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VISUAL INTERACTIONS WITH OPTICAL DISPLAYS
WITH PARTICULAR REFERENCE TO BIOCULAR MAGNIFIERS

by

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A THESIS

SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

TO THE CITY UNIVERSITY, LONDON.

1975

"I see nobody on the road" said Alice.

"I only wish I had such eyes," the King remarked in a fretful tone. "To be able to see Nobody! And at that distance too! Why, it's as much as I can do to see real people, by this light!"

Alice Through The Looking Glass.

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ABSTRACT

Optical systems of large aperture which allow observers to view with both eyes a magnified image of a small object are now known as Biocular Magnifiers. For high magnification lenses of numerical apertures approaching unity are required and the control of aberrations becomes difficult. As the normal visual apparatus has adjustments for accommodation and vergence together with the fusion compulsion it may be able to accept larger aberrations in a magnifier than a photographic plate, say, can tolerate aberrations in a camera lens. Unfortunately, much more is known about visual thresholds than visual tolerances and no design specifications are available.

As a start in the formulation of these, this study tests the overall acceptability of some typical biocular magnifier designs in terms of visual performance, physiological changes and subjective assessments. Very little previous work exists but consideration is given to relevant papers on the measurement of visual acuity, visual perception and visual performance. With non-normal conditions as introduced by magnifier aberrations reported work concerns only visual fatigue and adaptation phenomena which are also reviewed.

A system was built to present to subjects a visual task which simulates that of driving a vehicle. Monitors of visual performance and muscular balance were constructed while an experimental method was designed which allows the analysis of performance while eliminating major sources of bias. Experiments have been carried out to measure visual performance under relatively gross differences in aberration level. In particular aberrations which change the effective accommodation-convergence requirements have been studied and performance variations with the muscular balance of subjects have been found.

Arising from this, the magnitude of the work needed to specify acceptable aberrations for biocular magnifiers can be assessed. Major areas of study are suggested with an appeal for commonality of methods so that future results may be comparable.

ACKNOWLEDGEMENTS

The interest and direction of my principal supervisor, Prof.R.J.Fletcher is acknowledged with very many thanks for the loan of various pieces of apparatus and for many challenging discussions. I also acknowledge the assistance of my additional supervisor, Dr.G.F.Moore, of Pilkington Bros.

As an employee of Pilkington Bros., Optical Division, I record my thanks to Dr. L.H.A. Pilkington, Chairman, and Mr. A.J. Milne, Managing Director, for permission to undertake this work and for their continuing support of it.

Most of this work was carried out as part of a development contract for the Ministry of Defence, Procurement Executive. I am grateful for Mr. E.A. Richards' permission to incorporate it into this thesis.

During the experimental part of this study I received assistance in numerous ways and acknowledge this with thanks to the following:-

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Mr. J. Shanklin (PPE) who built part of the apparatus and manually recorded viewing times for subjects 1 - 25.

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Mr. R. Knockton (Pilkington Bros.) who carried out the filming for the visual tasks

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CHAPTER 1

GENERAL DESCRIPTION & PURPOSE OF STUDY

1.1 Introduction

This study concerns the design of lenses intended for visual use. That is, someone is going to look through them. The best designs are those which suit the user and through which he can perform his task most efficiently. As the visual apparatus of the normal subject is capable of adjustments such as accommodation and vergence and has a compulsion to fusion, it may be able to accept larger aberrations in these lenses than a photographic plate, say, can tolerate aberrations in a camera lens. Unfortunately, what the normal visual system can tolerate and possibly adapt to is not well known and the design of optical systems for visual use is often restricted by somewhat arbitrary ideas of what level of optical correction constitutes a satisfactory design.

Optical Design normally proceeds by balancing various aberrations to obtain the required level of resolution (Rogers 1969). For lenses accepting larger cones of light (lower f/no.) or wider fields of view the reduction of the residual aberration becomes more difficult. Thus a level of optical correction which is more critical than necessary will limit the aperture and field of resultant designs.

These factors, in themselves, constitute "aberrations" of a sort. If, for example, the field of view of a surveillance device is restricted, the observer will have to scan it more over the area he wishes to see. This will reduce his effectiveness just as much as if the system suffered from astigmatism or distortion. Again, if the aperture of this system is reduced to the point where only one eye can be used by the observer and then only when it is located within a very small area, his performance may be impaired, particularly if the intended use is on a moving vehicle.

The effect of restricted head movement is related to the comfort of the observer. A similar connotation is associated with the words 'eye relief' as the distance from optical equipment to the necessary location of the eye. Following the same path, the words 'visual comfort' have been coined by the writer as an overall design aim of visual systems and 'visual discomfort' then embraces not only the aberrations of the system (as related to binocular vision) but also the aperture and field of view effects.

The purpose of this study is to quantify as far as possible what constitutes a satisfactory level of optical correction for visual comfort. In this work the disciplines of optical design and ophthalmic optics are brought together while the main experimental work involves human factors as well as physiological optics with a bias toward the former. The results are analysed on a statistical basis. The work is therefore very much of a bridging nature and it is at times necessary to recap basic principles in the disciplines concerned.

Detailed information for particular optical designs is usually proprietary to the company concerned. In this study, various designs proprietary to Pilkington P.E. Limited, St. Asaph, North Wales have been investigated. For this reason the outline drawings used do not include details of curvature, thickness, glass types, etc.

1.2 Biocular Systems

Most optical display systems impose some constraints on the observer. Some require him to accommodate to a particular extent. A microscope or focimeter, for example, expect him to close or ignore the information arriving at one eye, unless they have a binocular attatchment. As most people have a dominant eye this is generally acceptable but in the use of night vision devices the monocular arrangement results in a further effect. The ~~brightness~~ luminance of the object seen with the used eye is commonly 10 ft.lamberts over a 50^{o} to 70^{o} field of view. In normal usage the other eye is in ambient illumination which is less than 10^{-2} ft.lamberts or else the device has no purpose. This unbalanced illumination results in unbalanced adaptation. A proportion of military personnel have reported feelings of nausea under this condition.

