
Upon entering the darkened room the subject was required to adjust his chair to a height which would enable him to comfortably view the screen using the brow pad to position his head. He was informed about the red reference lamp in the centre of the screen and shown the brightness control, it being left to him to choose a non-distracting intensity for this lamp. Next, an explanation was given to the observer about the actual method to be used, especially the need for his eyes to be adapted to the screen luminance before any tests could be commenced. The subject was told about looking away from an object at low luminances so that the image fell on the periphery (predominantly rod covered area) of the retina. It was necessary to give the observer a guide to the size of angle required to avert his vision and it was also mentioned that to avoid the blind spot, the image must fall on the non-nasal side of the retina, i.e. when viewing with the right eye only, the subject must look away to the right of a suspected stimulus. Fig. 4.1a shows the position of the blind spot and Fig. 4.1b shows the effect of the blind

FIG. 4-1(a)



PLAN VIEW OF A SECTION THROUGH THE LEFT EYE SHOWING
THE ANGULAR POSITION OF THE BLIND SPOT

FIG. 4-1 (b)



After Pirenne
(1967) 'Vision
and the Eye'
2nd Ed. A.B.P.
London

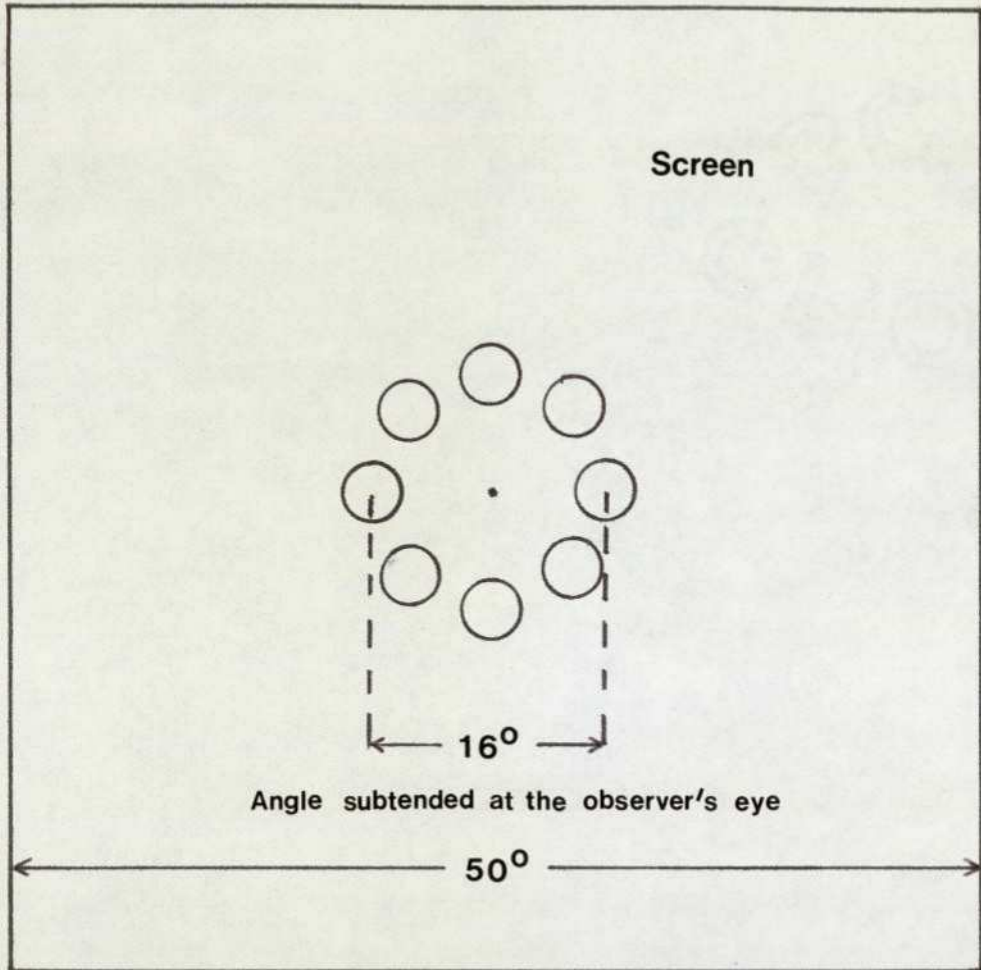
VARIATION OF THE NUMBER OF
RECEPTORS ACROSS THE HUMAN RETINA

spot on the number of receptor cells across the retina.

The overhead lights were switched off and the subject was allowed to adapt to the luminance to be used in the first experiment. This adaptation time varied from 5 minutes to 25 minutes depending upon the screen luminance being used. A preliminary run was then attempted, the subject using two eyes to view the stimuli. The stimuli were presented in random order of size, contrast and position. They could appear in any one of eight positions round the central red reference point (Fig. 4.2). The possible positions lay on a circle, the position of any stimuli being 8° from the central marker. The main test involved circular stimuli subtending 200 minutes of arc at the observer's eye, but interspersed with these were a few objects subtending 50 minutes of arc. This was to eliminate the possibility that the subject would become conditioned to looking only for one size of target. The range of contrasts was from 0.01 to 0.30. Only when it was clear that the observer had become conversant with the task were the main bulk of readings commenced.

The subject, viewing with two eyes, was shown the stimuli randomly; a typical result sheet is given in Table 4.1, and to each stimulus he was required to respond, using clockface nomenclature to describe its position. This first test consisted of showing each stimulus three times although not necessarily always in the same order as given on the result sheet. This helped to prevent both conscious and subconscious learning of the slide order. The subject was allowed unlimited time to respond, although it was emphasised that by taking a long time to search for an object he ran the risk of becoming tired towards the latter stages of the test.

FIG. 4-2



THE EIGHT POSSIBLE POSITIONS OF THE DETECTION STIMULUS

SUBJECT: N.C. PREFERRED EYE: RIGHT

TASK: CONTRAST DETECTION

AMBIENT LUMINANCE = $1.30 \times 10^{-3} \text{ Cd M}^{-2}$

DATE: 22.5.73

Slide Number	Slide position at 0° rotation	Contrast	LEFT EYE				RIGHT EYE				BOTH EYES			
			Rotation of slide				Rotation of slide				Rotation of slide			
			0°	90°	180°	270°	0°	90°	180°	270°	0°	90°	180°	270°
1	●+	0.23	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
2	●+	0.11	xxx	x✓x	✓✓x	x✓x	xx✓	x✓x	✓xx	x✓✓	✓x✓	✓✓✓	✓✓x	✓✓✓
* 3	●+	0.29	x✓✓	✓✓✓	✓x✓	✓✓✓	✓✓✓	✓✓✓	✓x✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
4	●+	0.05	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	x✓x	✓xx	✓xx
5	●+	0.14	x✓x	✓✓x	✓x✓	✓✓x	x✓✓	✓✓x	✓x✓	✓x✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
* 6	●+	0.15	x✓x	xx✓	xxx	✓xx	xx✓	xxx	xx✓	✓xx	xx✓	x✓x	✓✓x	xxx
7	●+	0.02	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
* 8	●+	0.08	xxx	xx✓	xxx	✓xx	xxx	✓xx	xxx	xxx	xxx	xx✓	xxx	xx✓
9	●+	0.19	✓✓✓	✓x✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓
10	●+	0.01	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
11	●+	0.08	xxx	x✓x	xxx	xxx	xx✓	xxx	x✓x	xxx	✓x✓	x✓✓	✓x✓	x✓x
12	●+	0.03	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
13	●+	0.04	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx	xxx
14	●+	0.06	x✓x	xxx	xxx	xxx	xxx	xxx	xxx	xxx	x✓✓	xxx	x✓x	✓xx

TABLE 4.1

EXAMPLE OF A RESULTS SHEET (* signifies 50' arc target)

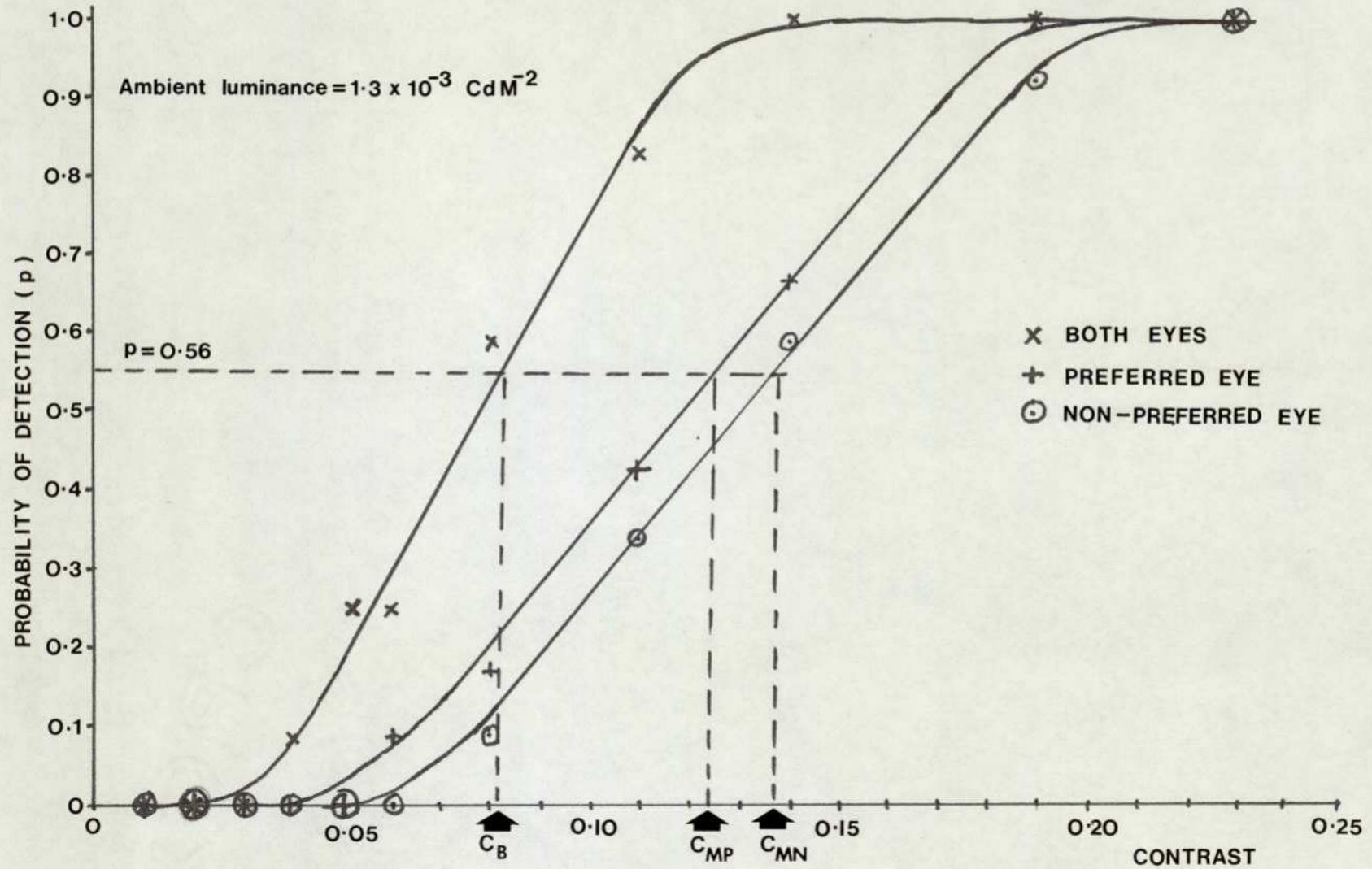
Next a black mask was fitted into the left-hand side of the brow pad and another test carried out with the subject using only his right eye. Before carrying out this test the slides were all rotated through 90° in a clockwise direction. Again each stimulus was presented three times. This procedure was repeated, using the left eye only, after the slides had been rotated through another 90° (clockwise). Introduction of the obscuring mask did not alter the 50° field of view seen by the observer.

After rotating the slides clockwise by another 90° , another binocular test was carried out and this procedure was repeated throughout the experiment until the slides had been rotated by a total of 3 complete revolutions, by which time twelve readings had been obtained for each slide binocularly, with the right eye and with the left eye.

The tests were carried out in this way so that a subject was not required to perform very long testing sequences without a break. It also allowed a check to be made throughout the experiment on how consistently the observer was performing the task. Also, by moving the stimuli around the field of view from test to test, any preferences for particular regions of the field were effectively nullified, because each stimulus was presented in each of the four quadrants of the screen.

The subject's responses were simply marked $\checkmark$ or **X** (Table 4.1), a **X** denoting either a wrong answer or a 'not seen' answer. From these answers a 'probability of seeing' table was calculated and the result was a sigmoid type of curve, an example of which is shown in Fig. 4.3. Each observer underwent the experiment described four times, each time involving a different ambient luminance and each

FIG. 4.3



RESULTS OF SUBJECT (N.C) VIEWING A 200' ARC DARK OBJECT ON A LIGHT BACKGROUND

luminance level being assigned to a different day of the week for a given subject. In this way the observers were only required to undergo tests for about 3 hours in any one day.

After each complete experiment the brow pad was wiped with disinfectant to prevent any possible spreading of infection from individual to individual.

4.2 Subjective Results

The subject was requested to use clockface nomenclature to describe the position of the stimulus because it was found at an early stage in the experiments that the use of points of the compass could cause confusion after about half an hour of tests. Subjects were very prone to confusion between east and west, i.e. right and left.

Observers were encouraged to make remarks about the appearance of the screen and their general feelings throughout the experiment. The most common remarks were that the object appeared to move, to intermittently become visible and invisible and also that bright spots of light appeared on the screen. These remarks were taken to represent the slow scanning of the eyeball, the variation of the visual threshold with time and the existence of retinal noise (becoming obvious at low retinal illuminations) respectively.

There were examples of subjects losing their ability to distinguish size difference. At certain points in the experiment a subject would admit surprise that although he knew the position of a stimulus, he could not say whether it was the large (200' arc) or small (50' arc) object. His surprise seems justified when considering the fact that the difference in surface area between the two sizes of object was 16 times.

Eighteen of the 20 subjects declared a distinct preference for binocular vision, mentioning that they thought it was far easier to view with two eyes. Nobody expressed a preference for monocular vision. Although some subjects also thought that it was easier to view with their preferred eye than with the other eye and that they were getting better results with the preferred eye, this was not always borne out in the results. The one very noticeable fact was that observers became more tired more rapidly when viewing monocularly. This fact prompted a subsidiary test to find out just how much the method of viewing affected the observer's fatigue rate; the results are given in Chapter 7.

4.3 Numerical Results

The measured contrast thresholds are shown in Table 4.2. All thresholds were taken as the contrast at which the probability of detection was 0.50. Allowance was made for a correct response being made by chance, as follows. Twelve responses were recorded for each stimulus contrast. At threshold the observer would give 6 correct responses, but as the stimulus could only fall in one of eight possible places on the screen, the observer could, by chance alone, give one in eight correct answers. So at threshold the subject would be expected to give $6 + 6/8$ correct responses out of 12, i.e. probability of detection $p = 0.56$.

Appendices 1.1 - 1.4 give the individual results and these measured monocular/binocular threshold ratios are shown graphically (fig. 4.4) for the four ambient luminances. The drawing of smooth curves through these plotted points is not justified on a strictly statistical basis but does help to give a good indication of the trend.

SUMMARY OF THE CONTRAST DETECTION RESULTS

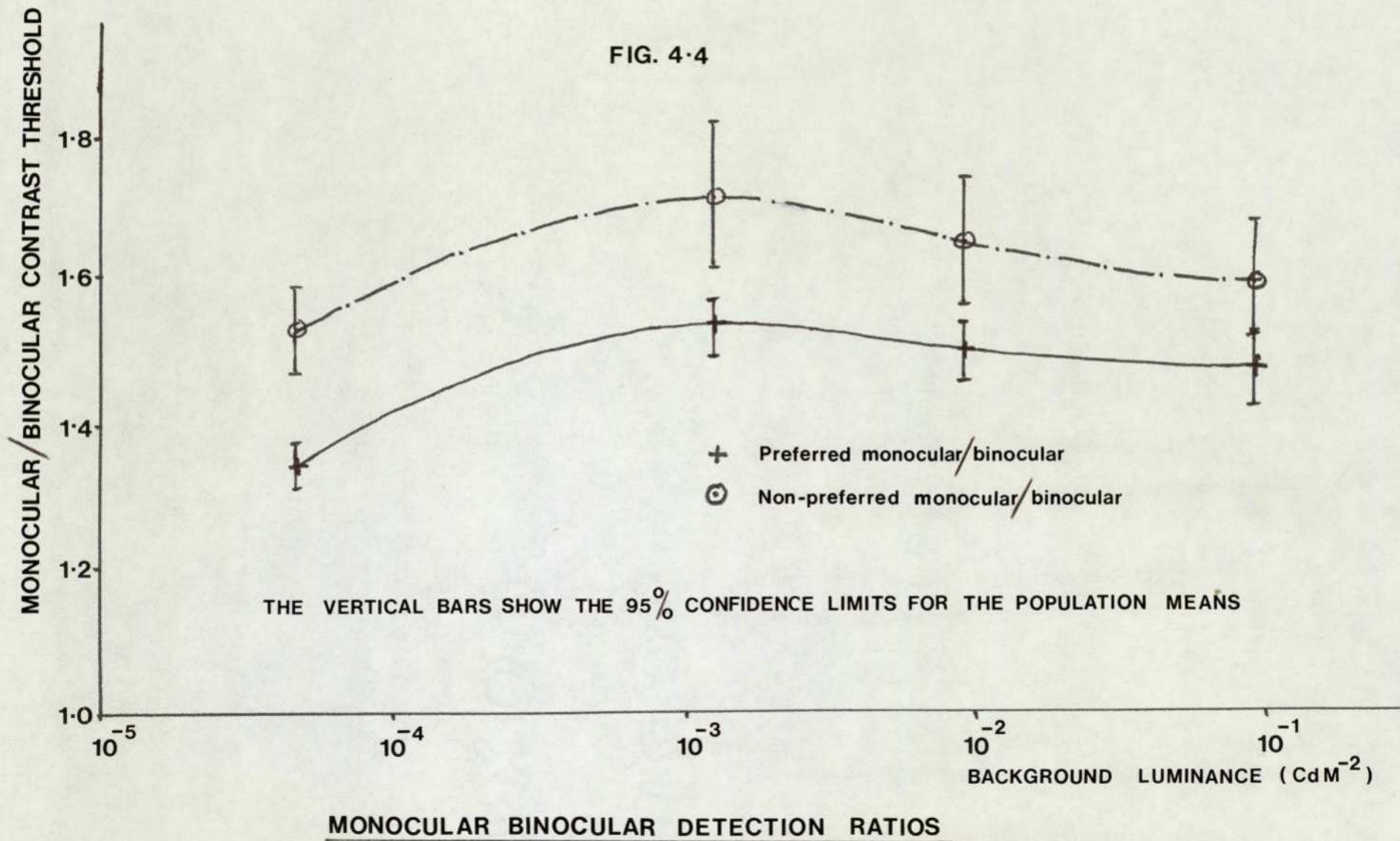
Background luminance (Cd M ⁻²)	C _{MP}	C _{MN}	C _B	$\frac{C_{MP}}{C_B}$	Standard devi- ation	$\frac{C_{MN}}{C_B}$	Standard devi- ation
1.0 x 10 ⁻¹	0.056	0.061	0.038	1.48	0.10	1.61	0.16
0.9 x 10 ⁻²	0.095	0.104	0.063	1.51	0.09	1.66	0.19
1.3 x 10 ⁻³	0.126	0.140	0.082	1.54	0.09	1.72	0.20
4.7 x 10 ⁻⁵	0.228	0.257	0.169	1.35	0.07	1.53	0.13

C_B is the binocular contrast threshold (mean of 20)

C_{MP} is the preferred eye monocular contrast
threshold (mean of 20)

C_{MN} is the non-preferred eye monocular contrast
threshold (mean of 20)

TABLE 4.2



The 95 per cent confidence limits (calculated using the Student t-test) are shown and it can be seen that the preferred eye/binocular ratio is more closely defined than the non-preferred eye/binocular ratio. This is a direct result of the fact that the scatter in the monocular results is greater for the non-preferred than for the preferred eye. The reason for this is possibly that some subjects found viewing with their non-preferred eye quite difficult, especially at low luminances when they were required to "look-off" at the same time. This difficulty resulted in a few abnormally high values of contrast threshold.

Statistical analysis was used in answering the following questions:

- a) Do the monocular/binocular ratios differ significantly from unity?
- b) Does the preferred monocular/binocular ratio differ significantly from the non-preferred monocular/binocular ratio?
- c) Is the variation of the monocular/binocular ratio with luminance significant? This particularly applies at the lowest ambient luminance.

The Student t-test was used, tests being performed in every case at the 0.05 significance level. This means that if, on the basis of the t-test, two sample means are accepted as being equal, the probability that this assumption is incorrect is less than 0.05.

In using 't' statistics to test for equality of sample means it is assumed that the samples have equal variances, i.e. the same as that of the normal population from which they are taken. In this case only sample variances are known and the F-test was used first of all to test for equality of these variances. In the cases where the

F-test indicated unequal sample variances a weighted value for the number of degrees of freedom was calculated using the unbiased sample estimates of variance (from Hoel, 1966). Using this calculated value of the number of degrees of freedom the t-test was used in the normal way.

After analysis it was found that the answers to the three questions above were as follows:

- a) All the measured monocular/binocular ratios differ significantly from unity. This means that the monocular contrast thresholds differ significantly from the binocular thresholds at each luminance level.
- b) At each luminance the non-preferred monocular/binocular ratio was significantly greater than the preferred monocular/binocular ratio.
- c) Variation of monocular/binocular ratio with ambient luminance is not significant at the three highest levels but a significant reduction in the value of this ratio occurs at the lowest luminance level.

4.4 Control Tests

Although not enough time was available to conduct extensive control experiments it was decided that tests could be carried out on two subjects to demonstrate any obvious effects caused by variation of:

- a) Shape, and
- b) Viewing distance.

The two control subjects had already performed the main tests and the control results are shown against their main experimental results in Table 4.3. Both controls were carried out in exactly the same manner as the main experiment except that the shape was changed to

RESULTS OF THE CONTROL EXPERIMENTS (ORIGINAL RESULTS SHOWN IN PARENTHESES)

Stimulus at infinity

Subject	Background luminance (Cd M ⁻²)	Threshold for preferred eye (C _{MP})	Threshold for non-preferred eye (C _{MN})	Binocular Threshold (C _B)	C _{MP} /C _B	C _{MN} /C _B
R.H.	1.0 x 10 ⁻¹	0.050 (0.050)	0.065 (0.061)	0.032 (0.031)	1.56 (1.61)	2.03 (1.97)
J.T.	1.0 x 10 ⁻¹	0.066 (0.062)	0.074 (0.070)	0.042 (0.040)	1.57 (1.55)	1.76 (1.75)
R.H.	4.7 x 10 ⁻⁵	0.230 (0.225)	0.270 (0.275)	0.178 (0.180)	1.29 (1.25)	1.52 (1.53)
J.T.	4.7 x 10 ⁻⁵	0.262 (0.256)	0.278 (0.290)	0.198 (0.197)	1.32 (1.30)	1.40 (1.47)

Square stimulus

Subject	Background luminance (Cd M ⁻²)	Threshold for preferred eye (C _{MP})	Threshold for non-preferred eye (C _{MN})	Binocular Threshold (C _B)	C _{MP} /C _B	C _{MN} /C _B
R.H.	1.0 x 10 ⁻¹	0.048 (0.050)	0.058 (0.061)	0.030 (0.031)	1.60 (1.61)	1.93 (1.97)
J.T.	1.0 x 10 ⁻¹	0.064 (0.064)	0.072 (0.070)	0.040 (0.040)	1.60 (1.55)	1.80 (1.75)
R.H.	4.7 x 10 ⁻⁵	0.227 (0.225)	0.280 (0.275)	0.182 (0.180)	1.25 (1.25)	1.54 (1.53)
J.T.	4.7 x 10 ⁻⁵	0.260 (0.256)	0.275 (0.290)	0.200 (0.197)	1.30 (1.30)	1.38 (1.47)

TABLE 4.3

a square of the same area as the 200' arc circular object and the viewing distance was increased to infinity by positioning a lens and prism in front of each eye (details in Chapter 3).

Two colour-defective subjects (deuteranopes) were tested in exactly the same way as the other subjects in the main tests. Their results are shown in Table 4.4.

Although it is statistically impossible to compare the control tests with the results of the main experiment some useful observations can be made. For the two subjects who underwent the shape and viewing distance control tests, their results agreed completely with their results in the main experiment, within the limits of experimental error. Also, from Table 4.4, it can be seen that the results obtained from the two deuteranopes fall within the 95 per cent probability limits for the estimated population mean (given in Table 4.2). Although this fact is not statistically significant, the fact that no extraordinary effects were noted during their tests would seem to show that the monocular/binocular contrast detection threshold would not be expected to differ from the norm simply as a result of an observer being a deuteranope. Of course, the introduction of colour contrast effects would probably lead to a completely different conclusion.

4.5 Summary of the Contrast Detection Results

As before, significant differences between means have been concluded from the use of the t-test; in every case tests were performed at the 0.05 significance level.

- a) The binocular threshold was significantly lower than either of the monocular thresholds at all luminances. Also,

RESULTS OBTAINED FROM TWO COLOUR-DEFECTIVE SUBJECTS (DEUTERANOPES)

Subject N.C. Preferred Eye: Right

Background luminance (Cd M ⁻²)	Threshold for preferred eye (C _{MP})	Threshold for non-preferred eye (C _{MN})	Binocular Threshold (C _B)	C _{MP} /C _B	C _{MN} /C _B
1.0 x 10 ⁻¹	0.054	0.060	0.038	1.42	1.58
0.9 x 10 ⁻²	0.100	0.108	0.065	1.54	1.66
1.3 x 10 ⁻³	0.123	0.137	0.082	1.50	1.67
4.7 x 10 ⁻⁵	0.224	0.258	0.165	1.36	1.56

Subject J.M. Preferred Eye: Right

Background luminance (Cd M ⁻²)	Threshold for preferred eye (C _{MP})	Threshold for non-preferred eye (C _{MN})	Binocular Threshold (C _B)	C _{MP} /C _B	C _{MN} /C _B
1.0 x 10 ⁻¹	0.072	0.084	0.046	1.57	1.83
0.9 x 10 ⁻²	0.115	0.129	0.075	1.53	1.72
1.3 x 10 ⁻³	0.134	0.150	0.088	1.52	1.70
4.7 x 10 ⁻⁵	0.242	0.275	0.175	1.38	1.57

TABLE 4.4

the preferred-eye threshold was significantly lower than that obtained for the non-preferred eye.

- b) The differences between the monocular/binocular ratios measured at ambient luminances between 1.3×10^{-3} and $1.0 \times 10^{-1} \text{ Cd M}^{-2}$ were not significant, but the lower value obtained at a luminance of $4.7 \times 10^{-5} \text{ Cd M}^{-2}$ was significant. The possible reasons are discussed in Chapter 8.
- c) In general the binocular contrast threshold was more precisely defined than either of the monocular thresholds. This was reflected in the fact that the binocular 'probability of detection' curve (fig. 4.3) was generally of steeper gradient than either of the monocular curves.
- d) The scatter of values of the binocular contrast thresholds measured for 20 observers was less than that for either of the monocular thresholds.
- e) It appears that the monocular/binocular ratio is not changed by increasing the viewing distance from 1.3 metres to infinity, nor by using a square stimulus rather than a circular one of the same area.
- f) From subjective remarks made during the tests it was apparent that observers generally preferred viewing binocularly, and the fatigue effect, whether real or imaginary, seemed to be greater for monocular viewing. This observation is considered more fully in Chapter 7.

g) Any subjective preferences for particular positions of the stimuli on the screen were not discernible from the responses obtained. The effect of possible bias in this direction was minimised by projecting each stimulus an equal number of times in four different positions on the screen. These positions were 90 degrees apart.

CHAPTER 5

THE VISUAL ACUITY TASK

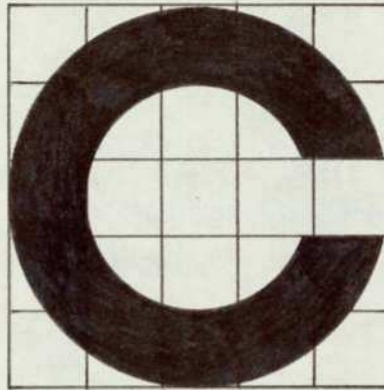
Although many of the subjects used in this part of the experiment had previously undergone the contrast detection task some new observers were needed to replace those who had become unavailable. These new subjects were required, as before, to demonstrate 6/6 acuity in each eye - in certain cases with the aid of spectacles. As before, a total of twenty observers were involved. Appendix 2.16 shows the distribution of ages of the observers.

5.1 Procedure

The same basic apparatus was used as before except that different slides were used, this time projecting Landolt rings onto the screen in groups of four. The measured visual acuity was the reciprocal of the angular subtense (in minutes of arc) of the Landolt gap which was just discernible. A range of gap sizes from 0.8 to 130 minutes of arc was used, each slide containing four rings of slightly different sizes. Fig. 5.1(a) shows the method of drawing a Landolt ring and fig. 5.1(b) shows a typical slide layout, the gap being allowed randomly to fall in any of four positions (top, bottom, left or right). A range of slides was made for five target to background contrasts, viz. 0.70, 0.30, 0.10, 0.03, 0.01. Four background luminances were used, ranging from 7.1 to 3.6×10^{-4} Cd M⁻². At each ambient luminance level the same basic procedure was used, which is as follows.

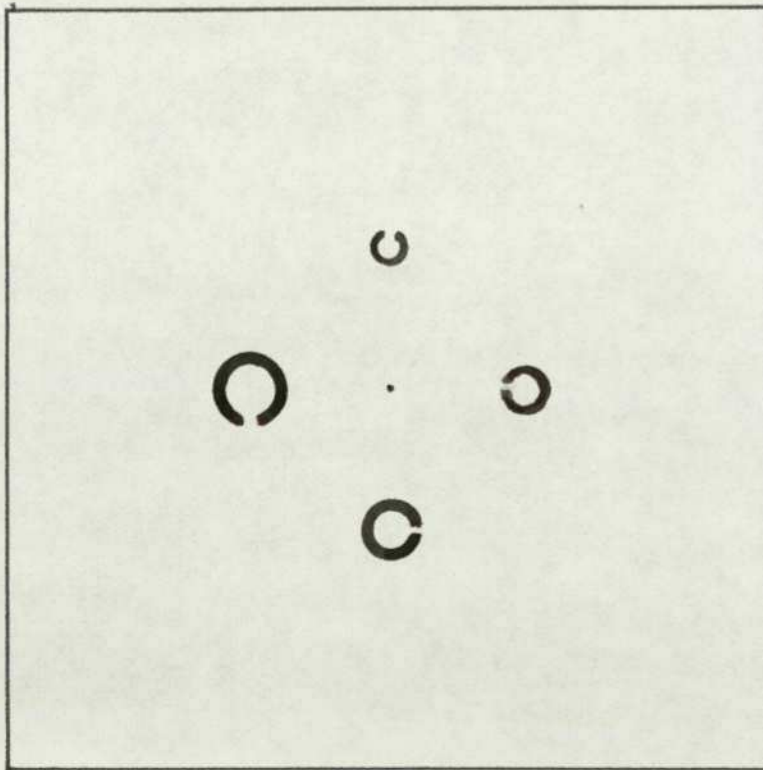
The subject, after adjusting his chair to a height which enabled him to comfortably view the screen, was allowed to adapt to the

FIG. 5-1(a)



CONSTRUCTION OF THE LANDOLT RING

FIG. 5-1 (b)



EXAMPLE OF A SLIDE USED FOR MEASURING ACUITY

particular luminance involved. During this time an explanation was given to him about the actual method to be used. The subject was told about the red reference lamp at the centre of the screen, it being left to him to choose a non-distracting intensity using the control potentiometer provided. Also he was told or reminded about the "averted vision" method of detection at lower luminance levels. Next the actual method of response was explained. For each slide projected, the subject was required to give the position of the gap for each of the four rings which surrounded the reference lamp. The subject was required to respond in a given order, i.e. top, right, bottom and left, simply to organise the recording of the results. He was allowed an unlimited response period. Sometimes he would correct a previous response whilst trying to detect one of the other gaps, and this was allowed so long as he made a positive decision before the slide was changed. A practice run was made before the main results were written down and throughout the experiment the subject was allowed to rest at will.

Using slides of the highest contrast (0.70) and the subject viewing binocularly, responses for the various ring sizes were recorded as either correct or incorrect. The ring sizes were gradually reduced as the test progressed until a point was reached where the subject could distinguish none of the four gaps on the slide. This generally meant that by using two or sometimes three slides a region of uncertainty could be established. As before in the detection task a sigmoid probability curve was obtained by taking twelve readings for each slide in the region of uncertainty, the slides being rotated and reversed between sightings so that the observer could not predict the positions of the gaps either intentionally or subconsciously.

This procedure was subsequently repeated for right eye viewing and left eye viewing, the field of view of the non-viewing eye being obscured in each case by the use of a black mask.

The complete procedure was then repeated at the same luminance level for the other four contrasts of target. Having completed the testing at the highest ambient luminance, the next level was selected by the use of the neutral density filters, and the entire process repeated. As the background luminance was lowered so the subjects found that they were unable to detect the lowest contrast rings at all, i.e. the contrast of the rings was below the contrast threshold of their eye at that luminance. At a luminance of $3.6 \times 10^{-4} \text{ Cd M}^{-2}$ only the rings having contrasts of 0.70, 0.30 and 0.10 could be used.

The period of testing for any given subject was limited to three hours in any day and the number of readings taken depended very much on the individual involved. Subjects were encouraged to remark about any visual effects which they noticed during the tests, but in fact much less comment occurred during the acuity task than during the detection task.

Throughout the experiment checks were made on the luminance at the screen and the contrast of the rings using a telephotometer; the luminance was held at a stable value by monitoring the mains voltage to the projector using a rheostat and a digital voltmeter.

NOTE: The experimenter always had access to a master list from which he could ascertain the position of each Landolt gap being projected simply by knowing which of the 8 possible slide orientations was being used. The orientation of the slide in the projector was

changed randomly after each group of 4 responses associated with the slide had been recorded.

5.2 Results

From the numerical results a graph was plotted: 'probability of gap detection' versus reciprocal of gap width. The acuity was taken as that value for which the probability of gap detection was 0.50. Allowing for the fact that the subject could have given 25 per cent of correct responses by chance alone (the gap could fall in one of only 4 positions on the ring), by the same reasoning which was used in chapter 4, the threshold was taken at a probability level of 0.63.

The individual results are listed as appendices 2.1 - 2.15 and a summary of these results is given as table 5.1 and shown as figs. 5.2 - 5.5. Although the inclusion of the 95 per cent probability limits on the figures was desirable, it was impracticable as it reduced the clarity of the graphs. In all four graphs the drawing of connecting lines is intended to demonstrate trends only.

As in the analysis of the detection results, the Student t-test was used after the F-test showed the equality or non-equality of variances. As before, in cases where the variances were shown to be unequal, a weighted value of the number of degrees of freedom was used. Significance was judged at the 0.05 level. It was found that:

- (i) binocular acuity is significantly greater than monocular acuity at all luminances considered, and
- (ii) there is a significant increase in the binocular/monocular ratio as the contrast is decreased.

TABLE 5.1 SUMMARY OF ACUITY RESULTS

Background luminance (Cd M ⁻²)	M _p	M _{np}	B	B/M _p	σ	B/M _{np}	σ
<u>CONTRAST 0.70</u>							
7.1	0.97	0.94	1.02	1.06	0.08	1.08	0.07
1.0 x 10 ⁻¹	0.45	0.43	0.50	1.11	0.09	1.18	0.10
3.4 x 10 ⁻³	0.09	0.09	0.10	1.12	0.15	1.17	0.16
3.6 x 10 ⁻⁴	0.06	0.06	0.07	1.15	0.09	1.23	0.09
<u>CONTRAST 0.30</u>							
7.1	0.81	0.79	0.87	1.07	0.07	1.10	0.09
1.0 x 10 ⁻¹	0.23	0.22	0.27	1.19	0.11	1.23	0.14
3.4 x 10 ⁻³	0.06	0.06	0.08	1.22	0.11	1.35	0.19
3.6 x 10 ⁻⁴	0.027	0.026	0.034	1.23	0.07	1.33	0.11
<u>CONTRAST 0.10</u>							
7.1	0.22	0.21	0.26	1.18	0.18	1.26	0.18
1.0 x 10 ⁻¹	0.07	0.06	0.09	1.27	0.13	1.41	0.17
3.4 x 10 ⁻³	0.018	0.015	0.024	1.39 (18)	0.13	1.61 (18)	0.15
3.6 x 10 ⁻⁴	0.013	0.011	0.017	1.38 (10)	0.08	1.64 (10)	0.10
<u>CONTRAST 0.03</u>							
7.1	0.09	0.09	0.12	1.27	0.13	1.39	0.21
1.0 x 10 ⁻¹	0.023	0.020	0.033	1.42 (15)	0.14	1.61 (15)	0.18
<u>CONTRAST 0.01</u>							
7.1	0.013	0.011	0.017	1.37 (17)	0.08	1.54 (17)	0.10

M is the preferred eye acuity
M is the non-preferred eye acuity
B is the binocular acuity

The circled numbers show how many readings make up the mean - all other means represent 20 readings