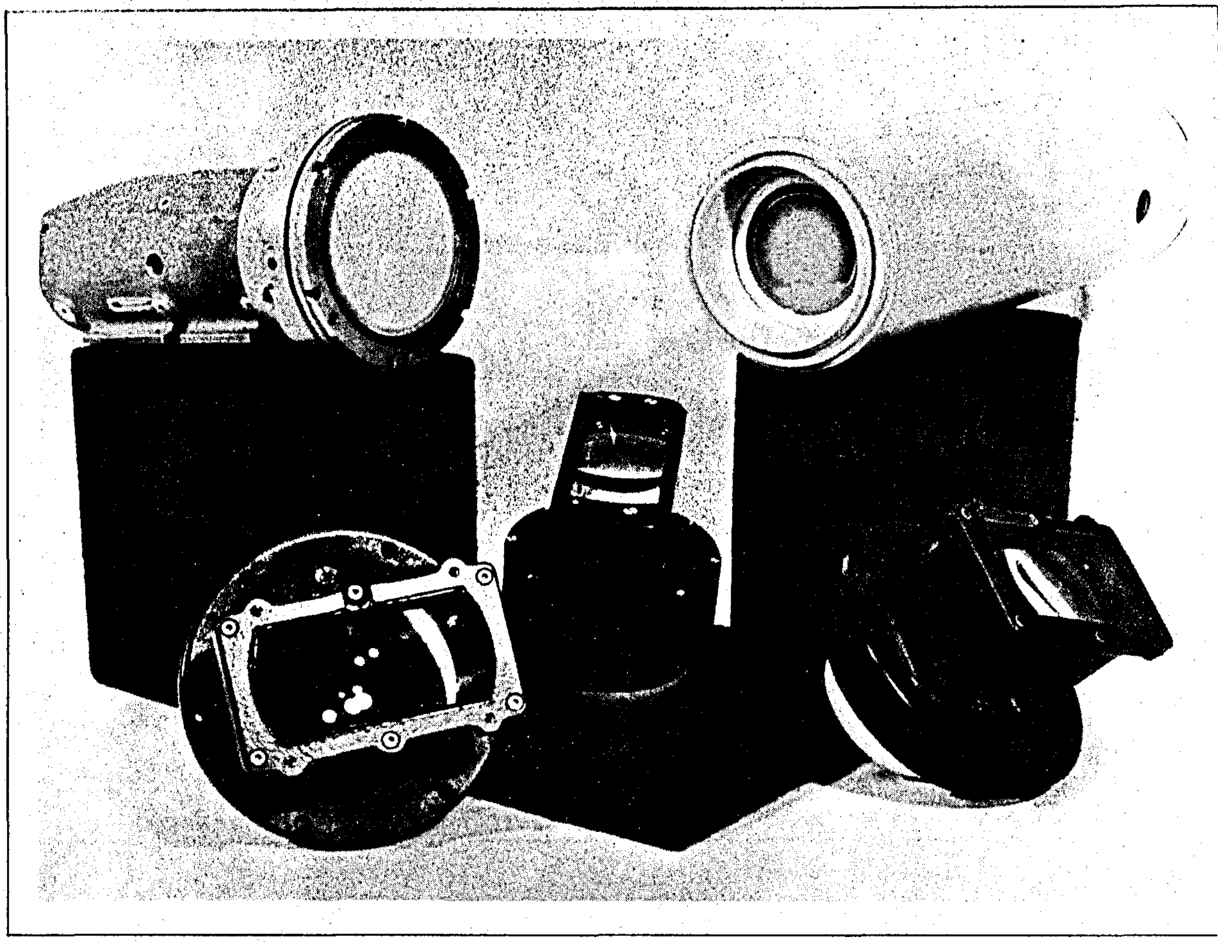
In one system designed to overcome this effect, two eyepieces were provided but the optical constraints limited the eye ring and eye relief values so that the observer had to put his eyes very close to the equipment. When in use in military vehicles, facial injuries from black eyes to broken noses were incurred. The biocular system is an attempt to overcome both these problems, by allowing two-eye viewing with large eye relief. Although large magnifiers for use by one or two eyes have been used for many years and the Head-up Display (Freeman 1969a/1969b) used in aircraft has been extant since the 1940's, high-magnification biocculars were first designed and built in the U.S.A. and U.K. during 1971.

However, these lenses were designed without any great understanding of the visual aspects of their aberrations. The correction levels arrived at were largely determined by what was technically feasible although the final balance was, in the case of the P.P-E Bimag lens, determined by ideas propounded by the writer (Rogers 1972). A description of the general parameters of this lens is provided in Figs. 1 & 2.

In May 1972 at the instigation of the writer, a two-day meeting on this subject was sponsored by the Optical Society of America and the Vision Committee of the National Academy of Sciences. This was entitled 'The Design of Biocular Systems' and in the publicity Prof.Robert Shannon of the University of Arizona stated that "Biocular Systems are those in which both eyes use different areas of the same optical system, from entrance pupil to exit pupil with no intervening discontinuity."

Some difference of opinion was voiced at the meeting and the writer published (Freeman 1973) a more detailed definition in Optics and Laser Technology which is in general agreement with Prof.Shannon.

FIG 1 DESCRIPTION OF PPE LTD., BIOCULAR



PPE Bimag biocular magnifier

P.N. 4644

x 5 50° biocular magnifier for 40 mm tubes

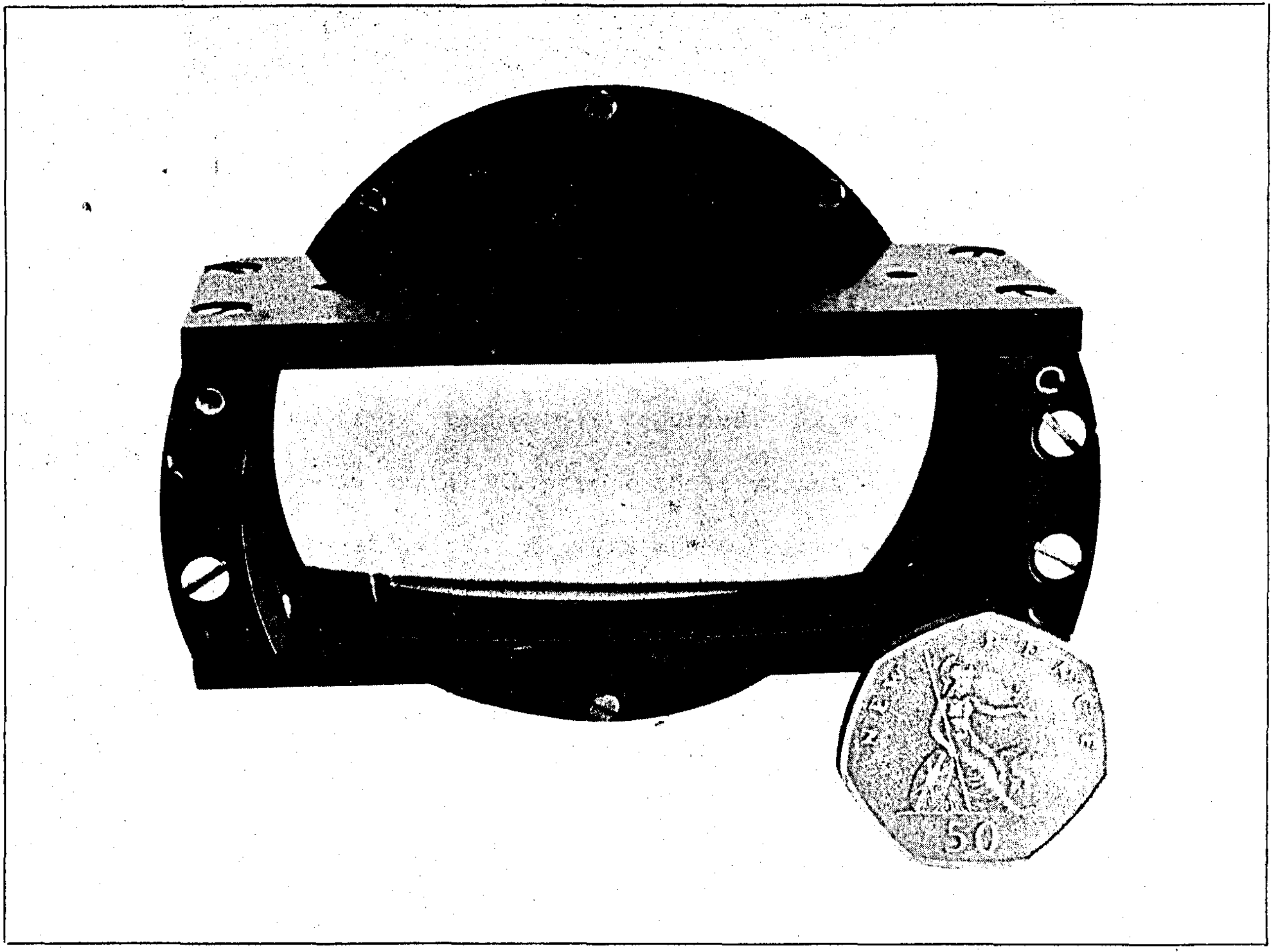
The PPE Bimag Biocular Viewer was designed to meet the requirement for a times five magnifier with a large eye-relief and pupil to enable operators to view a display tube of about 40 mm diameter with both eyes. The advantages of the system are that the eyes are not strained by picture differences and the user can move his head over reasonable distances without losing the display or hitting his face on projections.