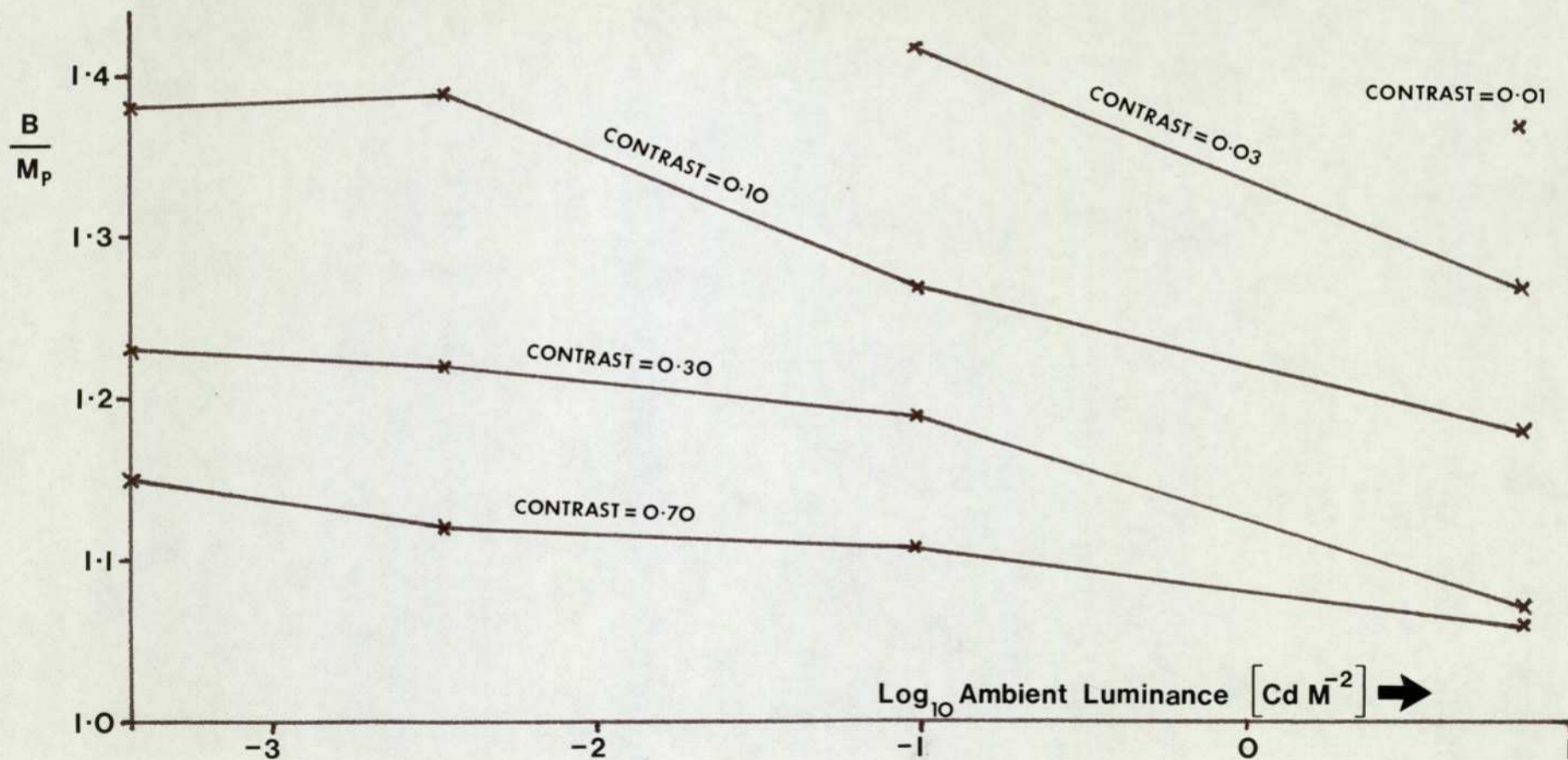


FIG. 5.2 VARIATION OF BINOCULAR/MONOCULAR (PREFERRED) ACUITY WITH LUMINANCE

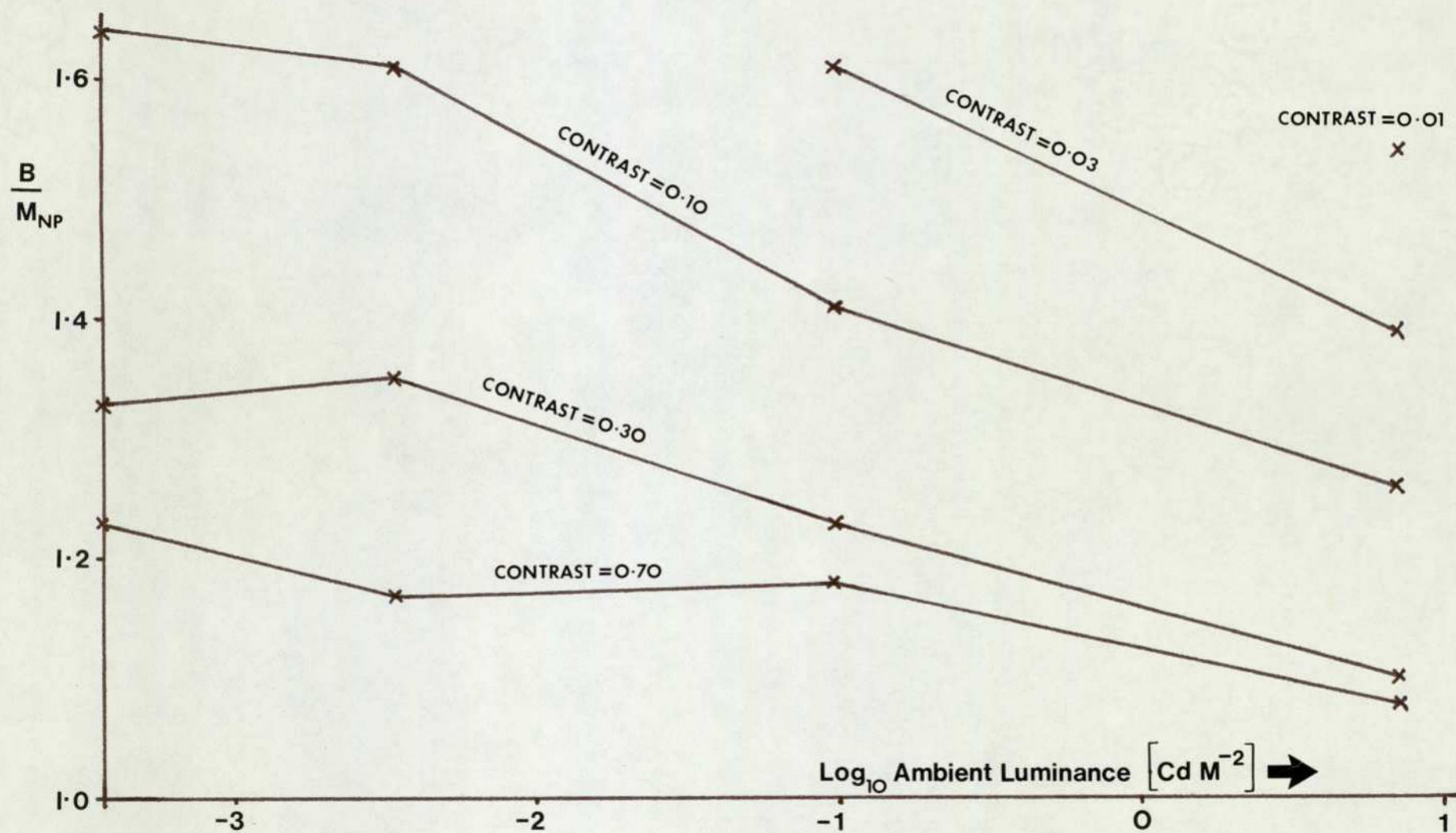


FIG. 5.3 VARIATION OF BINOCULAR/MONOCULAR (NON-PREFERRED) ACUITY WITH LUMINANCE

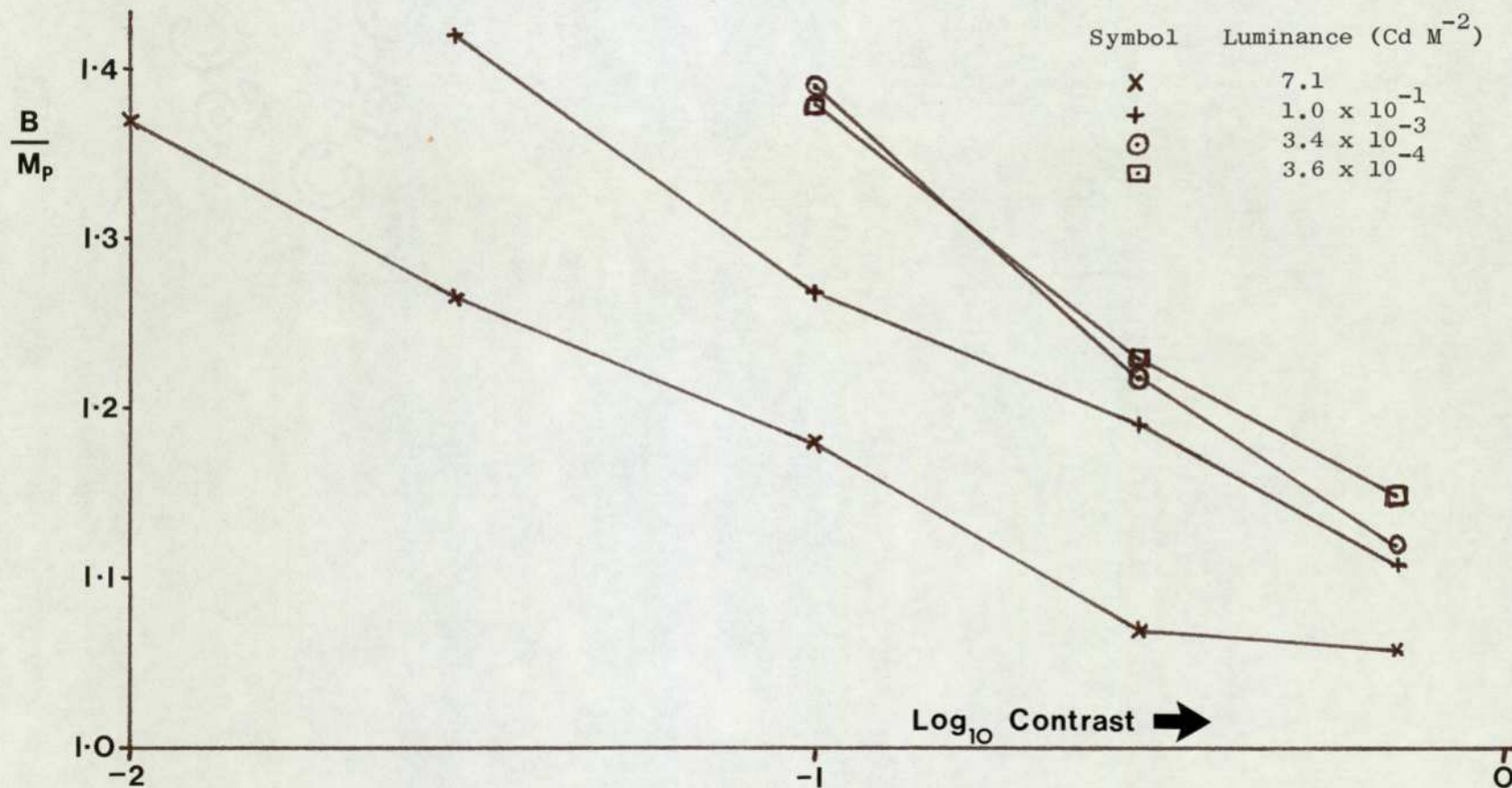


FIG.5.4 VARIATION OF BINOCULAR/MONOCULAR (PREFERRED) ACUITY WITH TARGET CONTRAST

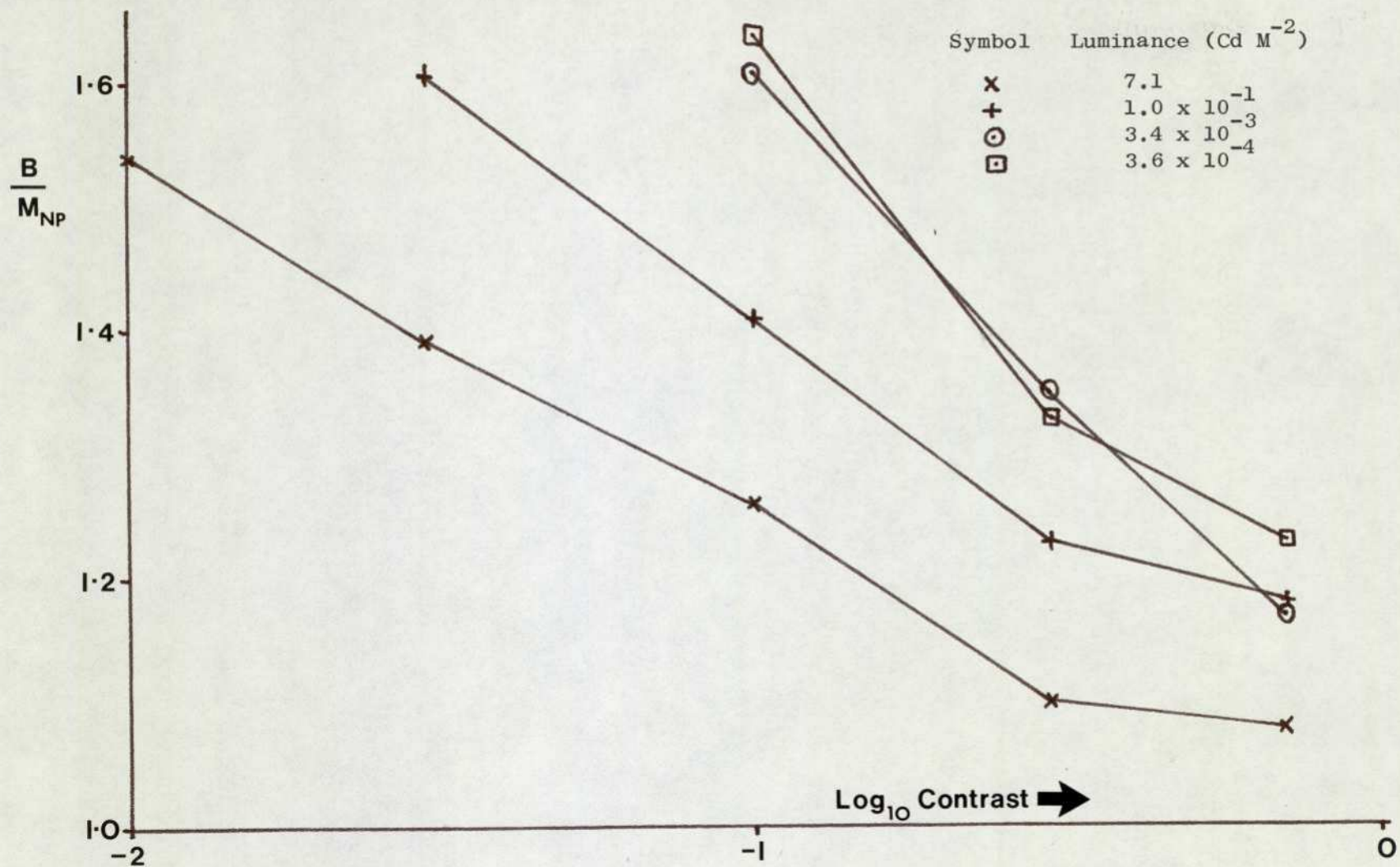


FIG. 5.5 VARIATION OF BINOCULAR/MONOCULAR (NON-PREFERRED) ACUITY WITH TARGET CONTRAST

A control test was performed with two subjects at two different luminances, one high and the other low. Both the subjects had already undergone the main tests. The control test involved the measurement of acuity at a viewing distance of infinity, this being achieved by the use of two lenses and two prisms as described in chapter 3. Although no strict analysis can be performed on the results, they fell well within the 95 per cent probability limits for the means obtained at a viewing distance of 1.3 metres. In fact from table 5.2 it can be seen that the differences between the results obtained at 1.3 metres and infinity were very small indeed.

5.3 Summary of the Acuity Results

- a) At luminances between 7.1 Cd M^{-2} and $3.6 \times 10^{-4} \text{ Cd M}^{-2}$ binocular acuity is significantly greater than monocular acuity.
- b) As the contrast between stimulus and background was decreased from 0.70 to 0.01 there is a significant increase in the binocular/monocular ratio.
- c) It appears that the binocular/monocular acuity ratio is not significantly affected as the viewing distance is changed from 1.3 metres to infinity.
- d) Subjective remarks during the acuity tests were noticeably fewer than those made during the detection task, although subjects did show a marked preference for binocular viewing.
- e) Subjective preferences for particular positions of the stimuli at the screen were not evident.

TABLE 5.2 ACUITY RESULTS FOR STIMULI AT INFINITY
(ORIGINAL RESULTS SHOWN IN PARENTHESES)

Subject	Stimulus Contrast	Acuity for preferred eye M_p	Acuity for non-preferred eye M_{np}	Binocular Acuity B	B/M_p	B/M_{np}
<u>Luminance = 7.1 Cd M^{-2}</u>						
I.B.	0.70	0.99 (1.01)	0.90 (0.92)	1.04 (1.07)	1.05 (1.06)	1.16 (1.16)
R.H.	0.10	0.23 (0.24)	0.23 (0.23)	0.25 (0.26)	1.09 (1.08)	1.09 (1.13)
I.B.	0.03	0.10 (0.10)	0.09 (0.10)	0.14 (0.14)	1.40 (1.40)	1.56 (1.40)
<u>Luminance = $3.4 \times 10^{-3} \text{ Cd M}^{-2}$</u>						
I.B.	0.70	0.10 (0.10)	0.09 (0.10)	0.10 (0.10)	1.00 (1.00)	1.11 (1.00)
R.H.	0.30	0.06 (0.06)	0.05 (0.05)	0.07 (0.07)	1.17 (1.17)	1.40 (1.40)
R.H.	0.10	0.013 (0.015)	0.013 (0.014)	0.020 (0.023)	1.54 (1.53)	1.54 (1.64)

CHAPTER 6

THE VISUAL RECOGNITION TASK

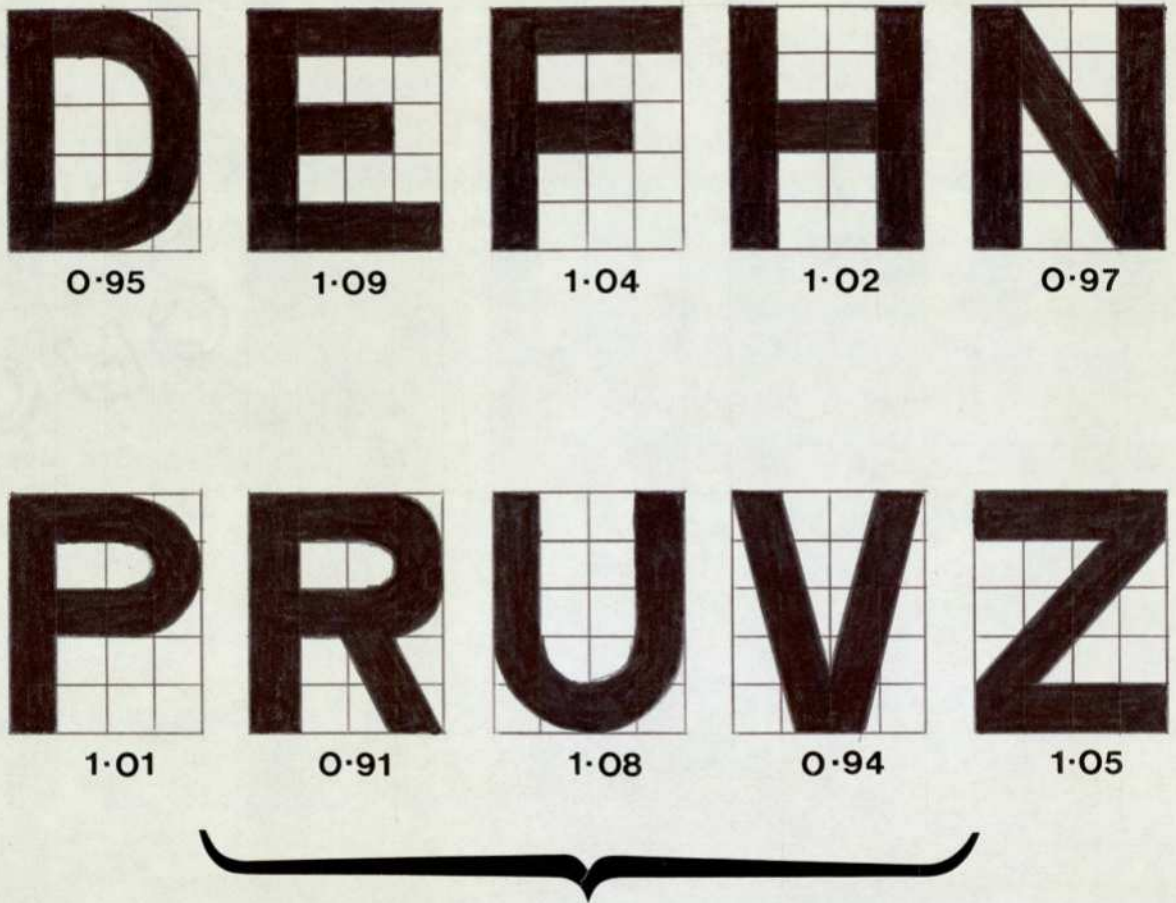
6.1 Procedure

The same twenty subjects who were involved with the acuity task also underwent the recognition task. This meant that they were all familiar with the method of viewing and the adaptation procedure. As before, in the acuity task, four background luminances were used, ranging from 7.1 to $3.6 \times 10^{-4} \text{ Cd M}^{-2}$. The method involved measuring both monocularly and binocularly, the contrast threshold for the recognition of specific letters of the alphabet.

The letters were chosen on the basis of work which has been summarised by Bennett (1965). Ten non-serif, upper-case letters were used and their form and type are shown in fig. 6.1. Their relative legibilities (based on the Snellen O having a legibility of 1.00) are shown, the letters having been chosen to be equally legible to within ± 10 per cent. Also it was important that each letter could be confused with at least one other, e.g. E with F, R with P, U with V, etc. This meant that the subject was much less easily able to make a judgement based on vague form only.

The letters were constructed using a grid measuring four units by five units, the elemental width of each grid subtending 25' arc at the observer's eye. Eighty such slides were constructed covering a range of contrasts from 0.01 to 0.70. When projected on to the screen the letters appeared singly just below the red reference lamp at the centre of the screen, i.e. the task did not involve a search.

FIG. 6.1



RELATIVE LEGIBILITIES from BENNETT (1965)

NON-SERIF LETTERS USED IN THE RECOGNITION TASK

The procedure was as follows. After adapting to the ambient luminance and adjusting the red reference lamp to a non-distracting level the subject was required to respond to each slide in turn by naming the letter appearing on the screen. The letters were projected randomly in both type and contrast and as before a total of twelve responses from each contrast in the threshold region was recorded so that a probability curve could be plotted. A "not seen" answer or a wrong answer were both recorded as a negative response. The subject had been told the list of letters being used so that a response corresponding to a letter not included in the list rarely occurred. If it did happen, the subject was reminded of the list and was allowed to change his mind.

The experiment was performed both binocularly and monocularly for both eyes, the subject being given no time limit within which to make a decision. This complete procedure was repeated subsequently at the three other luminances, the observers keeping to a time limit of 3 hours of experimentation in any one day.

6.2 Results

A graph of "probability of recognition", p_r , was plotted against contrast and the threshold was taken as the contrast at which $p_r = 0.50$. As in both the previous tasks allowance was made for a correct response occurring by chance. In this case the subject had a 1 in 10 chance of making a correct response by chance alone. (This assumes that the observer knew which ten letters were involved.) At threshold therefore, a subject would be expected to give $6 + 6/10$ correct responses out of 12, i.e. the probability of recognition was $p_r = 0.55$. Table 6.1 shows a typical results sheet.

EXAMPLE OF RESULTS SHEET

Task: RECOGNITION

Subject: T.C.

Preferred Eye: L

Luminance: $1.0 \times 10^{-1} \text{ Cd M}^{-2}$

Letter	Contrast	Binocular	Right Eye	Left Eye
U	0.06	✓✓✓✓	✓✓✓✓	✓x✓✓
E	0.08	✓✓✓✓	✓✓x✓	✓✓✓✓
H	0.02	x x x x	x x x x	x x x x
E	0.05	✓✓✓✓	x ✓ x ✓	✓ x ✓✓
P	0.04	x ✓✓✓	x x x x	✓ x x ✓
D	0.07	✓✓✓✓	✓✓x✓	✓✓✓✓
V	0.03	x x x ✓	x x x x	x x x x
P	0.08	✓✓✓✓	✓✓✓✓	✓✓✓✓
Z	0.06	✓✓✓✓	✓ x ✓✓	x x x ✓
F	0.04	✓✓✓✓	x x x x	x ✓ x ✓
N	0.09	✓✓✓✓	✓✓✓✓	✓✓✓✓
N	0.07	✓✓✓✓	✓✓✓✓	✓✓✓✓
R	0.02	x x x x	x x x x	x x x x
D	0.05	✓✓✓✓	x x x x	✓ x ✓ x
H	0.03	x ✓ x x	x x x x	x x ✓ x
R	0.08	✓✓✓✓	✓✓✓✓	✓✓✓✓
V	0.09	✓✓✓✓	✓✓✓✓	✓✓✓✓
F	0.04	✓ x ✓✓	x x x x	x ✓ x x
Z	0.07	✓✓✓✓	✓ x ✓✓	✓✓✓✓
E	0.05	✓✓✓✓	x ✓ x x	✓✓✓✓
N	0.09	✓✓✓✓	✓✓✓✓	✓✓✓✓
D	0.02	x x x x	x x x x	x x x x
R	0.03	✓ x x x	x x x x	x x x x
H	0.06	✓✓✓✓	✓✓✓✓	✓✓x x

TABLE 6.1

On this basis appendices 3.1 - 3.4 give the results obtained by individual observers and a summary is given as table 6.2. As before the t-test was used to show the significance of the results obtained. The ratio of monocular/binocular recognition contrast threshold has been plotted (fig. 6.2) showing the 95 per cent confidence limits for the population means. The statistical analysis of these figures was performed in precisely the same way as was used in the contrast detection task, i.e. the F-test to decide whether or not the variances could be considered equal and the t-test to decide whether the difference between two means could be considered significant (based on the 0.05 level of significance). It was required to find answers to the following questions.

- a) Is there a significant difference between the monocular and binocular thresholds?
- b) Is there a significant difference between the preferred and the non-preferred monocular threshold?
- c) Is there variation of the monocular/binocular ratio with ambient luminance?
- d) Are the recognition threshold ratios significantly different from those obtained for the contrast detection task?

Analysis shows that the monocular/binocular ratio is greater than unity at all four luminances, making the answer to question a) 'yes'.

The difference between the preferred and non-preferred monocular thresholds is significantly different except at the lowest luminance. At the three higher luminances the non-preferred monocular threshold is always the greater.

SUMMARY OF THE RECOGNITION RESULTS

Background luminance (Cd M ⁻²)	M _{np}	M _p	B	M _p /B	σ	M _{np} /B	σ
7.1	0.022	0.020	0.016	1.30	0.19	1.45	0.19
1.0 x 10 ⁻¹	0.072	0.067	0.050	1.33	0.09	1.43	0.09
3.4 x 10 ⁻³	0.23	0.22	0.16	1.34	0.15	1.43	0.17
3.6 x 10 ⁻⁴	0.49	0.47	0.38	1.27	0.14	1.32	0.18

B is the binocular threshold (mean of 20).

M_p is the preferred monocular threshold
(mean of 20).

M_{np} is the non-preferred monocular threshold
(mean of 20).

σ is the standard deviation.

TABLE 6.2

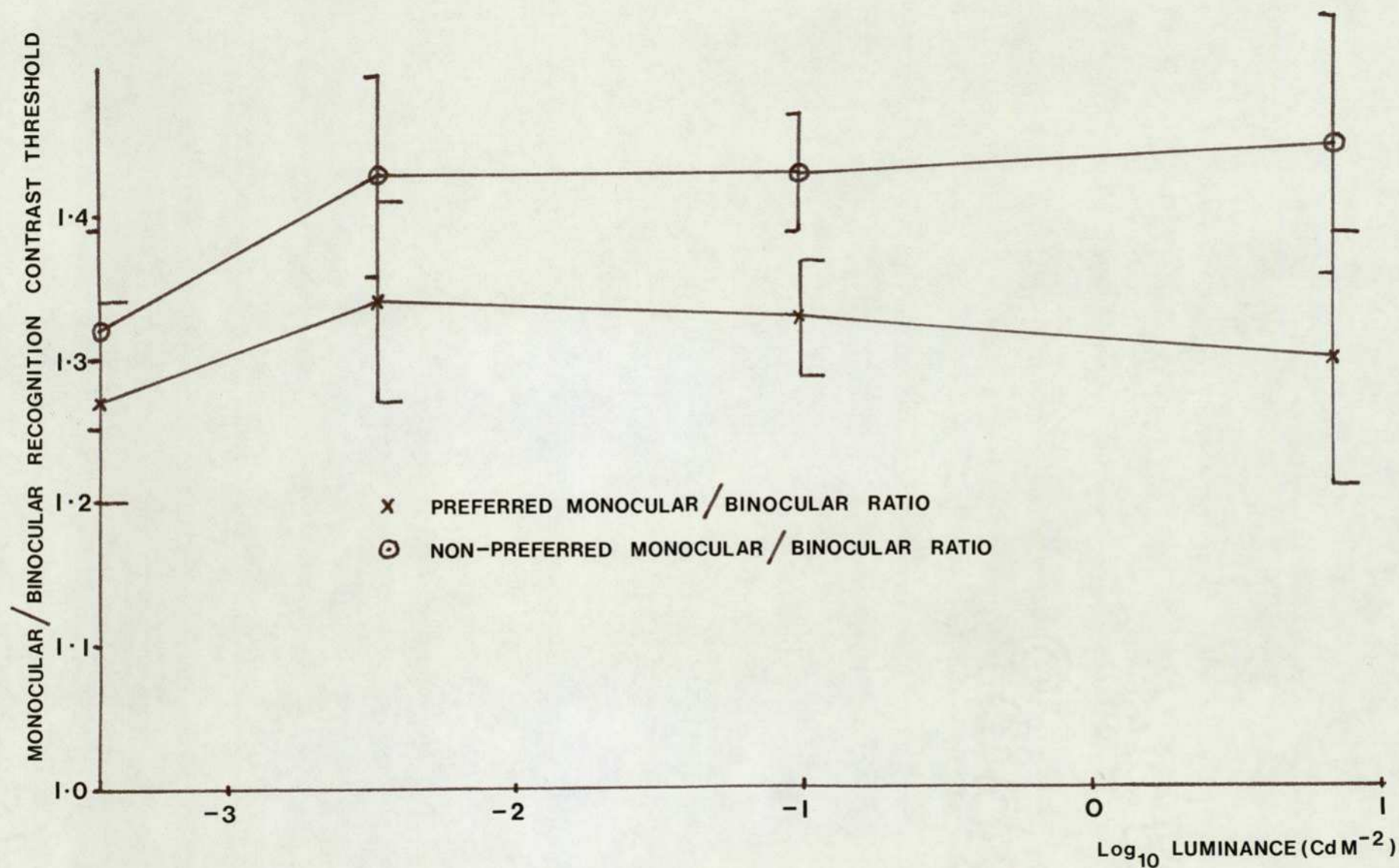


FIG. 6-2 VARIATION OF MONOCULAR/BINOCULAR RECOGNITION THRESHOLD WITH LUMINANCE

Unlike the contrast detection task the answer to question c) is 'no'. The monocular/binocular ratio does not drop significantly at the lowest luminance. However, it can be seen from fig. 6.2 that the ratio does tend to decrease as the luminance falls below about 10^{-3} Cd M⁻², even though the significance of this drop does not reach the 0.05 level on the t-test. If it had been possible to repeat the experiment at a luminance below 10^{-4} Cd M⁻² this conclusion may well have been reversed.

Question d) poses a problem because the detection task and the recognition task were not, unfortunately, performed at exactly the same four luminances. However, because in both cases the variation of the monocular/binocular ratio was not significant above 10^{-3} Cd M⁻² a simple comparison was carried out, using the t-test, at luminances of 1×10^{-1} and approximately 10^{-3} Cd M⁻². At both levels the recognition monocular/binocular ratio was found to be significantly lower than that obtained for the contrast detection task. The difference was highly significant.

6.3 Summary of the recognition results

The monocular/binocular curves are very similar to those obtained for the contrast detection task except that there is not a significant reduction of the ratio at the lowest luminance. This conclusion may have been reversed if it had been possible to perform the recognition experiment at the same very low luminance which was used for the detection task. The reason was that, in order to work at 3.6×10^{-4} Cd M⁻², very high contrast stimuli would have been needed and the photographic technique used for producing the slides did not allow high enough values to be attained. It is possible that results could be

obtained at this luminance by constructing non-photographic slides.

Apart from the difference mentioned above, the general recognition results lead to the same basic conclusion obtained from the detection task, except that the binocular advantage is smaller.

CHAPTER 7

MISCELLANEOUS OBSERVATIONS

7.1 Comparison of Results Obtained from Male and Female Observers

Although the observers employed in all three tasks were predominantly male (17 male and 3 female) it is pertinent to divide the results into two separate groups in an attempt to see whether there were any obvious differences. The t-test was used to compare the monocular/binocular ratios for each task at each luminance and, at the 0.05 significance level, no overall differences were found. In just 3 cases out of the total 46 a difference was found, but this was probably due to the fact that the means obtained for the female subjects were for only three individuals and statistically this is not a good sample size. However, in a general consideration of the results, the differences were negligible in all three tasks.

In defence of Blackwell's (1946) use of only female subjects when measuring contrast detection thresholds, no significant differences were found between male and female thresholds in the detection task.

7.2 The Effect of Changing the Threshold Probability Level

In all three tasks considered, the threshold was measured in the same manner, i.e. it was taken as the point at which the probability of a successful response was 0.50. Although this particular figure has been used by a large number of other experimentalists in psychophysics and it does have the advantage of falling in the middle of the linear portion of the sigmoid

curve, it does not necessarily give the most practical measure of a threshold. For example, there are certainly practical tasks which would require a much higher probability of a correct response before a stimulus would be accepted as 'seen'.

A general observation from the results of all three tasks is that the binocular probability curve was steeper than either of the monocular curves over the central, linear region. This fact allows the possibility that although the absolute values of the threshold would be raised by increasing the associated probability level, the monocular/binocular threshold ratio may not change significantly.

By interrogation of a number of subjects working under various conditions, it was found that they did not feel confident of having detected a stimulus unless the probability of detection were greater than 0.75, and in some cases as high as 0.90.

Blackwell (1946) put the probability level at greater than 0.90 for the confident detection of a stimulus when viewing binocularly.

It was decided to retabulate the contrast detection thresholds, taking the probability of detection at threshold to be 0.75.

As before, making allowance for correct detection by chance alone, the actual probability level used was 0.78. Table 7.1 shows comparative data for threshold probabilities of 0.50 and 0.75. The t-test was used at the 0.05 significance level to compare the two sets of figures.

Analysis shows that although the actual threshold values were significantly raised, the monocular/binocular ratios were not affected by raising the probability to 0.75. It would be much

COMPARISON OF CONTRAST DETECTION THRESHOLDS

for $p = 0.50$ and $p = 0.75$

Luminance (Cd M ⁻²)	p	M _p	σ	M _{np}	σ	B	σ	M _{p/B}	σ	M _{np/B}	σ
1.0×10^{-1}	0.50	0.056	0.013	0.061	0.014	0.038	0.008	1.48	0.11	1.61	0.16
	0.75	0.065	0.014	0.070	0.014	0.044	0.009	1.47	0.10	1.60	0.15
0.9×10^{-2}	0.50	0.095	0.016	0.104	0.021	0.063	0.009	1.51	0.09	1.66	0.19
	0.75	0.111	0.017	0.122	0.021	0.074	0.010	1.50	0.09	1.64	0.18
1.3×10^{-3}	0.50	0.13	0.016	0.14	0.022	0.08	0.009	1.54	0.09	1.72	0.20
	0.75	0.14	0.017	0.15	0.023	0.09	0.009	1.53	0.10	1.72	0.19
4.7×10^{-5}	0.50	0.23	0.031	0.26	0.035	0.17	0.023	1.35	0.07	1.53	0.13
	0.75	0.27	0.036	0.30	0.039	0.21	0.027	1.31	0.06	1.46	0.11

p is the probability of detection at threshold

σ is the standard deviation

TABLE 7.1

more difficult to recalculate the thresholds for a higher probability level because the sigmoid curve becomes less steep and less well defined. The shallower gradient means that small variations in probability reflect large changes in contrast. In order to define the curve accurately enough to be able to obtain adequate definition of the threshold contrast for $P = 0.90$, a much larger number of readings would have to be taken in the region of the threshold. This was not possible in the time available.

7.3 Investigation into Possible Differences between Monocular and Binocular Viewing when Considering Fatigue

a) Introduction

It was noticed, especially during the contrast detection task at low ambient luminances, that subjects required more frequent rests when viewing monocularly. Also complaints about retinal noise and apparent variation in screen luminance occurred at a far greater rate when subjects were using one eye only. It was decided to undertake a brief subsidiary experiment in an attempt to quantify any differences in the measured fatigue resulting from the two types of vision.

The main difficulty in designing the experiment was in choosing a satisfactory method of measuring fatigue. In the past many researchers had tended to use physiological changes. One such method is to measure the subject's blink rate, a higher rate supposedly indicating a greater measure of fatigue. However, it was considered more practical to measure the observer's performance, on the basis that fatigue would result in a worsening

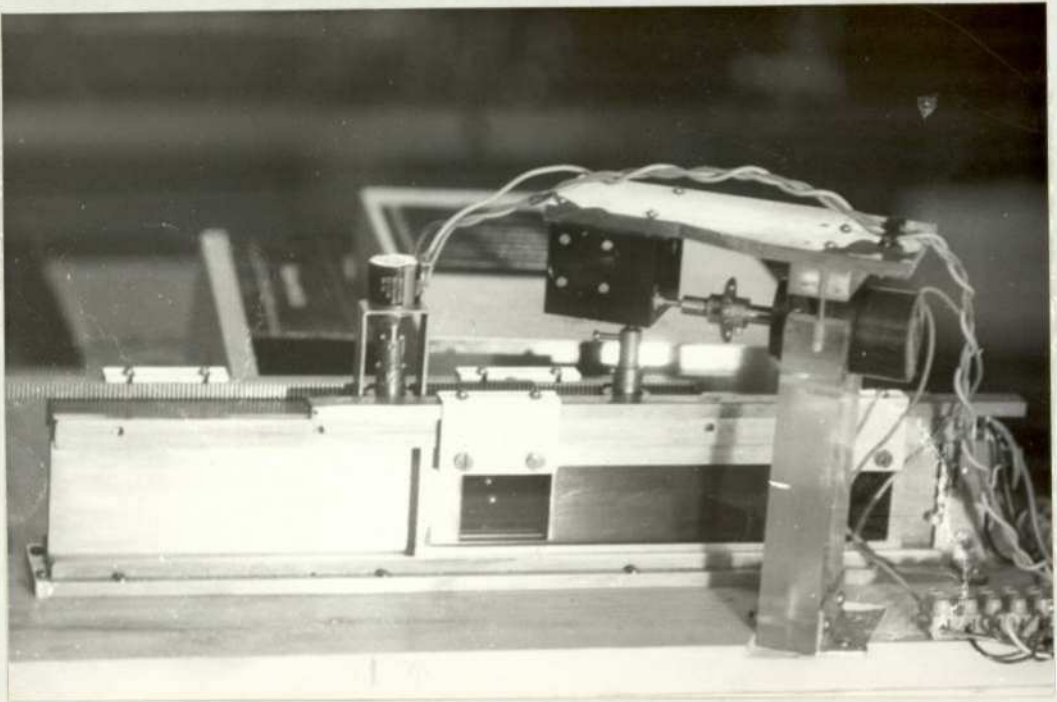
performance. As the task which indicated most possibility of fatigue, a contrast threshold measuring experiment was chosen.

b) Design of the apparatus

It was decided to measure the temporal variation of the contrast threshold under continuous testing conditions. Clearly a yes/no method would require too many responses to define a threshold at any particular elapsed time, so a continuously variable stimulus was chosen, the subject being required to adjust to a threshold level, the contrast of the stimulus. It was decided to repeat the experiment at both a photopic and a scotopic luminance level, in case the measured effect was more marked at a particular luminance.

Basically the layout was the same as in the main experiment. A projector was used to produce a 50 degree adaptation field on a white screen. A second projector was used to superimpose a circular bright stimulus on to the central region of this field. The stimulus subtended 7 degrees at the observer's eye. The luminance of the stimulus was varied by the use of two neutral density wedges moving in opposite directions. Motion of the wedges was achieved by the use of a geared electric motor which drove two racks in opposite directions, one of the racks being connected to each of the wedges (plate 5). The relative positions of the two wedges and hence the total optical density in the path of the stimulus was monitored by using another gearwheel turning between the two racks, connected via a shaft to a multi-turn potentiometer. A regulated voltage was connected across the ends of this potentiometer and the positions of the wedges was directly proportional to the potential difference between

PLATE 5



THE NEUTRAL DENSITY WEDGE MECHANISM

the end and the wiper of the potentiometer. This voltage was monitored by the use of a digital voltmeter. A calibration curve is shown as fig. 7.1 and a schematic layout for the stimulus projecting system is shown as fig. 7.2. The linearity of the wedge system was good and the rate of change of the system when operating was 0.28 ± 0.01 density units per second. (If the stimulus luminance is reduced by a factor N then the wedges are introducing $\log_{10} N$ density units to the stimulus luminance.)

The subject, viewing the screen at a distance of 1.3 metres, controlled the motion of the wedges by the use of a sprung switch. The experimentalist was able remotely to reverse the direction of motion of the wedges. He also had access to a digital clock and the digital voltmeter giving a direct readout of the attenuation factor introduced by the wedges. Calibration of the stimulus to background contrast associated with a given wedge position was performed by direct measurement at the screen using a telephotometer.

c) Method

There was sufficient time for only one subject to undergo the test. The subject adapted to the screen luminance (126 Cd M^{-2}) and, viewing the screen using only his preferred eye, pressed the sprung switch provided and this increased the stimulus contrast. At the point when the stimuli became just detectable, the subject released the switch. This stopped the wedges and the controller wrote down the time elapsed and the digital voltmeter reading. The controller then wound the wedges on in the same direction so that the contrast of the stimuli became suprathreshold.