The design incorporates PPE experience in the study of the parameters involved in vision ergonomics and the development of computer programmes enabling the lens designer to design the lens for two eye pupils.

The magnifier offers major space and power savings as it allows systems designers to replace 200 mm display tubes by 40 mm tubes. Because of the critical optical design it is necessary to modify the magnifier slightly to accommodate the range of windows on TV, CRT, image intensifier and convertor tubes, film, LED and other data display tubes and panels.

Custom designed combined displays, formats, magnifications and other parameter variations can be manufactured to specific requirements.

FIG 2 PARAMETERS OF PPE LTD., BIOCULAR



Specification

Magnification:	×5
Field Size:	40 mm diameter
Field Angle:	50°
Eye Relief:	Up to 120 mm for full horizontal field of view
Dioptre Setting:	2.5 D
Back Focus:	4 mm typical, available for CRT faceplates up to 10 mm
Field Curvature:	1.6 D
Supravergence:	5 mRads
Blur:	1 mRad
Distortion:	12%
Spectral Bandwidth:	1000 Å above 5000 Å 500 Å below 5000 Å

The above values are typical of a Bimag system; designs for a particular installation may have a different balance of parameters.

The use of a large lens system in front of both eyes means that the conditions for good binocular vision must be satisfied with a lens aperture of at least 80mm. In the night vision case described earlier the object comprises the phosphor of an image intensifier tube. These have a range of sizes, but a common value is 40mm diameter. To make the night vision device useful a field of view of 50° minimum is required. As will be discussed in more detail in Chapter 2 these values specify a lens aperture of f/0.5. At this aperture it is very difficult to meet the normal conditions for good binocular vision over 50° field of view. Hence we need to know the minimum conditions for good binocular vision. Even if the field and aperture values were relaxed so that the design was easier, it is still important to know the minimum quality required so that simpler, lighter or cheaper equipment may be designed.

In normal lens design work the effect of lens shapes on aberrations such as Spherical Aberration, Coma, Astigmatism, Curvature of field, Distortion, Chromatic Aberration and Higher-order Aberrations has been understood for many years and, in particular, the way in which these interact so that good resolution may be obtained at all points in the field of view. Even though the values of each aberration are far from small they may be balanced against each other to obtain good imagery.

When a magnifier is used visually, a completely different aberration scheme must be formulated to express the effect of lens shapes on the visual apparatus of the observer. This human photo-detector is at once more demanding and more accommodating than photographic plates or television camera tubes. Because the two pupils of the observer's eyes are much smaller than the magnifier the magnitude of the optical aberrations over these pupils will, in general, be very small. However, the location of these pupils places them very close to the edge of the lens so that the relative values of the optical aberrations in these places become important to the quality of binocular vision.

If the location of the image seen via the magnifier is not at a constant distance the eyes can accommodate to bring various parts into sharp focus. However, the eyes do not accommodate independently and may not accommodate accurately if some of the usual stimuli are absent or abnormal.

If the accommodation action brings other images into focus these may prove distracting. The eyes may also tire of studying an aberrated image or conversely they may learn how to deal with it so that any measure of their performance shows an improvement with use.

The study of optical aberrations has a continuous history reaching from the present day back to men like Seidel (1855) and Newton (1666) if not to earlier scientists. If this is the time scale for the study of aberrations associated with inanimate photo-detectors, one cannot expect a quick understanding to be obtained for visual aberrations which are associated with human photodetectors having an interactive capacity.

The lack of previous work directed towards two-eyed viewing through magnifiers is indicated by a complete absence of any reference to this subject at the ICO Conference on Vision through Optical Instruments (Munich,1971) and even at the Topical meeting on Biocular Magnifiers (Annapolis 1972) mentioned earlier most participants, including the writer, were asking questions rather than reporting successful studies.

In determining the scope of this study it was recognised that general work was required before particular matters could be determined. The general areas where an understanding is sought may be grouped into three comprising, firstly optical design to determine what sort of visual aberrations are produced by the usual bundles of positive and negative lenses roughly corrected for gross defects, secondly the relationship between visual performance and response of the visual apparatus to visual aberrations and thirdly the effect of time in terms of whether the visual performance got better or worse and what factors were influencing this.

This constitutes a considerable volume of knowledge which must be investigated before and during the design of any experimental study. Chapters 2, 3 and 4 report the results of the writer's efforts in these directions.

1.3 Scope of Experimental Study

In looking for general guidelines as to what level of correction is visually acceptable to observers the obvious experimental course is to present subjects with magnifiers of various levels of correction and assess their reactions, over a suitable period of time. These can be assessed on criteria related to their general condition - Fatigue, their ocular physiology - Impairment, and their task performance - Work Output. Each of these can be measured in more than one way.

Numerous visual tasks are possible which tax subjects in varying degrees. As the prime purpose is directed towards effects due to the magnifier rather than the task it is better that the task be rather straightforward although there is no certainty that difficulty of task and reaction to magnifier are completely independent.

The design criteria of magnifiers include the aperture and field and also their residual aberrations in terms of resolution, accommodation setting and variation, astigmatism, distortion, dynamic distortion etc. up to 10 distinct variables in all.

Inseperable from the task and magnifier is the apparent resolution, brightness and contrast of the viewed scene. Again this should be chosen to be as typical as possible so that effects due to the magnifier criteria may be examined. In one respect this may not be followed. The resolution of electronic displays is normally somewhat poorer than the visual acuity of the user, while that of 16mm film stock is no better when viewed at 50^{o} field of view. A limiting resolution of approximately 1mR is common and this is equivalent to about 6/18 vision.

With industrial magnifiers used with real objects this is not the case unless the aberrations of the lens so restrict it. In this study the overriding interest is in the magnification of electronic displays and the reduced visual acuity situation is discussed in more detail in Chapter 3.

The large number of variables in magnifier design makes it virtually impossible to examine each over a significant range of values, particularly when the interactions between variables may be significant. Each value would have to be designed into a specific magnifier which would then have to be constructed ready for use. To eliminate the other variables (aberrations) would require careful designs of four or five elements.

As a first step it was decided to run a general experiment using four widely different magnifiers to see if any gross interactions could be found. Following this, more narrow ranges of magnifiers could be examined, for the specific variables which seemed the more important.