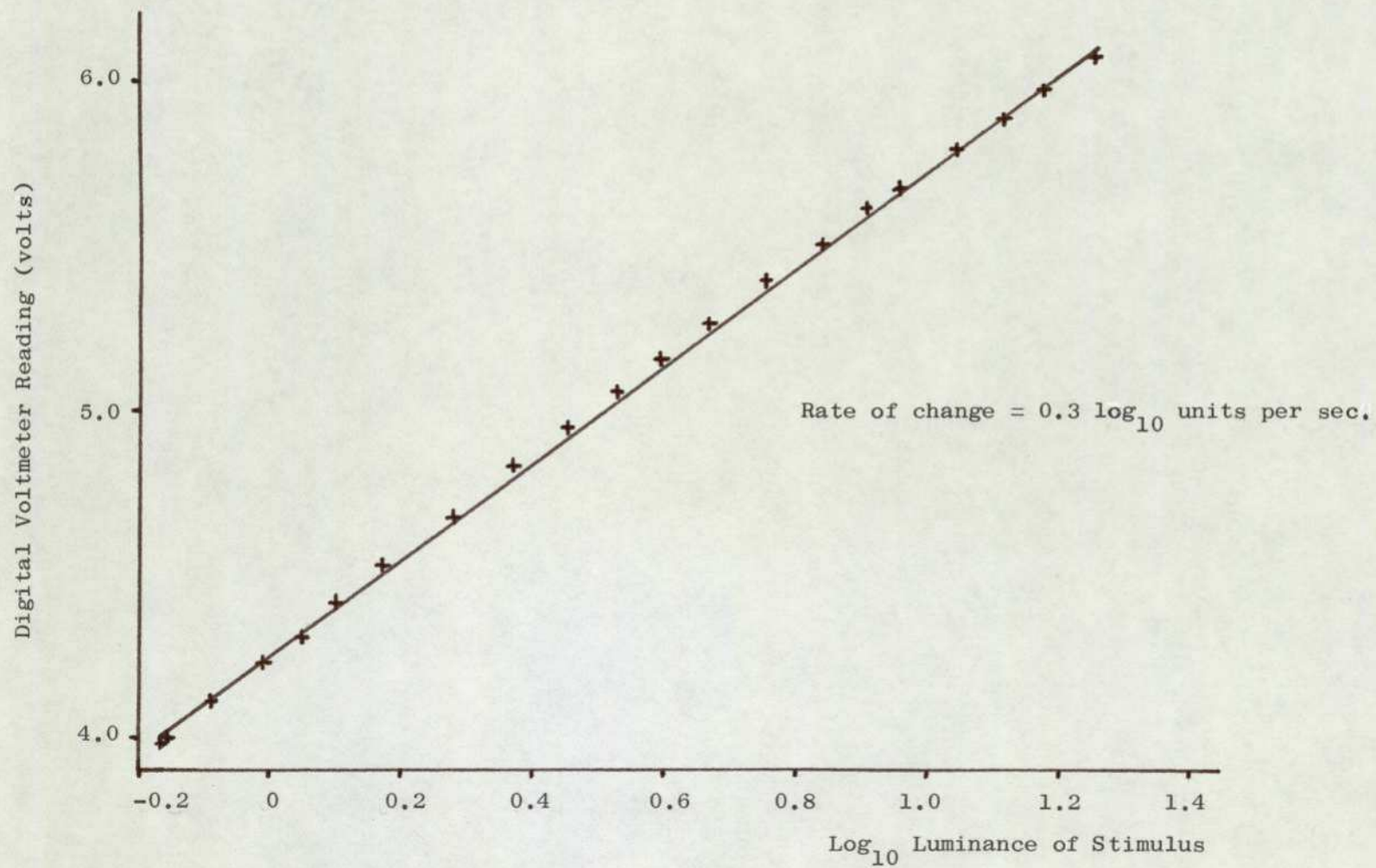


FIG. 7.1 CALIBRATION OF NEUTRAL DENSITY WEDGES

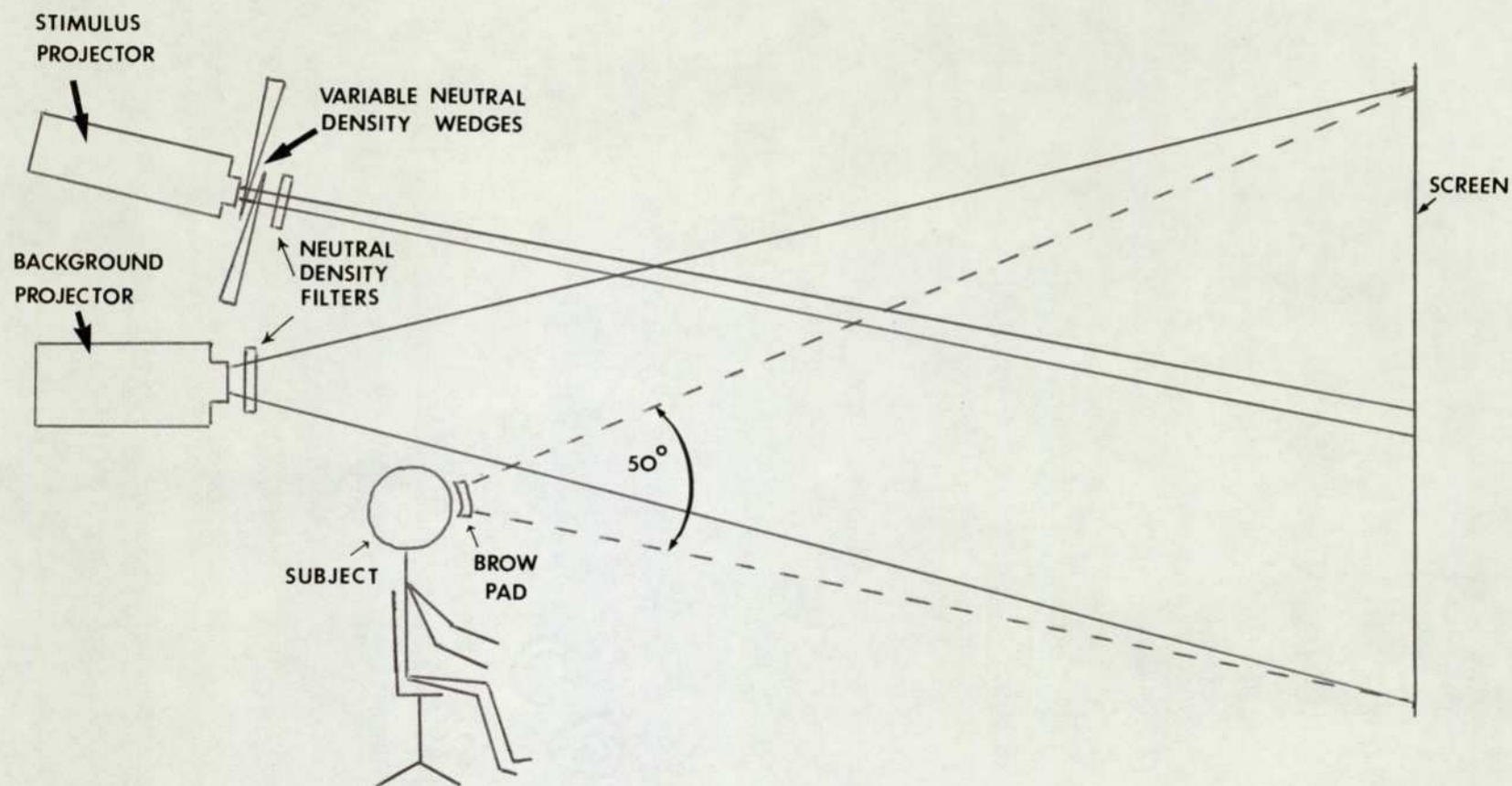


FIG. 7-2 SCHEMATIC LAYOUT OF FATIGUE EXPERIMENT [Not to Scale]

Stopping the wedges he then reversed the motor and the subject was required to press his switch again, this time reducing the stimulus contrast until it became just not detectable. Again the controller recorded the time and wedge position at threshold and wound the wedges so that the contrast of the stimulus became sub-liminal. This procedure was repeated for a total of two hours. No rests were allowed during this period.

The same experiment was repeated binocularly and also both monocular and binocular tests were repeated at an ambient luminance of 5×10^{-4} Cd M⁻². Not more than one test was performed in any one day.

d) Results

Figs. 7.3 - 7.6 show the results obtained by one observer. There appears to be no evidence for a reduction in performance over a period of two hours, although the subject complained of fatigue throughout the second hour in each case. There is also no noticeable increase in the scatter of the readings with time.

Although not strictly relevant to the study, it can be seen from fig. 7.7 that if consideration is given to the threshold for increasing contrast only, a periodic fluctuation in the liminal contrast is evident. Such a periodicity in visual sensitivity has been reported by others such as Lee, Lynch and Pounds (1945) who found a 5-8 minute modulation when measuring absolute thresholds. Also Bornschein (1951) found 5-10 minute periodicities in threshold luminance and Wertheimer (1953), measuring absolute binocular thresholds, found clear indications of periodic fluctuations of 4 minutes, 8 minutes and 2 days.

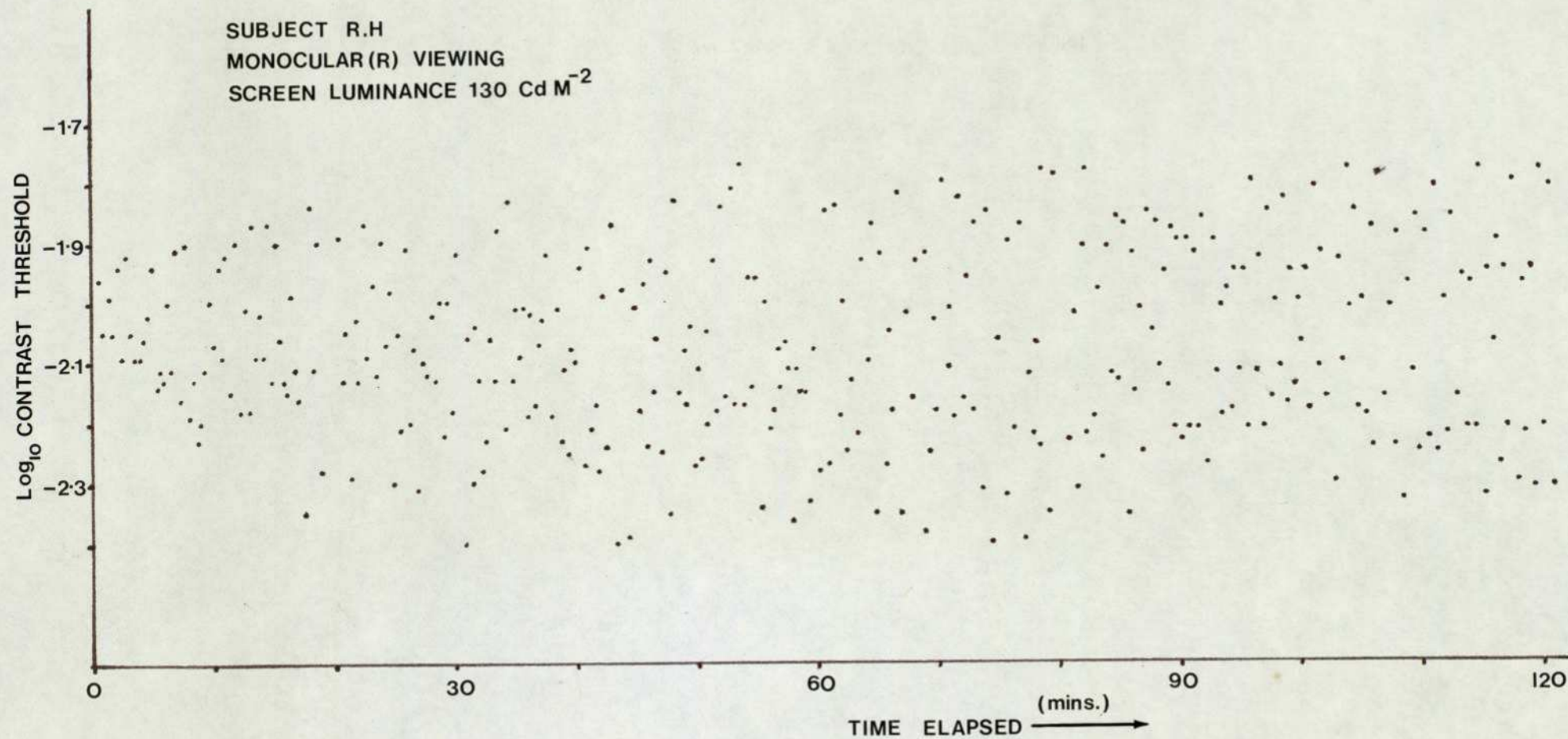


FIG. 7-3 VARIATION OF CONTRAST THRESHOLD WITH TIME [CONTINUOUS TESTING FOR 2 HOURS]

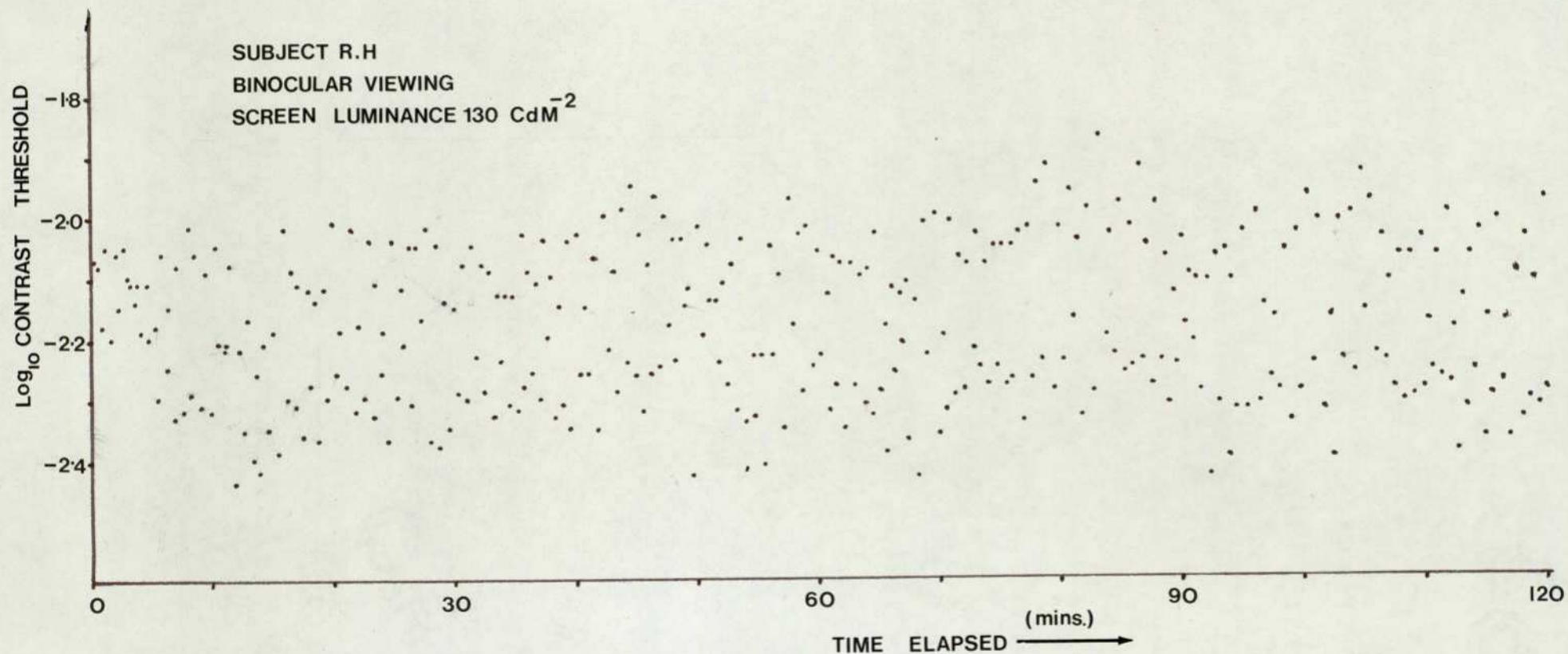


FIG. 7.4 VARIATION OF CONTRAST THRESHOLD WITH TIME [CONTINUOUS TESTING FOR 2 HOURS]

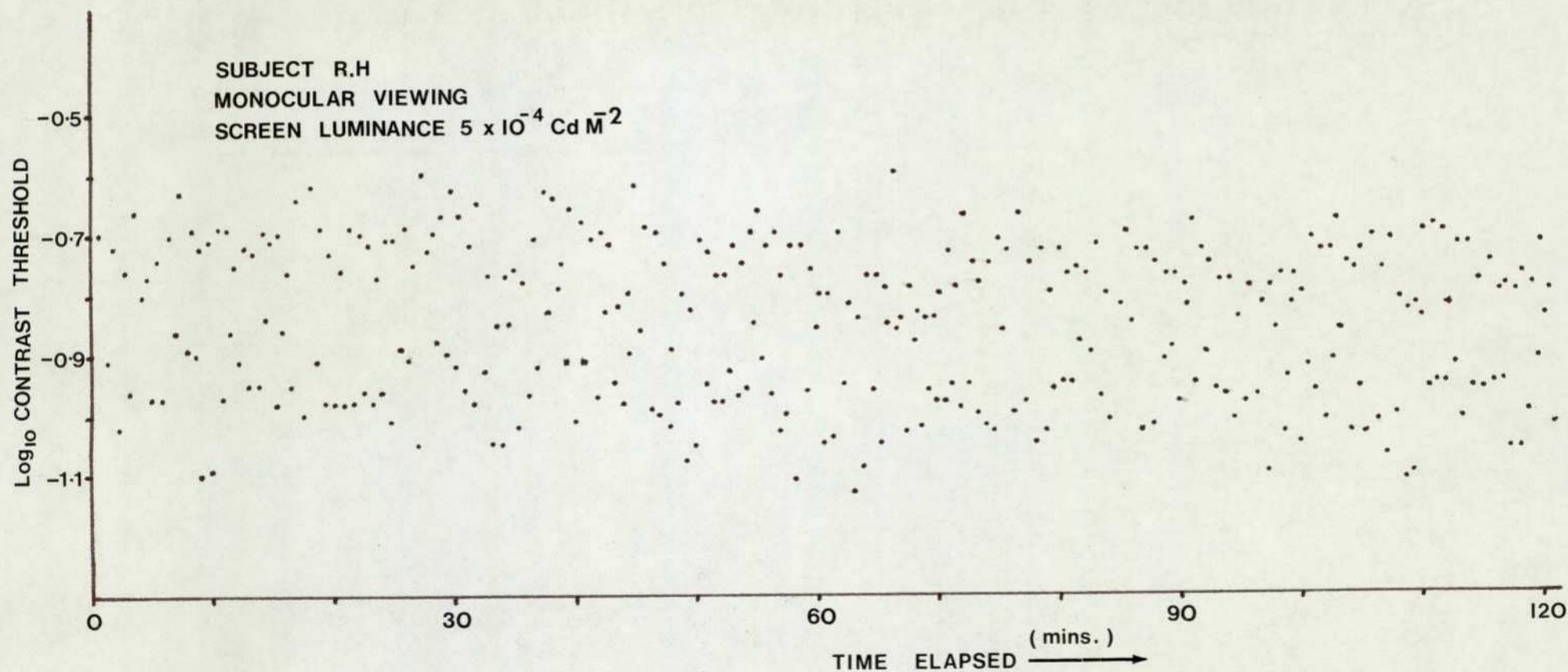


FIG. 7-5 VARIATION OF CONTRAST THRESHOLD WITH TIME [CONTINUOUS TESTING FOR 2 HOURS]

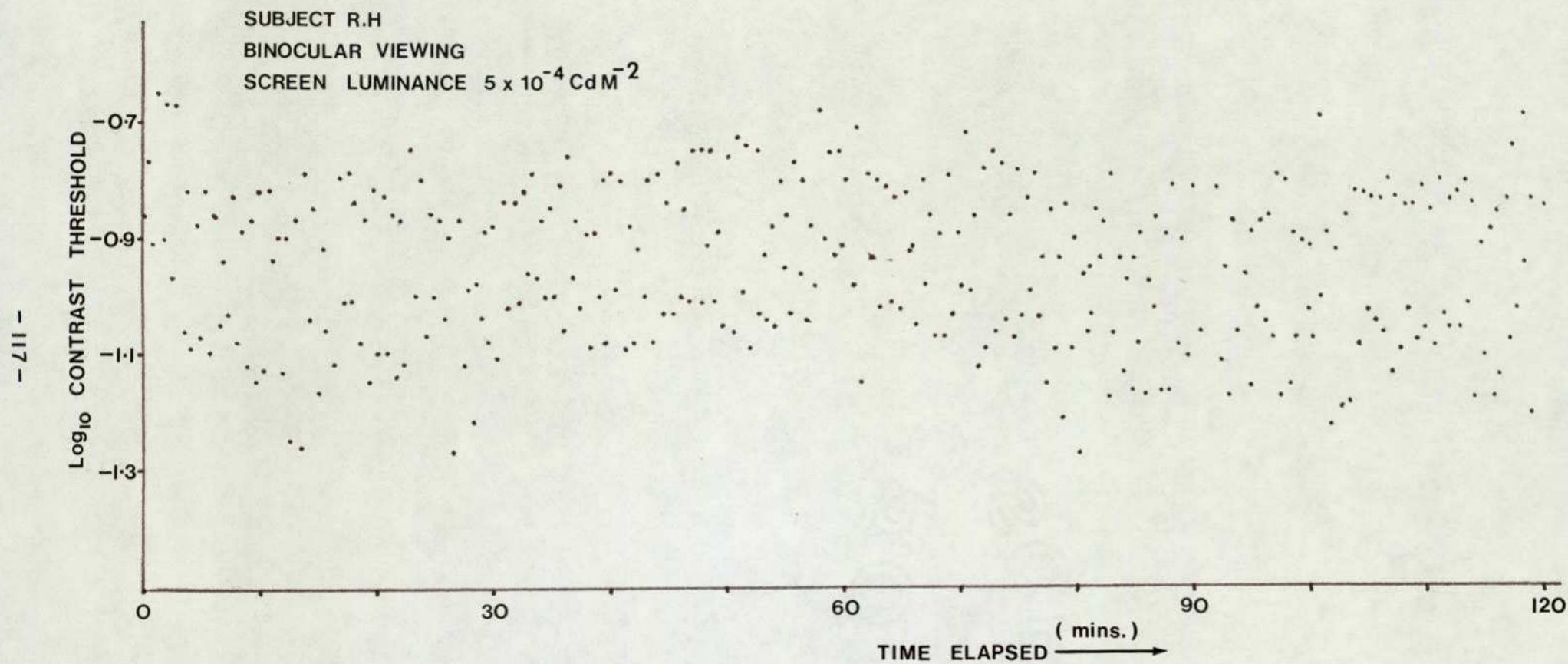


FIG. 7-6 VARIATION OF CONTRAST THRESHOLD WITH TIME [CONTINUOUS TESTING FOR 2 HOURS]

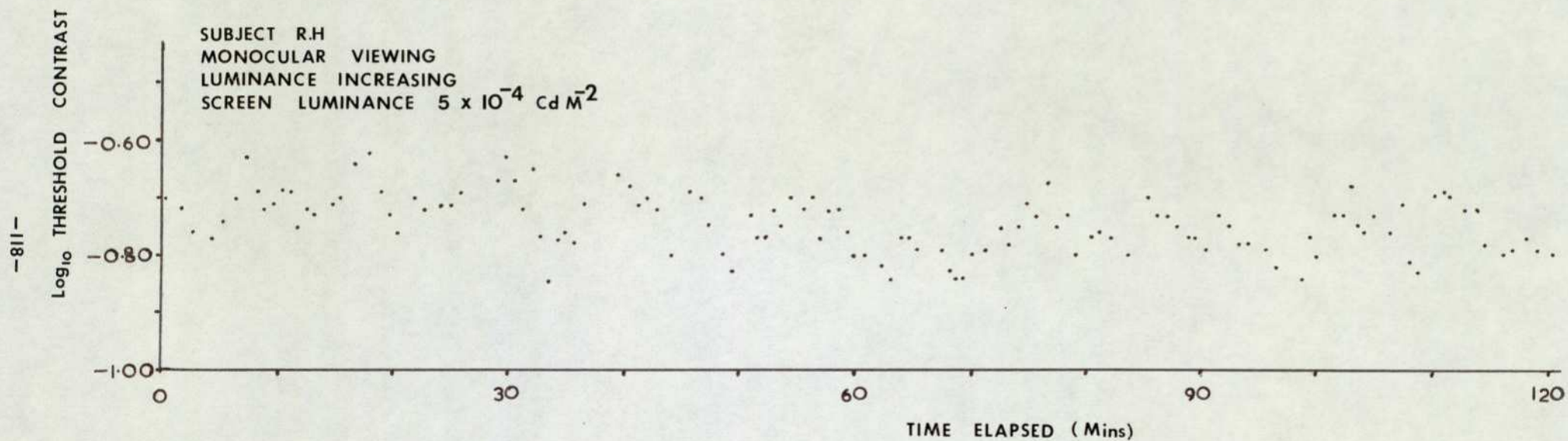


FIG. 7.7 OSCILLATION OF THRESHOLD CONTRAST

From the results obtained here it was found that the same trend appeared at both luminances, monocularly and binocularly. Also the oscillation occurred when measuring the threshold for decreasing contrast.