The visual task chosen was based on forward motion bringing objects closer for recognition. This is related to the driving task for which a significant number of magnifier designs are intended. This process was recorded on film so that each subject could be tested under consistent conditions. The 'recognition' criterion is seen to relieve the importance of subject motivation and vigilance to some extent but imposes tighter requirements on the resolution characteristics of each system as detailed in Chapter 5.

Of the three parameters related to subject reaction, fatigue was assessed by subjective assessment (using a modified comfort list), impairment by changes in heterophoria, work output by recognition time or size of objects. None of these can be stated to be obviously superior to any other approach. The reasons behind their choice are dealt with in the next three chapters.

Almost intuitively it has been felt that a large number of subjects would be required for more than just a few minutes each. As few of these would have a direct interest in the work or in optics or vision it seemed important that the visual task would be found to be interesting by most subjects, in the same way as the automatic games to be found in amusement arcades. This attempt to obtain stable motivation of each subject over his total time of testing (about 1½ hours) has been successful in that very few subjects have admitted to any boredom during their tests.

Over fifty subjects have been used in this study and none has quit before the end of the tests. Headaches and nausea have been reported by some while all have applied themselves to the task with good humour. The state of vision of each subject used had been previously checked on a 'MAVIS' vision screener and reached a given standard (chapter 5).

Thus forced-choice decisions have been made on three pieces of 'hardware':- Task, Magnifiers & Subjects, and also on three pieces of 'software':- Subjective Comfort, Muscular Balance, Moment of recognition. An assessment of their value in relation to future work is given in Chapter 7.

CHAPTER 2

OPTICAL DESIGN & VISUAL ABERRATIONS

2.1 Introduction

Before the digital computer was applied to Optical Design the major problem facing the lens designer was often the sheer labour involved in calculating the path of a ray through his proposed system. General equations of the imagery of optical systems do not allow a unique design solution for a given image quality, and so the design must proceed by calculating the performance of a basic design and then the change in this for detail changes within the design. If an improvement was found, further changes in the same direction may be made. The third-order Seidel aberrations could be calculated for each surface and the sum of these over the complete design would indicate the approximate image quality.

In most lenses the third-order approximation would be insufficient and a trigonometrical ray-trace of selected rays would be required. These had to be chosen with care so that the maximum information could be obtained from them in return for the work of the calculation. In this work the experienced lens designer developed an insight into the ways of lens types, power balances and element bending, which often went beyond the strictly mathematical calculations. When called upon to design lenses for visual use, it was natural for the designer to convert the lens requirements into the optical aberrations with which he was so familiar, and to calculate the design towards these target values.

In the case of eyepieces where the total optical system generates an eye-ring or Ramsden circle very little larger than the pupil of the eye, the conversion of the requirements in this way is relatively straightforward. The location of the eye is virtually fixed not only laterally but also along the axis. The image aberration across the eye-ring is directly transferred to the eye, and the degree of visual acuity may be calculated, although recent studies have shown that the aberrations of the eye may sometimes react favourably with those of the device (Overington, 1973b).

Where two eyes are used the requirements for binocular vision are related mainly to the mechanical design of such instruments as binoculars and binocular microscopes. It is not very expensive to over design, and so the tolerances on parallelism of binocular axes are generally set well inside visual requirements, and little effort has been made to find what reduction in parallelism can be tolerated.

When optical systems are used as magnifiers there is no eye-ring effect to locate the eye, and so the designs must be corrected for the larger area over which the eye may wander during use. The extension of this to biocular magnifiers means that further visual requirements must be met. The most obvious of these is that the lens must be large enough to accept the larger inter-pupilliary distances. This leads firstly to some simple calculations regarding magnification and aperture.

If the minimum aperture for binocular viewing is assumed to be 75mm then the usual equation for magnification can be extended:-

$$\text{magnification} = \frac{250\text{mm}}{\text{e.f.l. (mm)}} = \frac{3.3}{\text{F/no}} \quad \ldots\ldots\ldots\ldots \quad 1$$

because F/no is given by $\frac{\text{e.f.l.}}{\text{Aperture}} = \frac{\text{e.f.l.(mm)}}{75}$

Thus for a magnification of x2.5 an F/1.3 is required. For a magnification of x6.5 an F/0.5 lens is needed. This is equivalent to a numerical aperture of unity which is the maximum possible in air.

A further approximate calculation links the format size of the object viewed and the F/no with the field of view obtained:-

$$\text{Field of view (degrees)} = \frac{\text{format (mm) x57}}{\text{e.f.l. (mm)}} = \frac{\text{format (mm) x57}}{\text{75mm x F/no.}} \quad \ldots\ldots \quad 2$$

where one radian is assumed to equal 57 degrees. Thus, for a given format there is a maximum field of view which can be obtained as the F/No. approaches F/0.5.

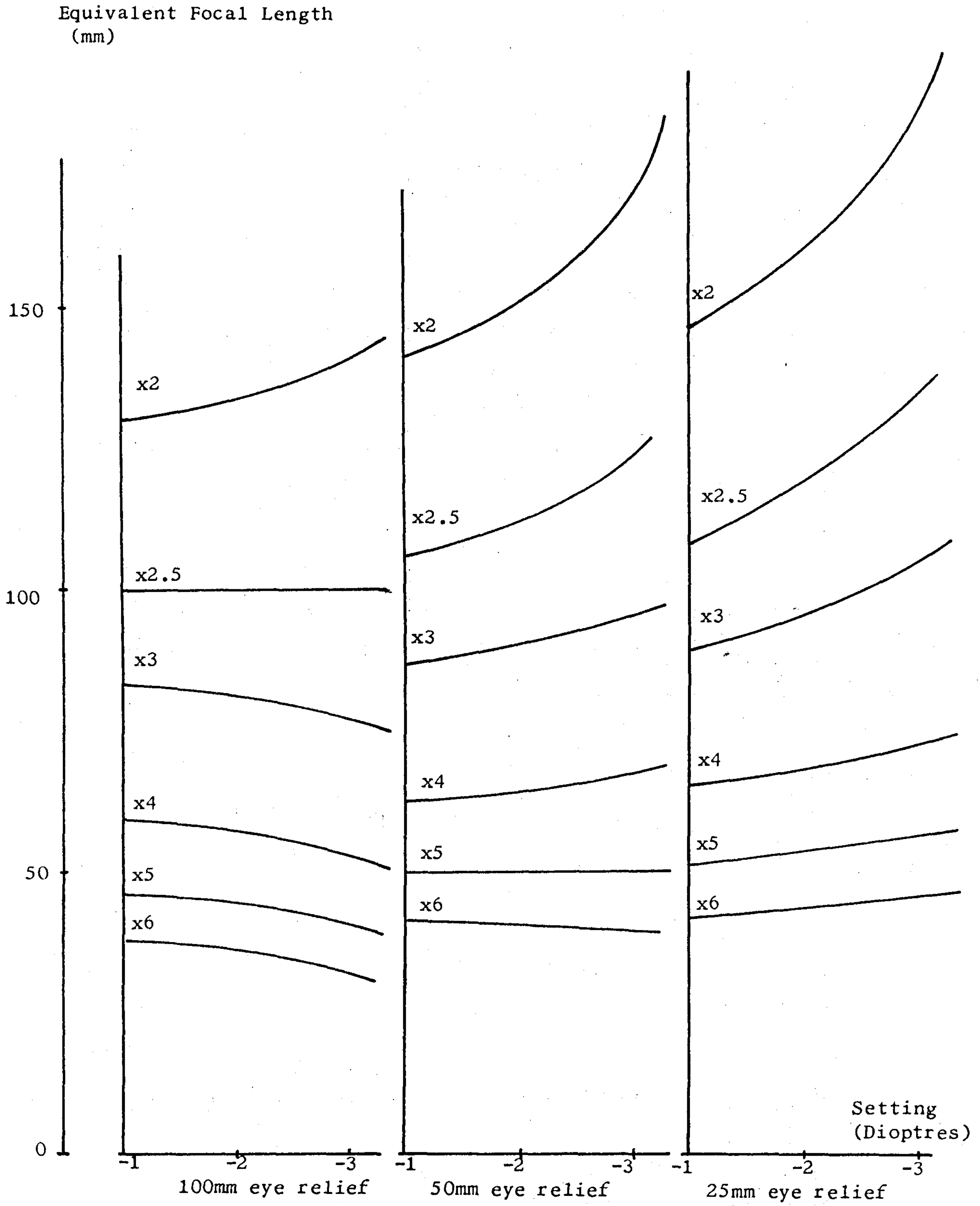
However, with magnifiers the image need not be at infinity which is tacitly assumed by the simple expressions above. If the image location is expressed in terms of the divergence of the light leaving the magnifiers (for which the eyes must converge and accommodate to see clearly) this can be measured in dioptres and is usually called the Dioptric Setting of the magnifier, being generally negative.