The significance of one observer's results is very small, but it would appear that the results obtained support the view that there exists a periodicity of ~ 8 minutes in visual sensitivity to luminance contrast.

e) Conclusions

This was not intended to be a major experiment, and the results of one individual are not to be regarded as a definitive measurement of fatigue. However, the experiment seems to indicate a negative result where a positive one was expected. A task involving muscular effort would be expected to reflect fatigue more readily and perhaps the experiment should be repeated for more complex tasks, and certainly for a greater number of subjects. Unfortunately time was not available for an extension of this kind.

CHAPTER 8

SUMMARY AND GENERAL CONCLUSIONS

The aim of this study was to provide the optical designer with sufficient information to enable him to make a rational choice between a monocular and a binocular instrument. Before this present study very little comparative data existed except perhaps in the absolute threshold domain where the published results appear to be very contradictory. The three tasks chosen for the study were intended to represent those most likely to be encountered by the user of an optical instrument and therefore give the designer a realistic basis upon which to compare the two types of vision.

The results show trends which appear to extend beyond the limitations of the separate tasks. The contrast detection task shows results which are similar to those obtained for the recognition task, and this was expected because the recognition task involved the measurement of a contrast threshold. However, it appears that the degree of binocular summation involved in the more complex task of recognition is less than that involved in detecting a simple contrast difference. This is probably because the recognition of letters of the alphabet involves both the resolution of a contrast difference and also the spatial structure. The summation in both cases was greater than could reasonably be expected on the basis of simple probability summation alone. A demonstration of this statement is given below.

If P_R and P_L are the probabilities of detection of a given stimulus using the right eye and left eye respectively, then the probability of binocular detection, P_B , assuming the eyes to be two independent channels is given by

$$P_B = 1 - (1 - P_R)(1 - P_L)$$

From the results of the contrast detection experiment a typical set of results has been taken (fig. 8.1) and from the measured values of P_R and P_L a predicted probability curve has been calculated (shown as a dotted curve) for binocular detection. It can be seen quite clearly that the calculated curve and the experimental curve are well separated.

For the comparison of contrast thresholds, Campbell and Green (1965) showed a monocular/binocular ratio of approximately $\sqrt{2}$ at a high luminance level (80 Cd M^{-2}). This ratio can be explained, as they did, by considering the noisy output from two matched channels, the standard error of the sum of n independent measurements of a random or noisy process decreasing as $\sqrt{n}$. However, the assumption that the two eyes are matched, or indeed independent channels, is more than should be reasonably assumed in most cases.

This work on the comparison of monocular and binocular contrast thresholds has been extended in the present study to cover much lower luminance levels than appear in the published literature. It is now possible to conclude that the ratio of about $\sqrt{2}$ holds down to luminance levels as low as $4.7 \times 10^{-5} \text{ Cd M}^{-2}$. The present study has been based on the results of 20 observers and this has introduced a scatter in the results which was not so

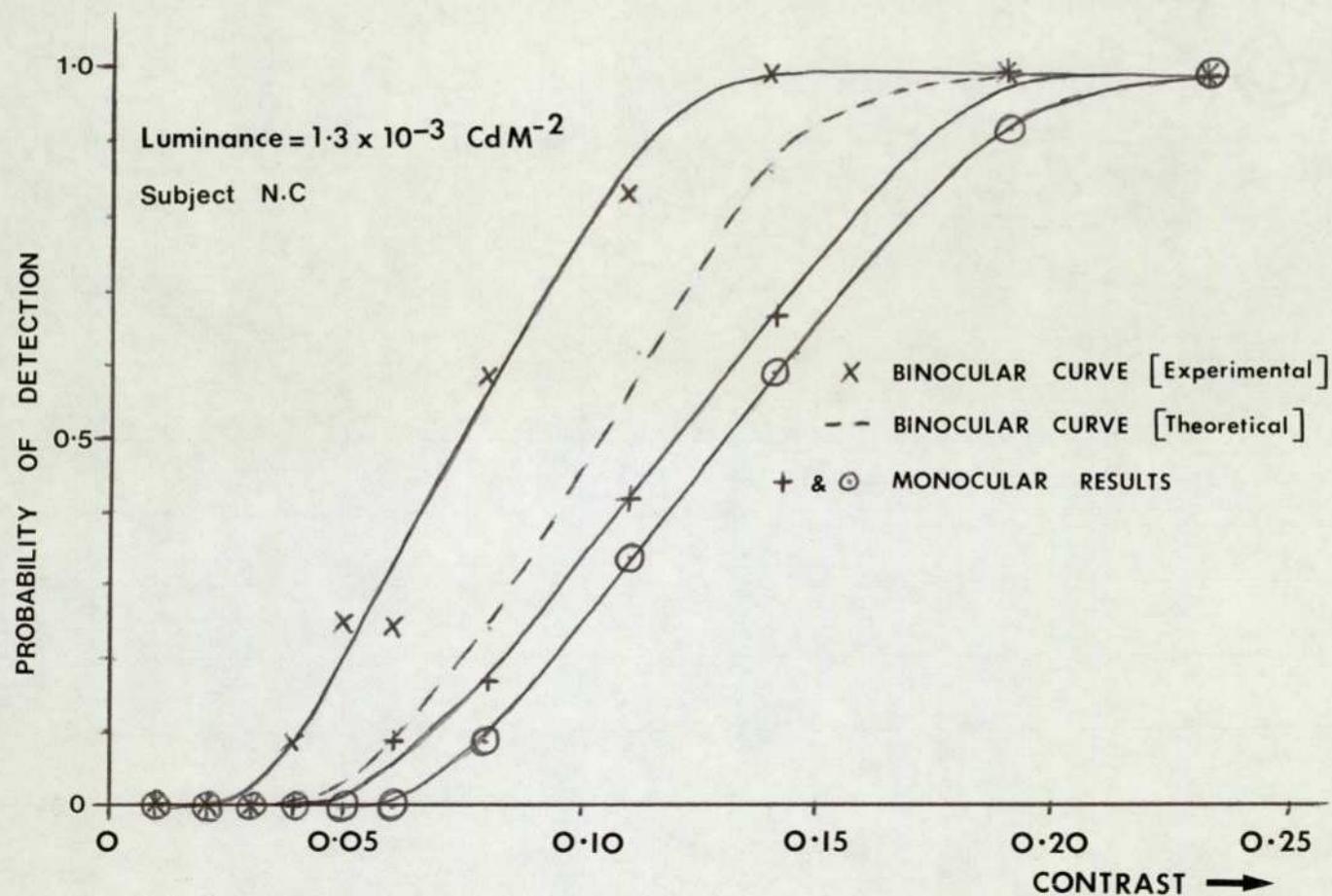


FIG. 8.1 BINOCULAR DETECTION CURVE EXPECTED FROM PROBABILITY THEORY [dashed curve]

obvious in Campbell and Green's study which involved only two subjects. On the basis of 20 observers' results it seems that for luminances below 0.1 Cd M^{-2} the monocular/binocular ratio is higher than $\sqrt{2}$; in fact, nearer to 1.5 when comparing preferred monocular vision with binocular, and greater than 1.6 when considering non-preferred monocular viewing. The present work has also shown a significant reduction in binocular superiority at the very lowest luminance ($4.7 \times 10^{-5} \text{ Cd M}^{-2}$). A possible explanation for this is that at a background luminance of $4.7 \times 10^{-5} \text{ Cd M}^{-2}$ the subjects found considerable difficulty in focussing their eyes on the plane of the screen, even in the presence of the red reference lamp. This means that there is a possibility that at certain times the two images of a given stimulus did not fall on corresponding regions of the two retinae when the subject was viewing binocularly.

The stimulation of corresponding retinal areas is necessary for maximum physiological summation and Thorn and Boynton (1974) have suggested that it was this lack of correspondence on the two retinae which accounted for Pirenne's (1943) low monocular/binocular absolute threshold ratio. Pirenne found that the ratio had a value of approximately 1.25 which he could explain quite simply in terms of probability summation. The stimulation of non-corresponding retinal regions could well be the reason for other experimentalists finding little or no evidence for physiological binocular summation. It is, however, impossible in most cases to check on this possibility from the published literature.

Similarly, the experimental work on monocular versus binocular acuity has been carried out to a much lower level of luminance and contrast than has been considered in the past. The acuity results show that the binocular/monocular ratio is dependent heavily upon the contrast involved. At very high contrast levels (i.e. approx. -1.0) the binocular/monocular ratio agrees well with the value of 1.07 obtained by Campbell and Green at high luminance. Horowitz (1949) found a value of 1.05 at a luminance level of 130 Cd M^{-2} using Landolt rings. This value increased to 1.18 as he decreased the luminance to 0.06 Cd M^{-2} .

This study has extended the available data to cover luminance levels down to $3.6 \times 10^{-4} \text{ Cd M}^{-2}$, where for high contrast stimuli the ratio was measured as 1.15, and has extended the contrast range to as low as 0.01 at which level the measured binocular/monocular ratio was 1.37 at a luminance of 7.1 Cd M^{-2} . Generally, as the contrast is decreased (i.e. the modulus of the contrast is decreased) the superiority of binocular vision becomes more evident, until at the region of limiting contrast the ratio approaches that obtained in the simple contrast detection task. This result is really to be expected because at very low contrast levels the size of the Landolt gap which is just discernible becomes so large that the distinction between acuity and contrast detection becomes virtually non-existent.

In the past there seems to have been no published work on the comparison between monocular and binocular recognition.

Although very limited, the present study does at least show that the difference between monocular and binocular letter recognition is significant in the contrast domain, and yet again emphasises

the higher efficiency of binocular vision when used to detect a contrast difference. An overall value for the monocular/binocular recognition contrast threshold ratio can be taken as 1.3 when the monocular viewing involves the preferred eye and 1.4 when it involves the non-preferred eye.

Although the subsidiary fatigue experiment showed no noticeable reduction of contrast threshold over long periods the subject was feeling very uncomfortable after two hours of monocular viewing and this could be a crucial factor in a 'real-life' situation where an observer has little motivation for performing the task at hand. Even if he is highly motivated, a lack of self-confidence in his ability to perform a given task could undermine an observer's general performance. A possible solution could be the design of a biocular type of instrument where a monocular instrument is made more comfortable by the use of a beam splitter and two eyepieces. This would enable an observer to view as though he were using a binocular. The disadvantages of a biocular as compared with a binocular are that biocular vision lacks stereoscopic relief and also the maximum amount of light through each eyepiece can only possibly be 50% of that originally entering the object glass. In practice this figure is likely to be near 40% and for this reason a biocular instrument is only recommended for use in situations where illumination is abundant.

Conclusions

It appears that the main advantage of binocular vision, from the tasks considered, lies in the contrast domain. The relevance of this fact can be demonstrated by consideration of the attenuating effect of the atmosphere. Appendix 6 gives an

example of converting the monocular/binocular contrast threshold to a ratio of threshold ranges through the atmosphere and in practical problems involving the atmosphere this is a much more realistic method of using the results. The optical designer now has the facility, when designing a telescope, to take account of binocular superiority in the same way which, in the past, he has used the superiority of a magnifying instrument over the unaided eye, i.e. the increase in effective range for a given target.

As a result of these investigations the optical designer has now considerably more data on which to base his choice between a monocular and binocular instrument. The next logical step is to extend the investigation to cover more complex objects. The choice of such objects would depend upon the task for which an optical instrument was being designed and would at some point require the introduction of colour effects. For more complex tasks the effect of monocular fatigue would be expected to be reflected in a subject's reduced performance after a long period of observation.

APPENDIX 1.1 DETECTION RESULTS (Background luminance: $1.0 \times 10^{-1} \text{ CdM}^{-2}$)

SUBJECT	PREFERRED EYE	PREFERRED EYE CONTRAST THRESHOLD (M_p)	NON-PREFERRED EYE CONTRAST THRESHOLD (M_{np})	BINOCULAR CONTRAST THRESHOLD (B)	$M_{p/B}$	$M_{np/B}$
FB	R	0.040	0.044	0.030	1.33	1.47
JP	R	0.040	0.040	0.024	1.67	1.67
MF	R	0.050	0.053	0.033	1.52	1.61
RH	R	0.050	0.061	0.031	1.61	1.97
MP	R	0.056	0.056	0.040	1.40	1.40
DS	R	0.036	0.052	0.027	1.33	1.93
MC	R	0.036	0.039	0.026	1.38	1.50
PM	R	0.052	0.055	0.033	1.58	1.67
TM	L	0.070	0.078	0.047	1.49	1.66
JT	R	0.062	0.070	0.040	1.55	1.75
PB	R	0.061	0.061	0.042	1.45	1.45
PH	R	0.070	0.070	0.046	1.52	1.52
PR	R	0.073	0.087	0.048	1.52	1.81
BJ	R	0.048	0.051	0.036	1.33	1.42
JD	R	0.079	0.083	0.047	1.68	1.77
ET	R	0.054	0.057	0.038	1.42	1.50
IB	R	0.066	0.071	0.046	1.43	1.54
JG	R	0.040	0.044	0.027	1.48	1.63
SH	R	0.062	0.064	0.045	1.38	1.42
GA	R	0.075	0.075	0.047	1.60	1.60
MEAN OF 20		0.056	0.061	0.038	1.48	1.61
STANDARD DEVIATION		0.013	0.014	0.008	0.11	0.16
95% CONFIDENCE LIMITS		± 0.0062	± 0.0067	± 0.0038	± 0.053	± 0.077

APPENDIX 1.2 DETECTION RESULTS (Background luminance: $0.9 \times 10^{-2} \text{ CdM}^{-2}$)

SUBJECT	PREFERRED EYE	PREFERRED EYE CONTRAST THRESHOLD (M_p)	NON-PREFERRED EYE CONTRAST THRESHOLD (M_{np})	BINOCULAR CONTRAST THRESHOLD (B)	$M_{p/B}$	$M_{np/B}$
FB	R	0.078	0.081	0.055	1.42	1.47
JP	R	0.071	0.073	0.048	1.48	1.52
MF	R	0.093	0.106	0.059	1.58	1.80
RH	R	0.077	0.101	0.048	1.60	2.10
MP	R	0.082	0.088	0.058	1.41	1.52
DS	R	0.076	0.084	0.050	1.52	1.68
MC	R	0.095	0.101	0.058	1.64	1.74
PM	R	0.110	0.122	0.069	1.59	1.77
TM	L	0.115	0.132	0.070	1.64	1.89
JT	R	0.089	0.099	0.062	1.44	1.60
PB	R	0.103	0.106	0.068	1.51	1.56
PH	R	0.112	0.112	0.070	1.60	1.60
PR	R	0.126	0.126	0.082	1.54	1.54
BJ	R	0.077	0.079	0.055	1.40	1.44
JD	R	0.112	0.137	0.070	1.60	1.96
ET	R	0.095	0.097	0.069	1.38	1.41
IB	R	0.102	0.102	0.066	1.55	1.55
JG	R	0.076	0.081	0.056	1.36	1.45
SH	R	0.091	0.109	0.067	1.36	1.63
GA	R	0.120	0.145	0.076	1.58	1.91
MEAN OF 20		0.095	0.104	0.063	1.51	1.66
STANDARD DEVIATION		0.016	0.021	0.009	0.09	0.19
95% CONFIDENCE LIMITS		± 0.0077	± 0.0101	± 0.0043	± 0.043	± 0.091

APPENDIX 1.3 DETECTION RESULTS (Background luminance: $1.3 \times 10^{-3} \text{ CdM}^{-2}$)

SUBJECT	PREFERRED EYE	PREFERRED EYE CONTRAST THRESHOLD (M_p)	NON-PREFERRED EYE CONTRAST THRESHOLD (M_{np})	BINOCULAR CONTRAST THRESHOLD (B)	$M_{p/B}$	$M_{np/B}$
FB	R	0.092	0.104	0.065	1.42	1.60
JP	R	0.116	0.153	0.070	1.66	2.19
MF	R	0.129	0.134	0.080	1.61	1.68
RH	R	0.109	0.114	0.066	1.65	1.73
MP	R	0.118	0.123	0.082	1.44	1.50
DS	R	0.119	0.122	0.079	1.51	1.54
MC	R	0.124	0.144	0.075	1.65	1.92
PM	R	0.133	0.139	0.082	1.62	1.70
TM	L	0.127	0.131	0.084	1.51	1.56
JT	R	0.114	0.118	0.076	1.50	1.55
PB	R	0.129	0.169	0.086	1.50	1.97
PH	R	0.165	0.178	0.101	1.63	1.76
PR	R	0.161	0.170	0.098	1.64	1.73
BJ	R	0.112	0.119	0.079	1.42	1.51
JD	R	0.131	0.182	0.082	1.60	2.22
ET	R	0.129	0.152	0.091	1.42	1.67
IB	R	0.129	0.139	0.080	1.61	1.74
JG	R	0.112	0.119	0.077	1.45	1.55
SH	R	0.122	0.149	0.086	1.42	1.73
GA	R	0.139	0.148	0.094	1.48	1.57
MEAN OF 20		0.126	0.140	0.082	1.54	1.72
STANDARD DEVIATION		0.016	0.022	0.009	0.09	0.20
95% CONFIDENCE LIMITS		± 0.0077	± 0.0105	± 0.0043	± 0.043	± 0.096

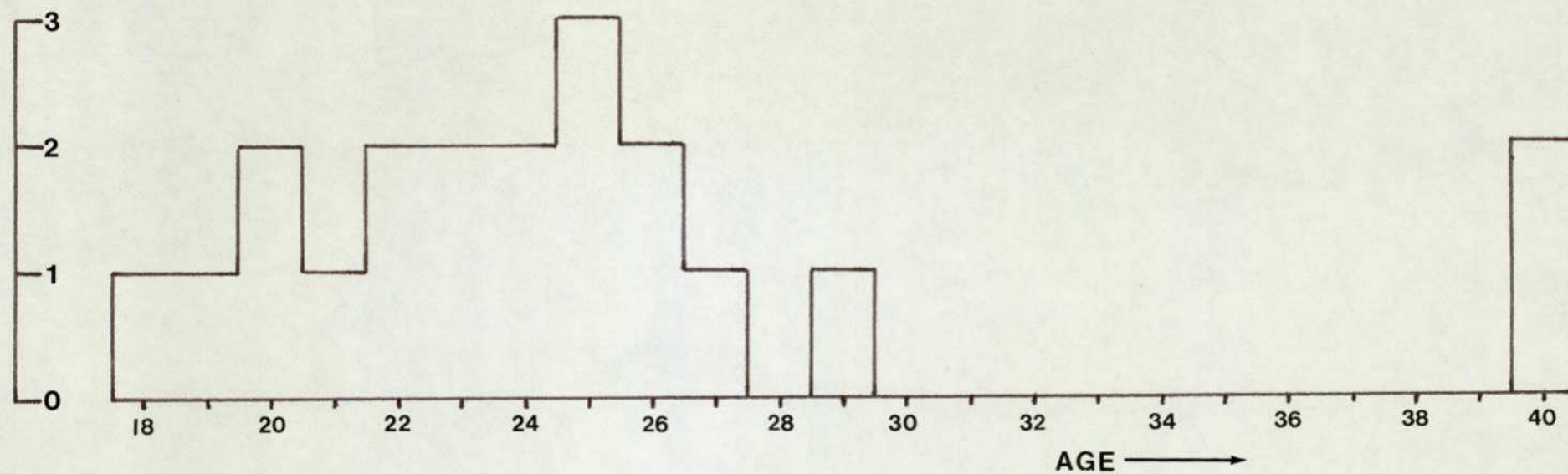
APPENDIX 1.4 DETECTION RESULTS (Background luminance: $4.7 \times 10^{-5} \text{ CdM}^{-2}$)