This dioptric setting affects the apparent magnification which is also influenced by the eye relief distance. If the eye relief is rmm and the setting S Dioptres the required equivalent focal length for the magnifier for a given apparent magnification is:-

$$\text{e.f.l.} = \frac{1000 + rS}{4A + S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3$$

where A is apparent magnification.

FIG.3. BIOCULAR MAGNIFIER ANALYSIS



Relations between e.f.l., apparent magnification, dioptric setting, and eye relief.

The graphs of Fig.3 are obtained if this is plotted for the range of settings, eye reliefs and apparent magnifications as shown. It is seen that the dioptric setting has a different action at the higher magnifications depending on the chosen eye relief distance.

Anderson & Moyers (1973) published the expression:-

$$P = \frac{250\text{mm}}{f\ (1+d)} \left(1 - \frac{S\ (f - r - \Delta)}{1000}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots 4$$

where P = power (apparent magnification)
f = effective focal length
d = distortion
S = Dioptric Setting (D in original)
r = eye relief (R in original)
Δ = nodal plane ~~location~~ separation

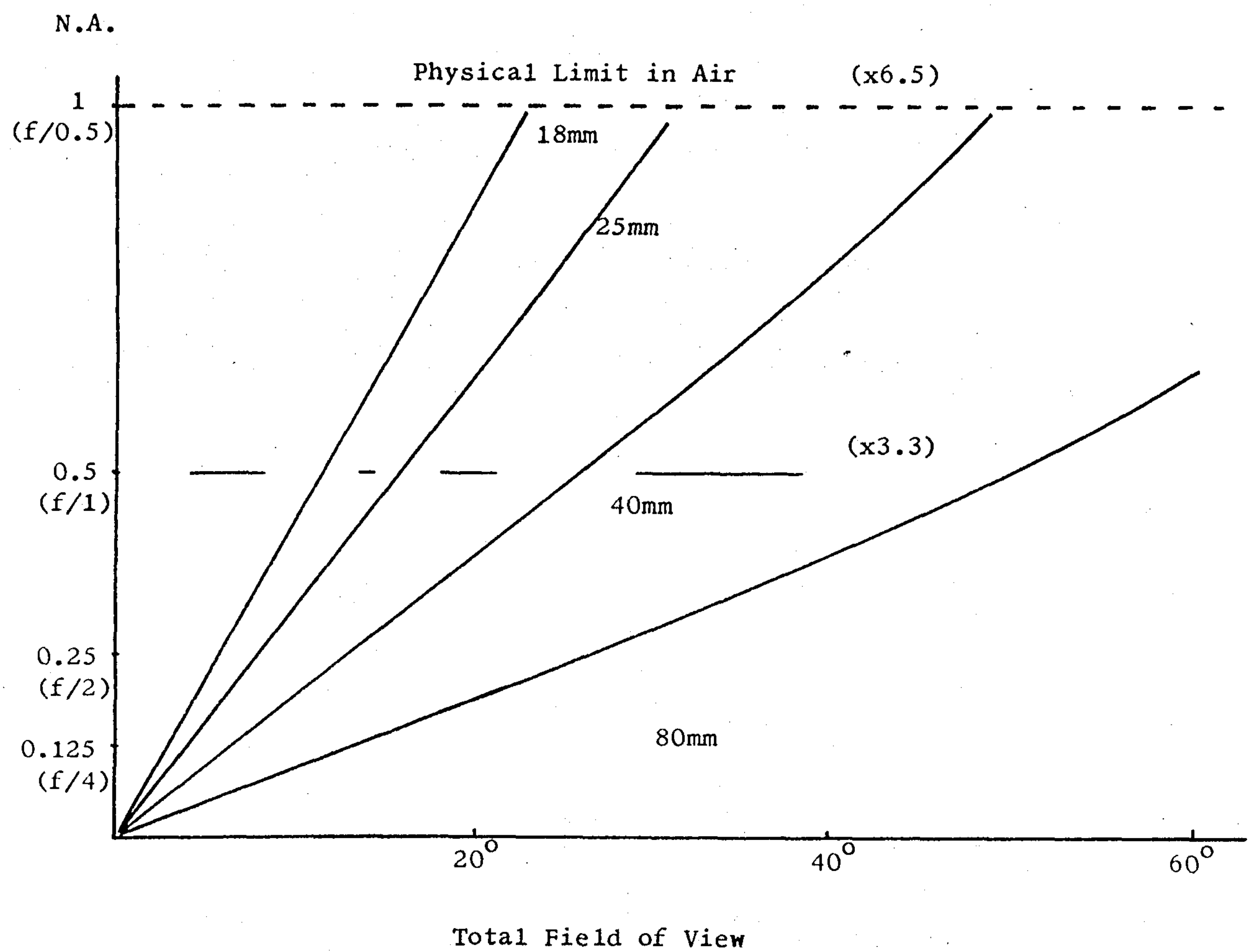
Expression 4 reduces to expression 3 if d and Δ are set to zero. If distortion is non-zero then the lens system does not have a single power while the nodal plane location depends on the design of the magnifier components.

Rogers (1972) assumed a dioptric setting of -2 and an eye relief of 50mm in calculations for Figure 4, which shows how the F/No. and object size define the field of view. For magnifications above x3.3 the lenses will be faster than f/1 which may be taken as a boundary between low and high magnification systems.

Low-powered magnifiers serve to show the relationship between optical design and visual requirements. High-powered systems requiring apertures close to the physical limit result in designs where high angles of incidence occur at lens surfaces and high order aberrations become major contributors to the performance.

FIG.4. BIOCULAR MAGNIFIER ANALYSIS

- (after Rogers (1972))



Biocular magnifier numerical aperture against field angle for various object sizes and -2 dioptre setting.

2.2 Low-powered Biocular Magnifiers

Lens design as a technical activity is very close to the profitability of commercial optical companies, and so designers rarely place explanatory papers in the scientific journals. Also, magnifiers have generally been considered far less important than objectives, so the resulting number of references dealing with their design becomes very small indeed.