SUBJECT	PREFERRED EYE	PREFERRED EYE CONTRAST THRESHOLD (M_p)	NON-PREFERRED EYE CONTRAST THRESHOLD (M_{np})	BINOCULAR CONTRAST THRESHOLD (B)	$M_{p/B}$	$M_{np/B}$
FB	R	0.227	0.275	0.162	1.40	1.70
JP	R	0.183	0.239	0.126	1.45	1.90
MF	R	0.185	0.194	0.134	1.38	1.45
RH	R	0.225	0.275	0.180	1.25	1.53
MP	R	0.188	0.226	0.148	1.27	1.53
DS	R	0.231	0.271	0.182	1.27	1.49
MC	R	0.247	0.314	0.199	1.24	1.58
PM	R	0.279	0.312	0.201	1.39	1.55
TM	L	0.245	0.260	0.183	1.34	1.42
JT	R	0.256	0.290	0.197	1.30	1.47
PB	R	0.237	0.247	0.174	1.36	1.42
PH	R	0.264	0.288	0.191	1.38	1.51
PR	R	0.246	0.260	0.173	1.42	1.50
BJ	R	0.188	0.188	0.149	1.26	1.26
JD	R	0.219	0.246	0.152	1.44	1.62
ET	R	0.246	0.252	0.181	1.36	1.39
IB	R	0.192	0.223	0.143	1.34	1.56
JG	R	0.203	0.220	0.145	1.40	1.52
SH	R	0.213	0.254	0.154	1.38	1.65
GA	R	0.292	0.302	0.204	1.43	1.48
MEAN OF 20		0.228	0.257	0.169	1.35	1.53
STANDARD DEVIATION		0.031	0.035	0.023	0.07	0.13
95% CONFIDENCE LIMITS		± 0.0149	± 0.0168	± 0.0110	± 0.034	± 0.062

APPENDIX 2.1 ACUITY RESULTS (Background luminance: 7.1 CdM^{-2})

Contrast = 0.70

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	1.00	1.00	1.05	1.05	1.05
BJ	R	0.69	0.88	0.88	1.28	1.00
GB	L	1.03	1.01	1.10	1.07	1.09
AG	R	0.85	0.91	1.03	1.21	1.13
JS	L	0.80	0.80	0.82	1.03	1.03
CE	R	1.09	1.04	1.04	0.95	1.00
SJ	R	0.91	0.73	0.91	1.00	1.25
RR	R	1.20	1.18	1.18	0.98	1.00
TM	L	1.10	1.10	1.15	1.05	1.05
MC	R	0.90	0.90	0.90	1.00	1.00
JP	R	1.05	1.05	1.20	1.14	1.14
TG	R	0.85	0.80	0.90	1.06	1.13
MR	L	1.12	0.98	1.12	1.14	1.00
TC	L	1.00	0.95	0.95	0.95	1.00
MF	R	0.81	0.76	0.84	1.04	1.10
DS	R	1.00	1.00	1.00	1.00	1.00
JT	R	0.99	0.89	1.00	1.01	1.12
PH	R	1.04	0.98	1.12	1.08	1.14
IB	R	1.01	0.92	1.07	1.06	1.16
RH	R	1.00	0.99	1.11	1.11	1.12
MEAN OF 20		0.97	0.94	1.02	1.06	1.08
STANDARD DEVIATION		0.12	0.11	0.11	0.08	0.07
95% CONFIDENCE LIMITS		± 0.058	± 0.053	± 0.053	± 0.038	± 0.034



APPENDIX 1.5 DISTRIBUTION OF SUBJECTS' AGES [DETECTION TASK]

APPENDIX 2.2 ACUITY RESULTS (Background luminance: 7.1 CdM^{-2})

Contrast = 0.30

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M) _p	NON-PREFERRED EYE ACUITY (M) _{np}	BINOCULAR ACUITY (B)	B/M _p	B/M _{np}
DL	R	0.95	0.95	1.00	1.05	1.05
BJ	R	0.65	0.81	0.81	1.25	1.00
GB	L	0.96	0.96	0.98	1.02	1.02
AG	R	0.88	0.85	0.95	1.08	1.12
JS	L	0.52	0.50	0.52	1.00	1.04
CE	R	0.72	0.56	0.72	1.00	1.29
SJ	R	0.60	0.58	0.62	1.03	1.07
RR	R	0.80	0.80	0.80	1.00	1.00
TM	L	0.88	0.75	0.91	1.03	1.21
MC	R	0.66	0.64	0.72	1.09	1.13
JP	R	0.95	0.90	0.98	1.03	1.09
TG	R	0.82	0.84	0.85	1.04	1.01
MR	L	0.85	0.80	0.88	1.04	1.11
TC	L	0.75	0.61	0.80	1.07	1.31
MF	R	0.77	0.83	0.91	1.18	1.09
DS	R	0.98	0.98	0.98	1.00	1.00
JT	R	0.90	0.90	0.97	1.08	1.08
PH	R	0.78	0.82	0.90	1.16	1.10
IB	R	0.81	0.84	0.92	1.13	1.10
RH	R	0.97	0.97	1.11	1.14	1.14
MEAN OF 20		0.81	0.79	0.87	1.07	1.10
STANDARD DEVIATION		0.13	0.14	0.14	0.07	0.09
95% CONFIDENCE LIMITS		±0.062	±0.067	±0.067	±0.034	±0.043

APPENDIX 2.3 ACUITY RESULTS (Background luminance: 7.1 CdM^{-2})

Contrast = 0.10

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	0.25	0.25	0.29	1.16	1.16
BJ	R	0.13	0.16	0.24	1.85	1.50
GB	L	0.28	0.26	0.32	1.14	1.23
AG	R	0.28	0.28	0.30	1.07	1.07
JS	L	0.20	0.17	0.22	1.11	1.29
CE	R	0.19	0.19	0.19	1.00	1.00
SJ	R	0.20	0.18	0.28	1.40	1.56
RR	R	0.26	0.24	0.29	1.12	1.21
TM	L	0.22	0.20	0.27	1.23	1.30
MC	R	0.20	0.18	0.25	1.25	1.39
JP	R	0.28	0.25	0.31	1.11	1.24
TG	R	0.25	0.22	0.27	1.08	1.23
MR	L	0.20	0.17	0.23	1.15	1.35
TC	L	0.18	0.14	0.24	1.33	1.71
MF	R	0.16	0.16	0.18	1.13	1.13
DS	R	0.24	0.21	0.29	1.21	1.38
JT	R	0.23	0.22	0.24	1.04	1.09
PH	R	0.18	0.18	0.21	1.17	1.17
IB	R	0.25	0.24	0.26	1.04	1.08
RH	R	0.24	0.23	0.26	1.08	1.13
MEAN OF 20		0.22	0.21	0.26	1.18	1.26
STANDARD DEVIATION		0.04	0.04	0.04	0.18	0.18
95% CONFIDENCE LIMITS		± 0.019	± 0.019	± 0.019	± 0.086	± 0.086

APPENDIX 2.4 ACUITY RESULTS (Background luminance: 7.1 CdM^{-2})

Contrast = 0.03

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	0.10	0.11	0.13	1.30	1.18
BJ	R	0.09	0.08	0.12	1.33	1.50
GB	L	0.12	0.11	0.12	1.00	1.09
AG	R	0.14	0.13	0.17	1.21	1.31
JS	L	0.09	0.08	0.10	1.11	1.25
CE	R	0.10	0.05	0.12	1.20	2.00
SJ	R	0.08	0.07	0.09	1.13	1.29
RR	R	0.10	0.09	0.13	1.30	1.44
TM	L	0.07	0.06	0.08	1.14	1.33
MC	R	0.07	0.05	0.09	1.29	1.80
JP	R	0.15	0.15	0.18	1.20	1.20
TG	R	0.08	0.09	0.10	1.25	1.11
MR	L	0.10	0.08	0.12	1.20	1.50
TC	L	0.06	0.05	0.08	1.33	1.60
MF	R	0.05	0.03	0.04	1.60	1.33
DS	R	0.12	0.12	0.15	1.25	1.25
JT	R	0.10	0.10	0.13	1.30	1.30
PH	R	0.07	0.07	0.10	1.43	1.43
IB	R	0.10	0.10	0.14	1.40	1.40
RH	R	0.09	0.08	0.13	1.44	1.44
MEAN OF 20		0.09	0.09	0.12	1.27	1.39
STANDARD DEVIATION		0.02	0.03	0.03	0.13	0.21
95% CONFIDENCE LIMITS		± 0.010	± 0.014	± 0.014	± 0.062	± 0.101

APPENDIX 2.5 ACUITY RESULTS (Background luminance: 7.1 CdM^{-2})

Contrast = 0.01

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M) _p	NON-PREFERRED EYE ACUITY (M) _{np}	BINOCULAR ACUITY (B)	B/M _p	B/M _{np}
DL	R	0.012	0.011	0.018	1.50	1.64
BJ	R	0.013	0.012	0.017	1.31	1.42
GB	L	0.013	0.012	0.018	1.38	1.50
AG	R	0.013	0.012	0.016	1.23	1.33
JS	L	-	-	0.013	-	-
CE	R	-	-	0.012	-	-
SJ	R	0.012	0.011	0.016	1.33	1.45
RR	R	-	-	0.014	-	-
TM	L	0.011	0.009	0.015	1.36	1.67
MC	R	0.013	0.011	0.017	1.31	1.55
JP	R	0.015	0.014	0.022	1.47	1.57
TG	R	0.012	0.012	0.017	1.42	1.42
MR	L	0.014	0.012	0.017	1.21	1.42
TC	L	0.010	0.010	0.015	1.50	1.50
MF	R	0.011	0.010	0.016	1.45	1.60
DS	R	0.012	0.011	0.017	1.42	1.55
JT	R	0.014	0.012	0.019	1.36	1.58
PH	R	0.011	0.009	0.016	1.45	1.78
IB	R	0.016	0.013	0.020	1.25	1.54
RH	R	0.014	0.012	0.019	1.36	1.58
MEAN OF 20		0.013	0.011	0.017	1.37	1.54
STANDARD DEVIATION		0.001	0.001	0.002	0.08	0.10
95% CONFIDENCE LIMITS		±0.0005	±0.0005	±0.0010	±0.042	±0.053

APPENDIX 2.6 ACUITY RESULTS (Background luminance: $1.0 \times 10^{-1} \text{ CdM}^{-2}$)

Contrast = 0.70

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M) _p	NON-PREFERRED EYE ACUITY (M) _{np}	BINOCULAR ACUITY (B)	B/M _p	B/M _{np}
DL	R	0.46	0.42	0.46	1.00	1.10
BJ	R	0.31	0.39	0.39	1.26	1.00
GB	L	0.42	0.39	0.45	1.07	1.15
AG	R	0.46	0.48	0.60	1.30	1.25
JS	L	0.38	0.36	0.46	1.21	1.28
CE	R	0.38	0.38	0.42	1.11	1.11
SJ	R	0.45	0.40	0.48	1.07	1.20
RR	R	0.56	0.54	0.62	1.11	1.15
TM	L	0.50	0.48	0.50	1.00	1.04
MC	R	0.40	0.40	0.45	1.13	1.13
JP	R	0.65	0.51	0.70	1.08	1.37
TG	R	0.46	0.44	0.50	1.09	1.14
MR	L	0.56	0.50	0.64	1.14	1.28
TC	L	0.50	0.33	0.45	0.90	1.36
MF	R	0.37	0.34	0.41	1.11	1.21
DS	R	0.38	0.42	0.45	1.18	1.07
JT	R	0.47	0.44	0.54	1.15	1.23
PH	R	0.45	0.43	0.48	1.07	1.12
IB	R	0.44	0.43	0.49	1.11	1.14
RH	R	0.45	0.43	0.51	1.13	1.19
MEAN OF 20		0.45	0.43	0.50	1.11	1.18
STANDARD DEVIATION		0.08	0.05	0.08	0.09	0.10
95% CONFIDENCE LIMITS		±0.038	±0.024	±0.038	±0.043	±0.048

APPENDIX 2.7 ACUITY RESULTS (Background luminance: $1.0 \times 10^{-1} \text{ CdM}^{-2}$)

Contrast = 0.30

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	0.19	0.21	0.24	1.26	1.14
BJ	R	0.19	0.19	0.20	1.05	1.05
GB	L	0.28	0.26	0.31	1.11	1.19
AG	R	0.29	0.29	0.30	1.03	1.03
JS	L	0.20	0.17	0.27	1.35	1.59
CE	R	0.17	0.17	0.23	1.35	1.35
SJ	R	0.18	0.17	0.19	1.06	1.12
RR	R	0.25	0.25	0.28	1.12	1.12
TM	L	0.28	0.25	0.30	1.07	1.20
MC	R	0.22	0.22	0.28	1.27	1.27
JP	R	0.25	0.25	0.29	1.16	1.16
TG	R	0.24	0.25	0.27	1.13	1.08
MR	L	0.25	0.22	0.31	1.24	1.41
TC	L	0.20	0.17	0.25	1.25	1.47
MF	R	0.19	0.18	0.24	1.26	1.33
DS	R	0.18	0.21	0.26	1.44	1.24
JT	R	0.25	0.23	0.29	1.16	1.26
PH	R	0.22	0.22	0.27	1.23	1.23
IB	R	0.27	0.25	0.28	1.04	1.12
RH	R	0.23	0.22	0.28	1.22	1.27
MEAN OF 20		0.23	0.22	0.27	1.19	1.23
STANDARD DEVIATION		0.04	0.03	0.03	0.11	0.14
95% CONFIDENCE LIMITS		± 0.019	± 0.014	± 0.014	± 0.053	± 0.067

APPENDIX 2.8 ACUITY RESULTS (Background luminance: $1.0 \times 10^{-1} \text{ CdM}^{-2}$)

Contrast = 0.10

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	0.06	0.06	0.08	1.33	1.33
BJ	R	0.07	0.06	0.07	1.00	1.17
GB	L	0.08	0.07	0.11	1.38	1.57
AG	R	0.11	0.11	0.13	1.18	1.18
JS	L	0.06	0.06	0.07	1.17	1.17
CE	R	0.06	0.06	0.08	1.33	1.33
SJ	R	0.05	0.04	0.07	1.40	1.75
RR	R	0.07	0.06	0.08	1.14	1.33
TM	L	0.07	0.06	0.09	1.29	1.50
MC	R	0.07	0.06	0.10	1.43	1.67
JP	R	0.10	0.08	0.12	1.20	1.50
TG	R	0.08	0.07	0.10	1.25	1.43
MR	L	0.06	0.05	0.08	1.33	1.60
TC	L	0.06	0.05	0.07	1.17	1.40
MF	R	0.05	0.05	0.07	1.40	1.40
DS	R	0.05	0.05	0.08	1.60	1.60
JT	R	0.08	0.07	0.10	1.25	1.43
PH	R	0.08	0.07	0.09	1.13	1.29
IB	R	0.07	0.07	0.08	1.14	1.14
RH	R	0.08	0.08	0.10	1.25	1.33
MEAN OF 20		0.07	0.06	0.09	1.27	1.41
STANDARD DEVIATION		0.02	0.02	0.02	0.13	0.17
95% CONFIDENCE LIMITS		± 0.010	± 0.010	± 0.010	± 0.062	± 0.082

APPENDIX 2.9 ACUITY RESULTS (Background luminance: $1.0 \times 10^{-1} \text{ CdM}^{-2}$)

Contrast = 0.03

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	-	-	-	-	-
BJ	R	-	-	-	-	-
GB	L	0.021	0.019	0.026	1.24	1.37
AG	R	0.029	0.025	0.032	1.10	1.28
JS	L	-	-	-	-	-
CE	R	-	-	-	-	-
SJ	R	0.016	0.015	0.021	1.31	1.40
RR	R	0.028	0.022	0.038	1.36	1.73
TM	L	-	-	-	-	-
MC	R	0.022	0.020	0.036	1.64	1.80
JP	R	0.025	0.022	0.039	1.56	1.77
TG	R	0.022	0.018	0.035	1.59	1.94
MR	L	0.025	0.023	0.036	1.44	1.57
TC	L	0.020	0.018	0.030	1.50	1.67
MF	R	0.018	0.017	0.028	1.56	1.65
DS	R	-	-	-	-	-
JT	R	0.026	0.024	0.035	1.35	1.46
PH	R	0.020	0.017	0.029	1.45	1.71
IB	R	0.027	0.023	0.036	1.33	1.57
RH	R	0.021	0.018	0.030	1.43	1.67
MEAN OF 20		0.023	0.020	0.033	1.42	1.61
STANDARD DEVIATION		0.004	0.003	0.005	0.14	0.18
95% CONFIDENCE LIMITS		± 0.0024	± 0.0018	± 0.0030	± 0.084	± 0.108

APPENDIX 2.10 ACUITY RESULTS (Background luminance: $3.4 \times 10^{-3} \text{ CdM}^{-2}$)

Contrast = 0.70

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	0.11	0.09	0.10	1.00	1.22
BJ	R	0.08	0.08	0.08	1.00	1.00
GB	L	0.11	0.11	0.13	1.18	1.18
AG	R	0.10	0.10	0.11	1.10	1.10
JS	L	0.06	0.06	0.06	1.00	1.00
CE	R	0.07	0.07	0.10	1.43	1.43
SJ	R	0.08	0.07	0.11	1.38	1.57
RR	R	0.10	0.10	0.13	1.30	1.30
TM	L	0.11	0.09	0.10	0.91	1.11
MC	R	0.09	0.09	0.09	1.00	1.00
JP	R	0.12	0.12	0.12	1.00	1.00
TG	R	0.11	0.11	0.11	1.00	1.00
MR	L	0.09	0.08	0.09	1.00	1.13
TC	L	0.08	0.08	0.10	1.25	1.25
MF	R	0.07	0.06	0.08	1.14	1.33
DS	R	0.08	0.08	0.11	1.38	1.38
JT	R	0.09	0.08	0.10	1.11	1.25
PH	R	0.07	0.07	0.08	1.14	1.14
IB	R	0.10	0.10	0.10	1.00	1.00
RH	R	0.10	0.10	0.11	1.10	1.10
MEAN OF 20		0.09	0.09	0.10	1.12	1.17
STANDARD DEVIATION		0.02	0.02	0.02	0.15	0.16
95% CONFIDENCE LIMITS		± 0.010	± 0.010	± 0.010	± 0.072	± 0.077

APPENDIX 2.11 ACUITY RESULTS (Background luminance: $3.4 \times 10^{-3} \text{ CdM}^{-2}$)

Contrast = 0.30

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	0.08	0.07	0.08	1.00	1.14
BJ	R	0.06	0.06	0.07	1.17	1.17
GB	L	0.07	0.07	0.08	1.14	1.14
AG	R	0.08	0.08	0.10	1.25	1.25
JS	L	0.04	0.03	0.05	1.25	1.67
CE	R	0.05	0.04	0.07	1.40	1.75
SJ	R	0.05	0.04	0.07	1.40	1.75
RR	R	0.08	0.08	0.10	1.25	1.25
TM	L	0.07	0.06	0.08	1.14	1.33
MC	R	0.07	0.06	0.09	1.29	1.50
JP	R	0.08	0.07	0.10	1.25	1.43
TG	R	0.07	0.06	0.09	1.29	1.50
MR	L	0.08	0.06	0.08	1.00	1.33
TC	L	0.06	0.06	0.07	1.17	1.17
MF	R	0.05	0.05	0.07	1.40	1.40
DS	R	0.05	0.05	0.06	1.20	1.20
JT	R	0.07	0.06	0.08	1.14	1.33
PH	R	0.04	0.04	0.05	1.25	1.25
IB	R	0.07	0.08	0.09	1.29	1.13
RH	R	0.06	0.05	0.07	1.17	1.40
MEAN OF 20		0.06	0.06	0.08	1.22	1.35
STANDARD DEVIATION		0.01	0.01	0.01	0.11	0.19
95% CONFIDENCE LIMITS		± 0.005	± 0.005	± 0.005	± 0.053	± 0.091

APPENDIX 2.12 ACUITY RESULTS (Background luminance: $3.4 \times 10^{-3} \text{ CdM}^{-2}$)

Contrast = 0.10

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	0.016	0.013	0.020	1.25	1.54
BJ	R	-	-	0.014	-	-
GB	L	0.027	0.020	0.034	1.26	1.70
AG	R	0.029	0.029	0.040	1.38	1.38
JS	L	-	-	-	-	-
CE	R	0.020	0.014	0.026	1.30	1.86
SJ	R	0.014	0.013	0.019	1.36	1.46
RR	R	0.025	0.020	0.031	1.24	1.55
TM	L	0.015	0.013	0.023	1.53	1.77
MC	R	0.014	0.013	0.020	1.43	1.54
JP	R	0.025	0.018	0.030	1.20	1.67
TG	R	0.014	0.013	0.019	1.36	1.46
MR	L	0.014	0.013	0.018	1.29	1.38
TC	L	0.014	0.012	0.021	1.50	1.75
MF	R	0.015	0.015	0.024	1.60	1.60
DS	R	0.017	0.013	0.024	1.41	1.85
JT	R	0.017	0.016	0.028	1.65	1.75
PH	R	-	-	-	-	-
IB	R	0.014	0.013	0.019	1.36	1.46
RH	R	0.015	0.014	0.023	1.53	1.64
MEAN OF 20		0.018	0.015	0.024	1.39	1.61
STANDARD DEVIATION		0.005	0.004	0.006	0.13	0.15
95% CONFIDENCE LIMITS		± 0.0027	± 0.0021	± 0.0031	± 0.069	± 0.080

APPENDIX 2.13 ACUITY RESULTS (Background luminance: $3.6 \times 10^{-4} \text{ CdM}^{-2}$)

Contrast = 0.70

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	0.05	0.05	0.06	1.20	1.20
BJ	R	0.06	0.05	0.06	1.00	1.20
GB	L	0.08	0.07	0.08	1.00	1.14
AG	R	0.06	0.06	0.08	1.33	1.33
JS	L	0.04	0.03	0.04	1.00	1.33
CE	R	0.04	0.04	0.05	1.25	1.25
SJ	R	0.05	0.05	0.06	1.20	1.20
RR	R	0.07	0.06	0.08	1.14	1.33
TM	L	0.08	0.07	0.09	1.13	1.29
MC	R	0.05	0.05	0.06	1.20	1.20
JP	R	0.08	0.07	0.09	1.13	1.29
TG	R	0.07	0.07	0.08	1.14	1.14
MR	L	0.06	0.05	0.07	1.17	1.40
TC	L	0.06	0.06	0.06	1.00	1.00
MF	R	0.06	0.06	0.07	1.17	1.17
DS	R	0.05	0.05	0.06	1.20	1.20
JT	R	0.08	0.07	0.09	1.13	1.29
PH	R	0.05	0.05	0.06	1.20	1.20
IB	R	0.07	0.06	0.08	1.14	1.33
RH	R	0.07	0.08	0.09	1.29	1.13
MEAN OF 20		0.06	0.06	0.07	1.15	1.23
STANDARD DEVIATION		0.01	0.01	0.01	0.09	0.09
95% CONFIDENCE LIMITS		± 0.005	± 0.005	± 0.005	± 0.043	± 0.043

APPENDIX 2.14 ACUITY RESULTS (Background luminance: $3.6 \times 10^{-4} \text{ CdM}^{-2}$)

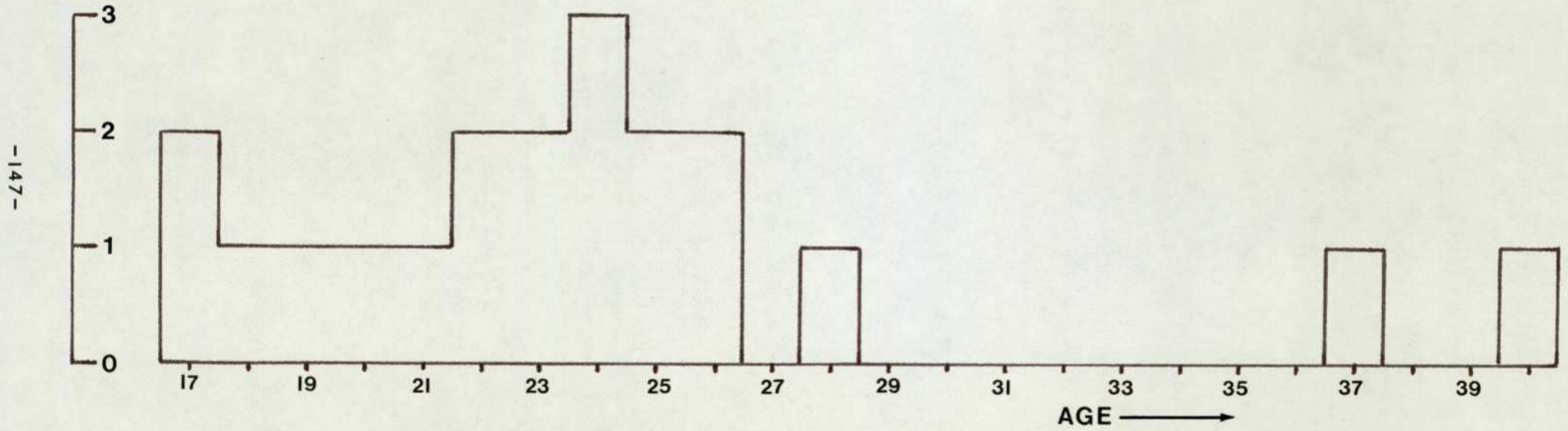
Contrast = 0.30

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	0.029	0.025	0.034	1.17	1.36
BJ	R	0.023	0.019	0.028	1.22	1.47
GB	L	0.034	0.034	0.045	1.32	1.32
AG	R	0.042	0.040	0.049	1.17	1.23
JS	L	0.015	0.013	0.019	1.27	1.46
CE	R	0.024	0.022	0.030	1.25	1.36
SJ	R	0.027	0.025	0.030	1.11	1.20
RR	R	0.031	0.029	0.042	1.35	1.45
TM	L	0.029	0.029	0.036	1.24	1.24
MC	R	0.022	0.018	0.025	1.14	1.39
JP	R	0.036	0.038	0.045	1.25	1.18
TG	R	0.022	0.020	0.028	1.27	1.40
MR	L	0.023	0.021	0.029	1.26	1.38
TC	L	0.028	0.025	0.036	1.29	1.44
MF	R	0.022	0.023	0.027	1.23	1.17
DS	R	0.022	0.019	0.030	1.36	1.58
JT	T	0.030	0.030	0.038	1.27	1.27
PH	R	0.024	0.023	0.029	1.21	1.26
IB	R	0.030	0.030	0.036	1.20	1.20
RH	R	0.035	0.033	0.040	1.11	1.21
MEAN OF 20		0.027	0.026	0.034	1.23	1.33
STANDARD DEVIATION		0.006	0.007	0.007	0.07	0.11
95% CONFIDENCE LIMITS		± 0.0034	± 0.0034	± 0.0034	± 0.034	± 0.053

APPENDIX 2.15 ACUITY RESULTS (Background luminance: $3.6 \times 10^{-4} \text{ CdM}^{-2}$)

Contrast = 0.10

SUBJECT	PREFERRED EYE	PREFERRED EYE ACUITY (M_p)	NON-PREFERRED EYE ACUITY (M_{np})	BINOCULAR ACUITY (B)	B/M_p	B/M_{np}
DL	R	-	-	-	-	-
BJ	R	-	-	-	-	-
GB	L	-	-	-	-	-
AG	R	0.014	0.011	0.020	1.43	1.82
JS	L	-	-	-	-	-
CE	R	-	-	-	-	-
SJ	R	0.012	0.011	0.015	1.25	1.36
RR	R	0.011	0.010	0.015	1.36	1.50
TM	L	0.013	0.010	0.018	1.38	1.80
MC	R	-	-	-	-	-
JP	R	-	-	-	-	-
TG	R	0.012	0.010	0.016	1.33	1.60
MR	L	0.013	0.010	0.015	1.15	1.50
TC	L	-	-	-	-	-
MF	R	-	-	-	-	-
DS	R	0.011	0.010	0.016	1.45	1.60
JT	R	0.014	0.011	0.020	1.43	1.82
PH	R	-	-	-	-	-
IB	R	0.011	0.011	0.017	1.55	1.55
RH	R	0.014	0.011	0.020	1.43	1.82
MEAN OF 20		0.013	0.011	0.017	1.38	1.64
STANDARD DEVIATION		0.001	0.001	0.001	0.08	0.10
95% CONFIDENCE LIMITS		± 0.0008	± 0.0008	± 0.0008	± 0.060	± 0.075



APPENDIX 2-16 DISTRIBUTION OF SUBJECTS' AGES [ACUITY & RECOGNITION TASKS]

APPENDIX 3.1 RECOGNITION RESULTS (Background luminance: 7.1 CdM⁻²)

SUBJECT	PREFERRED EYE	PREFERRED EYE CONTRAST THRESHOLD (M _p)	NON-PREFERRED EYE CONTRAST THRESHOLD (M _{np})	BINOCULAR CONTRAST THRESHOLD (B)	M _{p/B}	M _{np/B}
DL	R	0.020	0.022	0.013	1.54	1.69
BJ	R	0.015	0.015	0.013	1.15	1.15
GB	L	0.019	0.024	0.015	1.27	1.60
AG	R	0.015	0.020	0.014	1.07	1.43
MF	R	0.020	0.022	0.014	1.43	1.57
JS	L	0.027	0.027	0.020	1.35	1.35
CE	R	0.025	0.025	0.015	1.67	1.67
SH	R	0.024	0.024	0.020	1.20	1.20
RR	R	0.020	0.022	0.018	1.11	1.22
TM	L	0.023	0.027	0.016	1.44	1.69
MC	R	0.015	0.018	0.013	1.15	1.38
JP	R	0.015	0.015	0.011	1.36	1.36
TG	R	0.015	0.018	0.014	1.07	1.24
MR	L	0.027	0.030	0.025	1.08	1.20
TC	L	0.028	0.028	0.016	1.75	1.75
DS	R	0.016	0.018	0.014	1.14	1.29
JT	R	0.017	0.019	0.013	1.31	1.46
PH	R	0.027	0.030	0.019	1.42	1.58
IB	R	0.018	0.024	0.015	1.20	1.60
RH	R	0.018	0.020	0.013	1.38	1.54
MEAN OF 20		0.020	0.022	0.016	1.30	1.45
STANDARD DEVIATION		0.005	0.004	0.003	0.19	0.19
95% CONFIDENCE LIMITS		±0.0024	±0.0019	±0.0014	±0.091	±0.091

APPENDIX 3.2 RECOGNITION RESULTS (Background luminance: $1.0 \times 10^{-1} \text{ CdM}^{-2}$)

SUBJECT	PREFERRED EYE	PREFERRED EYE CONTRAST THRESHOLD (M_p)	NON-PREFERRED EYE CONTRAST THRESHOLD (M_{np})	BINOCULAR CONTRAST THRESHOLD (B)	$M_{p/B}$	$M_{np/B}$
DL	R	0.090	0.094	0.070	1.29	1.34
BJ	R	0.064	0.072	0.048	1.33	1.50
GB	L	0.060	0.070	0.051	1.18	1.37
AG	R	0.061	0.074	0.050	1.22	1.48
MF	R	0.058	0.065	0.047	1.23	1.38
JS	L	0.066	0.082	0.053	1.25	1.55
CE	R	0.095	0.095	0.069	1.38	1.38
SH	R	0.080	0.084	0.059	1.36	1.42
RR	R	0.057	0.070	0.043	1.33	1.63
TM	L	0.072	0.078	0.053	1.36	1.47
MC	R	0.066	0.066	0.043	1.53	1.53
JP	R	0.054	0.054	0.040	1.35	1.35
TG	R	0.058	0.058	0.042	1.38	1.38
MR	L	0.063	0.075	0.049	1.29	1.53
TC	L	0.044	0.048	0.035	1.26	1.37
DS	R	0.077	0.075	0.058	1.33	1.29
JT	R	0.067	0.062	0.045	1.49	1.38
PH	R	0.092	0.094	0.063	1.46	1.46
IB	R	0.061	0.063	0.045	1.36	1.40
RH	R	0.059	0.061	0.046	1.28	1.33
MEAN OF 20		0.067	0.072	0.050	1.33	1.43
STANDARD DEVIATION		0.013	0.013	0.009	0.09	0.09
95% CONFIDENCE LIMITS		± 0.0062	± 0.0062	± 0.0043	± 0.043	± 0.043

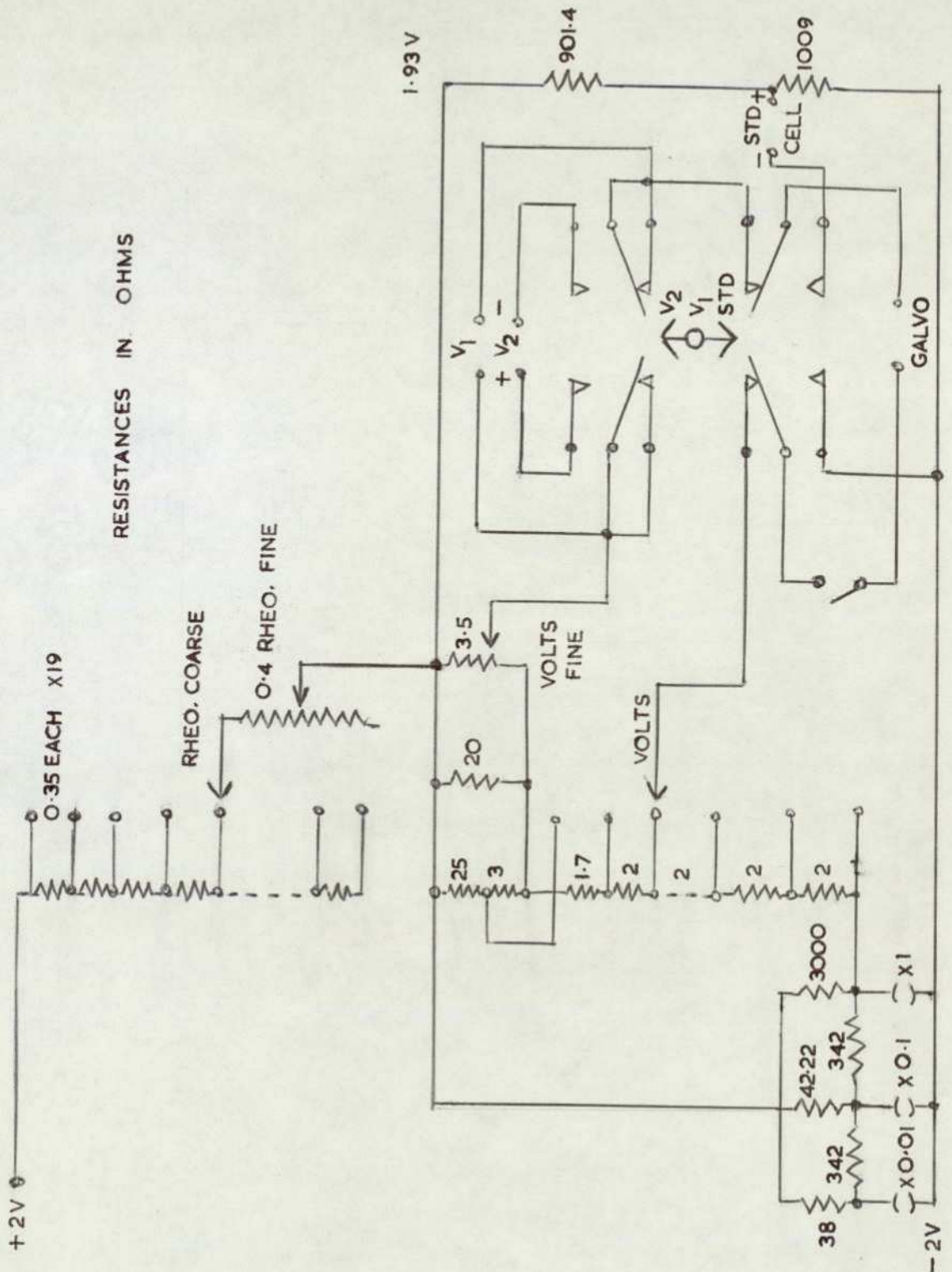
APPENDIX 3.3 RECOGNITION RESULTS (Background luminance: $3.4 \times 10^{-3} \text{ CdM}^{-2}$)

SUBJECT	PREFERRED EYE	PREFERRED EYE CONTRAST THRESHOLD (M_p)	NON-PREFERRED EYE CONTRAST THRESHOLD (M_{np})	BINOCULAR CONTRAST THRESHOLD (B)	$M_{p/B}$	$M_{np/B}$
DL	R	0.17	0.19	0.13	1.31	1.46
BJ	R	0.19	0.19	0.15	1.27	1.27
GB	L	0.18	0.22	0.14	1.29	1.57
AG	R	0.23	0.25	0.18	1.28	1.39
MF	R	0.18	0.20	0.14	1.29	1.43
JS	L	0.26	0.31	0.23	1.13	1.35
CE	R	0.28	0.31	0.22	1.27	1.41
SH	R	0.31	0.26	0.23	1.35	1.13
RR	R	0.18	0.21	0.15	1.20	1.40
TM	L	0.27	0.23	0.18	1.50	1.28
MC	R	0.24	0.25	0.21	1.14	1.19
JP	R	0.17	0.17	0.13	1.31	1.31
TG	R	0.17	0.19	0.16	1.06	1.19
MR	L	0.20	0.22	0.13	1.54	1.69
TC	L	0.20	0.20	0.12	1.67	1.67
DS	R	0.17	0.17	0.12	1.42	1.42
JT	R	0.20	0.23	0.14	1.43	1.64
PH	R	0.33	0.35	0.21	1.57	1.67
IB	R	0.21	0.23	0.15	1.40	1.53
RH	R	0.17	0.13	0.13	1.31	1.54
MEAN OF 20		0.22	0.23	0.16	1.34	1.43
STANDARD DEVIATION		0.05	0.05	0.04	0.15	0.17
95% CONFIDENCE LIMITS		± 0.024	± 0.024	± 0.019	± 0.072	± 0.082

APPENDIX 3.4 RECOGNITION RESULTS (Background luminance: $3.6 \times 10^{-4} \text{ CdM}^{-2}$)

SUBJECT	PREFERRED EYE	PREFERRED EYE CONTRAST THRESHOLD (M_p)	NON-PREFERRED EYE CONTRAST THRESHOLD (M_{np})	BINOCULAR CONTRAST THRESHOLD (B)	$M_{p/B}$	$M_{np/B}$
DL	R	0.45	0.45	0.35	1.29	1.29
BJ	R	0.51	0.47	0.40	1.28	1.18
GB	L	0.47	0.52	0.31	1.52	1.68
AG	R	0.40	0.37	0.34	1.18	1.09
MF	R	0.42	0.46	0.36	1.17	1.28
JS	L	0.54	0.60	0.41	1.32	1.46
CE	R	0.62	0.53	0.47	1.32	1.13
SH	R	0.64	0.66	0.60	1.07	1.10
RR	R	0.45	0.45	0.40	1.13	1.13
TM	L	0.52	0.52	0.36	1.44	1.44
MC	R	0.52	0.52	0.46	1.13	1.13
JP	R	0.35	0.30	0.22	1.59	1.36
TG	R	0.36	0.34	0.30	1.20	1.13
MR	L	0.48	0.55	0.43	1.17	1.28
TC	L	0.38	0.39	0.26	1.46	1.50
DS	R	0.44	0.46	0.38	1.16	1.21
JT	R	0.45	0.53	0.35	1.29	1.51
PH	R	0.59	0.73	0.45	1.31	1.62
IB	R	0.47	0.53	0.38	1.24	1.39
RH	R	0.35	0.43	0.30	1.17	1.43
MEAN OF 20		0.47	0.49	0.38	1.27	1.32
STANDARD DEVIATION		0.08	0.10	0.08	0.14	0.18
95% CONFIDENCE LIMITS		± 0.038	± 0.048	± 0.038	± 0.067	± 0.086

APPENDIX 4



MUIRHEAD D - 972 - A POTENTIOMETER CIRCUIT

Appendix 5

The following pages are copies of the calibration reports supplied by the National Physical Laboratories concerning the lamp and reflector which were used throughout the present investigations as a secondary calibration of luminance.

All the conditions specified in the reports were maintained whilst using the lamp and reflector as a luminance standard.

APPENDIX 6

Example of the prediction of binocular/monocular detection ranges from the contrast detection data

Duntley (1948) has shown that the basic expression for the contrast of an object to the horizon sky at a distance x is

$$C_x = C_o \exp \left(\frac{-x}{L} \right) \dots\dots\dots (i)$$

where C_o is the inherent contrast of the object (at $x = 0$) and L is the attenuation length or the reciprocal of the beam attenuation coefficient. Meteorological range, R , is defined by the expression

$$\frac{C_x}{C_o} = \frac{1}{50} = \exp \left(\frac{-R}{L} \right) \dots\dots\dots (ii)$$

So substituting for L in equation (i) we have

$$C_x = C_o \exp \left[\frac{-x}{R} \ln 50 \right] \dots\dots\dots (iii)$$

Let us now consider a particular situation. Let it be dusk (i.e. ambient luminance $\approx 0.1 \text{ Cd M}^{-2}$) and let the meteorological range be 20 km. The task involved is the detection of a given large object against the horizon sky. The detectability of such an object will depend on both its contrast and its size. For the sake of simplicity it is assumed that the observer is not limited by the size of the object, i.e. the problem is just the contrast of the target against its background. The target will be assumed to have an inherent contrast of -0.70 against the horizon sky.

From the results (chapter 4) the binocular contrast threshold at this luminance was -0.038 and the monocular threshold was -0.056. From equation (i) we can calculate the maximum detection range for monocular and binocular vision.

Let b be the maximum binocular detection range.

" m " " " monocular " "

$$\text{then } C_b = C_o \exp \left[\frac{-b}{R} \ln 50 \right] \dots\dots\dots (iv)$$

$$C_m = C_o \exp \left[\frac{-m}{R} \ln 50 \right] \dots \text{from equation (iii)}$$

$$\text{So } \frac{C_m}{C_b} = 1.48 = \exp \left(\frac{b-m}{R} \ln 50 \right)$$

Given that $R = 20$ km this reduces to

$$b - m = 2.004 \text{ km}$$

From equation (iv)

$$-0.038 = -0.70 \exp (-b \ 0.1956)$$

$$\text{giving } b = 14.895 \text{ km}$$

$$\text{so } m = 12.891 \text{ km}$$

This means that monocularly the target can be detected to a range of 12.891 km whereas binocularly this range is increased to 14.895 km, an increase of 2 km.

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