R. E. Hopkins (1946) in a very clear paper on the use of aspheric surfaces listed, at times arbitrarily, the optical requirements of a magnifier as follows:-

" (1) The field should be large. An apparent field of 60^{o} is ideal for most applications.

(2) The design should be such that the eye can be located at a comfortable distance from the magnifier when viewing the full field.

(3) The lens should be well corrected for spherical aberration over as large a pupil as possible. It is not sufficient to correct a magnifier over a 7 or 8mm pupil as is done in an eyepiece of a telescope or microscope.

(4) For a similar reason the coma should be well corrected.

(5) It is difficult to correct a magnifier for curvature of field. Therefore, this usually sets the limit to the practical field of view. For short focal length magnifiers the curvature of field becomes very serious and a 60^{o} field may become impossible to attain.

(6) Astigmatism should be eliminated if possible. In high power (sic) magnifiers it is customary to

flatten the field artificially by introducing astigmatism. However, we prefer a large amount of field curvature (4 to 8 dioptres) in preference to introducing as much as 2 dioptres of astigmatism.

(7) The most noticeable monochromatic defect in a magnifier is distortion. In order to avoid criticism of the design, the distortion must be reduced below 1% even at the cost of compromising other aberrations.

(8) Axial transverse colour and oblique transverse colour must also be well corrected. Two or three minutes of difference in angular position between an object seen in D light and F light is objectionable. The axial colour must again be corrected over as large a pupil as possible or there will be a critical position of viewing required to avoid colour fringes."

It is thus seen that the designer relates the visual requirements entirely to the Seidel aberrations. In the following paragraphs the limitations in terms of calculating effort show up with comments such as :-

"Since the distortion is negative but well-distributed between the two surfaces, the oblique distortion should not be very different from the third-order."

The author goes on to describe the performance of one of the designs as follows:-

"Coma and spherical aberration merely affect the apparent position of the field of view as the observer moves around the eye pupil. A movement of 1cm from the optical axis causes the image to move angularly 1.9'. This amount of movement is not objectionable if the magnifier is used monocularly. However, observers try to use it binocularly on account of its large diameter. If the observer has an inter-pupilary distance of 64mm and the lens is adjusted to collimate the paraxial rays, there will be at least 2^{o} divergence between the lines of sight for the two eyes. The present magnifier thus cannot be used binocularly."

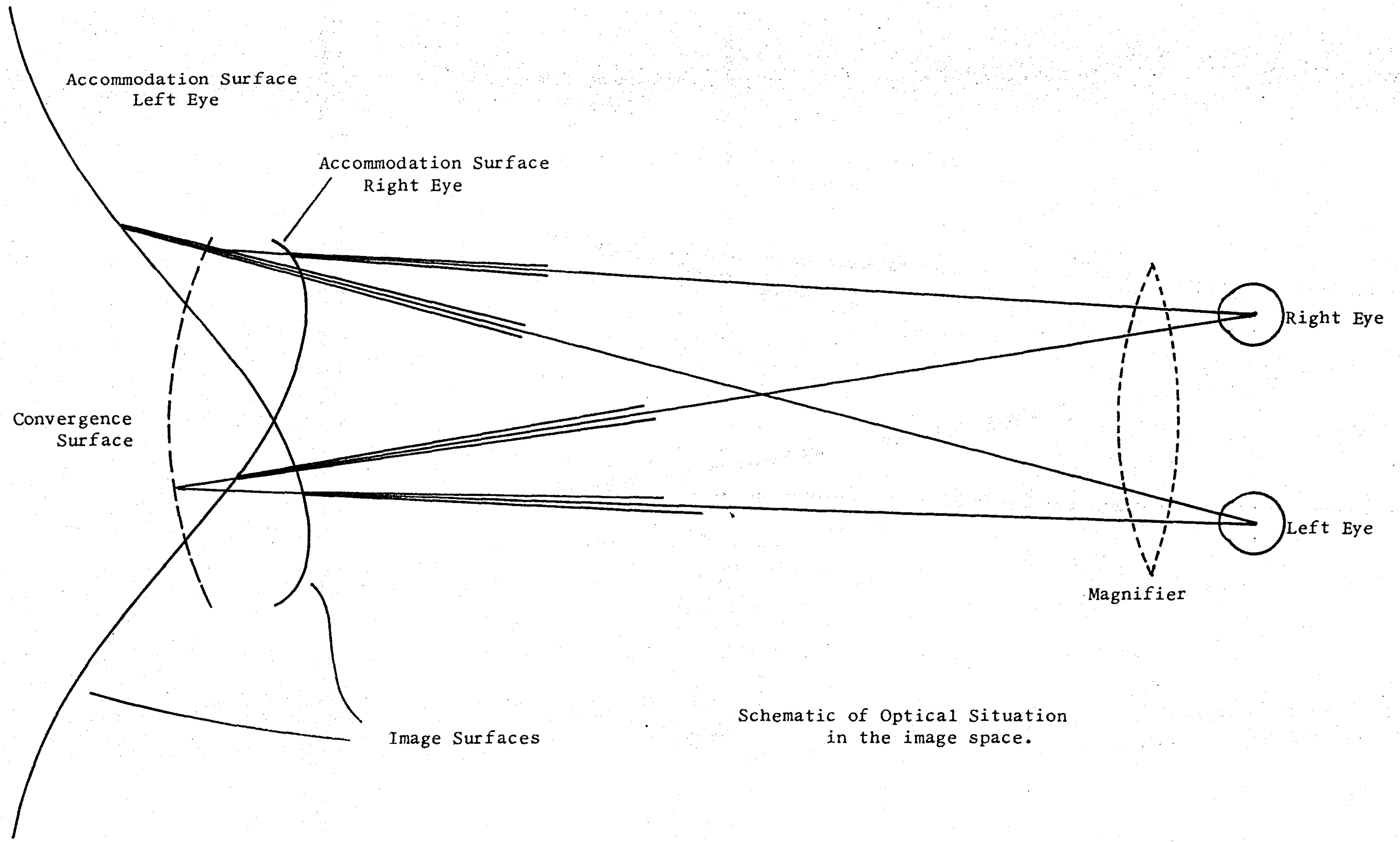
The author then goes on to discuss further improved designs without returning to the subject of binocular viewing. It is difficult to understand why the effect of defocussing the lens so that the binocular divergence shifted to convergence is not considered. The effects of astigmatism and curvature are related to the difference between the plane through the paraxial focus and the location of the image surface if the lens were used as an objective. These differences are then converted into dioptres "change of focus":-

0.5D Curvature
1.08D and 2.36D for Astigmatism.

That these are beyond the far point of the eye is not discussed. Essentially it comes down to an inability to calculate except with respect to the paraxial condition. In spite of this Hopkins has three major aberrations high-lighted. The curvature of field, astigmatism, and distortion. The choice between low curvature or low astigmatism is also a feature of high-power magnifiers.

An interesting exchange of papers occurred in Nature during 1949 when Coulman & Petrie (1949) noted the increasing interest in low-power lenses for industrial inspection purposes adding:-

FIG.5. BIOCULAR MAGNIFIER VISUAL PARAMETERS



Schematic of Optical Situation
in the image space.

"Nevertheless, to the best of our knowledge, no serious attempt has hitherto been made to correct these lenses for binocular vision, and as a result of extensive experiments in this connection it is now clear that a major contribution to the comfort of the use of such lenses over prolonged periods can be made by designing primarily for binocular viewing."

In reply to this Jeffree (1949) pointed out that the approach proposed by Coulman & Petrie amounted to the correction of coma for a stop at the position of the eyes. If freedom of eye movement were required the correction of spherical aberration would be necessary which would then bring about the coincidence of the monocular fields with the binocular field.

The whole correspondence is about single lenses, and Jeffree admits that if both spherical aberration and coma are corrected then neither a flat field nor absence of distortion can be obtained. Thus, a compromise is required in which none of these four aberrations are zero. However, the designs discussed relate to magnifications of about x2, and a field of view of less than 20°.

The need to relate the monocular and biocular fields was examined by the writer (Freeman, 1972) in his paper to the Biocular Magnifiers Meeting, Annapolis, 1972 from which Fig.5 is taken. This has also been investigated by Fry (1972,1969). Fry points out that when examining stereo pairs the eyes are working at non-normal accommodation-convergence values and yet

FIG 6

VISUAL ABERRATION

	Spherical	Coma
App. Dist. (Horiz.)	$\sigma_1 \rho^3 +$	$\sigma_2 \rho^2 V +$
App. Dist. (Vert.)		$\sigma_2 \rho^2 W +$
	Image Shift	Anamorphic
Two Eyes $(+\rho, -\rho)$	New Convergence	Zero

V, W Direction Cosines of Object Point

ρ Distance of eye from Magnifier Axis

ANALYSIS - APPARENT DISTORTION (after SANDS 1971)

Astig | Field Curve | Distortion

$$(3\sigma_3 + \sigma_4)\rho V^2 + (\sigma_3 + \sigma_4)\rho W^2 + \sigma_5 (V^3 + VW^2)$$

$$+ \sigma_3 \rho VW + \sigma_5 (V^2 W + W^3)$$

Mobile Distortion | Static Distortion

Varying Convergence | Zero

BALANCE with Fifth Order Oblique Spherical $\mu_4\ \mu_5\ \mu_6$

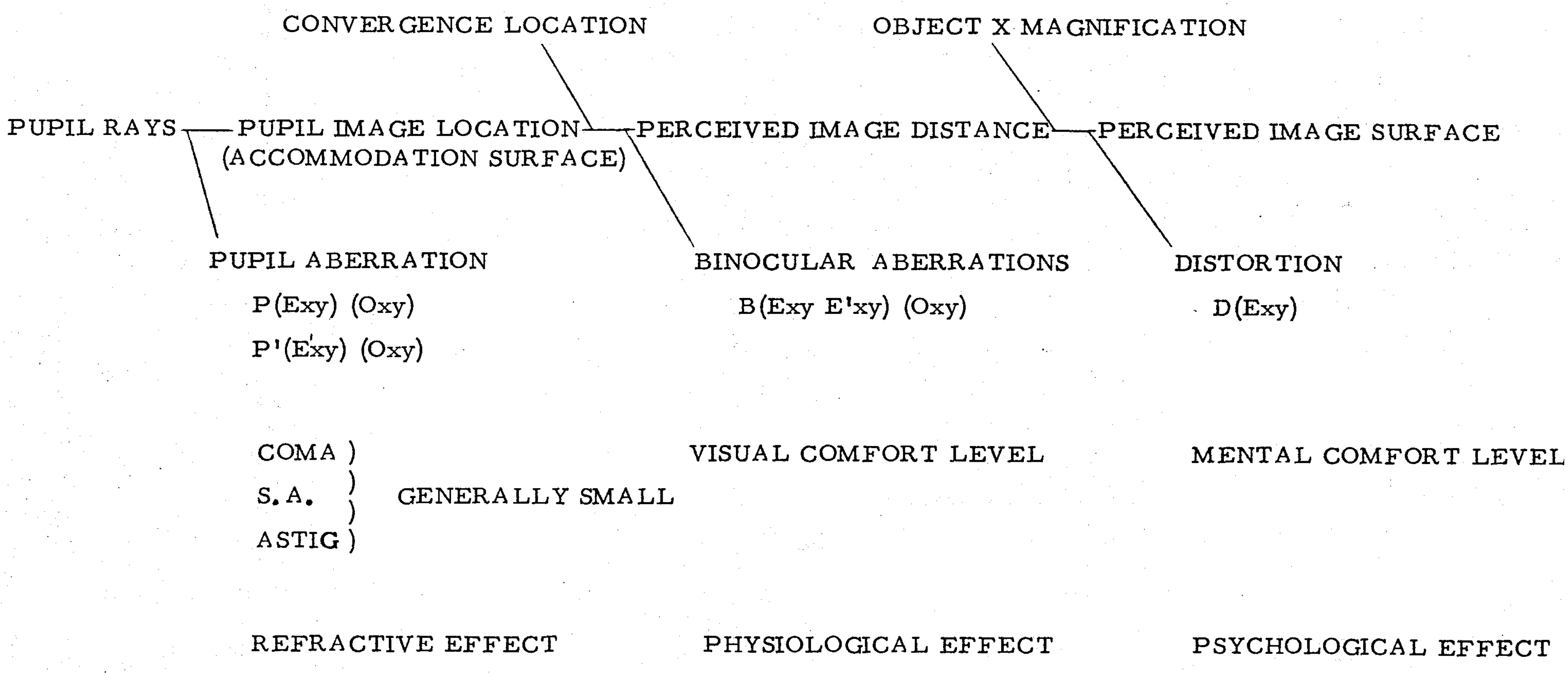
or with Fifth Order Linear Astigmatism $\mu_{10}\ \mu_{11}$

good stereoscopic acuity is obtained. With biocular magnifiers applied to 2-dimensional image surfaces some measure of the stereoscopic tolerance is required. With industrial magnifiers used binocularly some measure of the accuracy of the stereoscopic acuity is needed. With lenses of high numerical aperture the spherical aberration becomes extremely difficult to correct even with the use of aspheric surfaces. It is therefore of prime importance that the minimum amount of correction is used.

Thus the accommodation-convergence relationship and its variation from user to user becomes important.

The most comprehensive mathematical analysis of these aberrations to date is Sands(1971) who related Seidel third-order and fifth-order aberrations to visual aberrations using Hamiltonian Optics. His analysis is restricted to single eye viewing from an off-axis position, without relating this to binocular vision. A general resume of his results is contained in the equation given in Fig.6 which relates the major aberrations in the pointing directions of the eyes. The terms $\sigma_1, \sigma_2, \sigma_3$, etc., relate to the five Seidel co-efficients. Astigmatism and field curvature combine to image straight lines as curved lines, the curve direction depending on which side of the lens axis the eye is placed. If each eye were placed as is usual either side of the axis of a lens having this aberration, vertical lines on the object appear curved in different directions. For fusion, therefore, the convergence required of the eyes may be less at the top and bottom of the picture than in the centre. This gives an image surface convex to the observer which might be corrected by pin cushion distortion in the object. The spherical aberration

VISUAL ABERRATION SCHEME   FIG. 7



gives a new convergence when viewed binocularly but coma and distortion have no extra effect unless the eyes are assymmetrically located.

A visual aberration scheme drawing these ideas together has been suggested by the writer (Freeman 1972). Fig.7 shows that pupil aberrations generated across the pupils of each eye blur the image which is seen at an accommodative distance at which this blur is a minimum. This distance will vary with field angle and also with eye position.

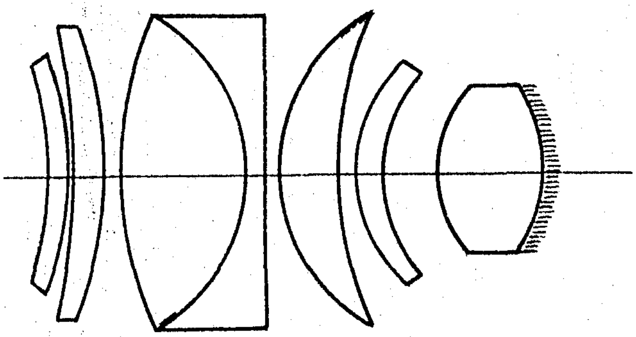
The pointing directions now combine to give a perceived image distance for each object point which will contain the anamorphic and mobile aberrations of Sands. These will also vary with field angle and eye position. The latter also means that the observer's interpupilliary distance will influence this.

Finally, the eye-brain system may override the visual aberrations where there are conflicting cues and apply experience to the scene in order to obtain a consistent image. The distortion of the magnifier (and of any electronic image) will have an influence but will not shift with eye position. Mobile distortions on the other hand will, if pronounced, make the retention of a consistent image more difficult.

In all these areas, the tolerances of the visual system are largely unknown although studies in pupil aberrations can be related to refractive defects and the corresponding reduction in visual acuity may be estimated. The immediate area of uncertainty therefore lies with the binocular aberrations, in particular the accommodation-convergence requirements but also how these work out when field curvature and astigmatism are present. These aberrations, together with a fourth arising from the high-powered biocular magnifier case form a reduced area of work which even then is considerably larger than that of a single study.

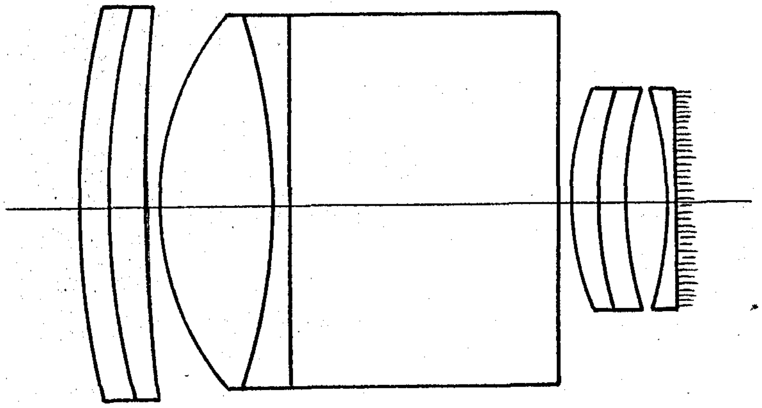
FIG.8. HIGH-POWER MAGNIFIERS FROM RECENT LITERATURE

SEAMAN 1971



F/1		x3.1
80mm e.f.l.	;	80mm Aperture
Setting	;	40mm Eye Relief
60mm format	;	45°F.O.V.
Parallax	;	Binoc.Overlap
Astig.	;	Field Curvature
Distortion	;	

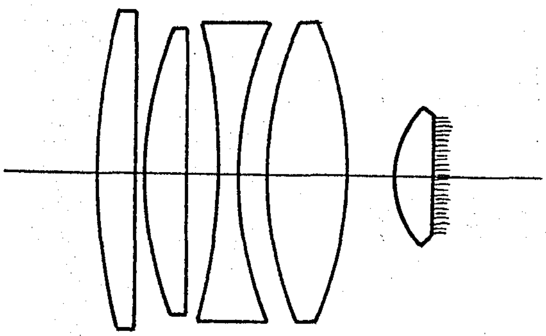
WALKER 1973



F/0.75	;	x3.3
78mm e.f.l.	;	88mm Aperture
-2D setting	;	75mm Eye Relief
40mm Format	;	30°F.O.V.
1mR Parallax	;	15° Binoc.Overlap
Astig.	;	Field Curvature

4% Distortion. (Negative)

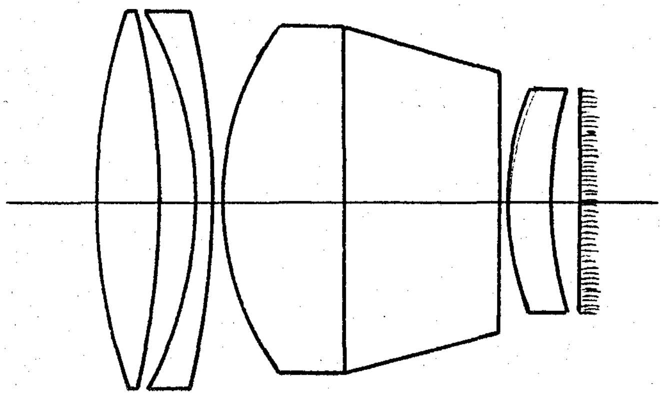
BRENNAN 1972 (ANDERSON 1973)



F/0.57	;	x4.5 (x5.1*)
47mm e.f.l.	;	83mm Aperture
-2.5D Setting	;	64mm Eye Relief
25mm Format	;	23° F.O.V.
Parallax	;	Binoc.Overlap
Astig.	;	1/8D Field Curv.

4.4% Barrel Distortion

ROGERS 1972



F/0.54	;	x5.6*
43mm e.f.l.	;	80mm Aperture
-2.5D Setting	;	50mm Eye Relief
40mm Format	;	50° F.O.V.
Parallax	;	20° Binoc.Overlap
0.2D Astig.*	;	1.6D Field. Curv.

18% Pincushion Distortion

2.3 High-Powered Biocular Magnifiers

Using the F/1 criterion as the divisor between high and low-power magnifiers it appears that the earliest high-power biocular magnifier was reported as recently as 1970 (Seaman, 1971 - as this is in the form of a United States Patent Specification there is an examination delay before publication). This was followed by the design with which the writer is associated, (Rogers, 1972) and this closely by a design from Baird-Atomic Inc. (Brennan 1972) which was not published until a year later (Anderson 1973). Earlier in that year (Walker 1973) a design from the Kollmorgen Corporation was described with a review of the visual problems to be overcome. No other designs have been found in the usual literature.

Fig.8 gives some indication of the optical components of these four designs together with as full a specification as can be gleaned from the papers. The Seaman design makes no real attempt to correct field curvature as a curved object (fibre-optic face-plate) is used. Spherical Aberration and Astigmatism are largely controlled by dividing the power over five positive components.

The Walker design tackles the problem of incorporating a 90° bend in the system as many applications require this. A field-flattening lens is used near to the object but the paper gives considerable prominence to the correction of parallax and requests information on how the relationship between accommodation and convergence may be used to the best advantage. Without any comment he states that the "common field" of magnifier is 50% (15°) of the total.

In his description of the Baird-Atomic magnifier Brennan states that "lenses have been successfully designed and built, and with an F number as fast as 0.7 and with the total field visible to the two eyes. It has been found that the common field does not have to be as large as 100%. Lenses with 70% common field have proved successful and an overlap as low as 18% to 20% allows enough field for fusing the images."

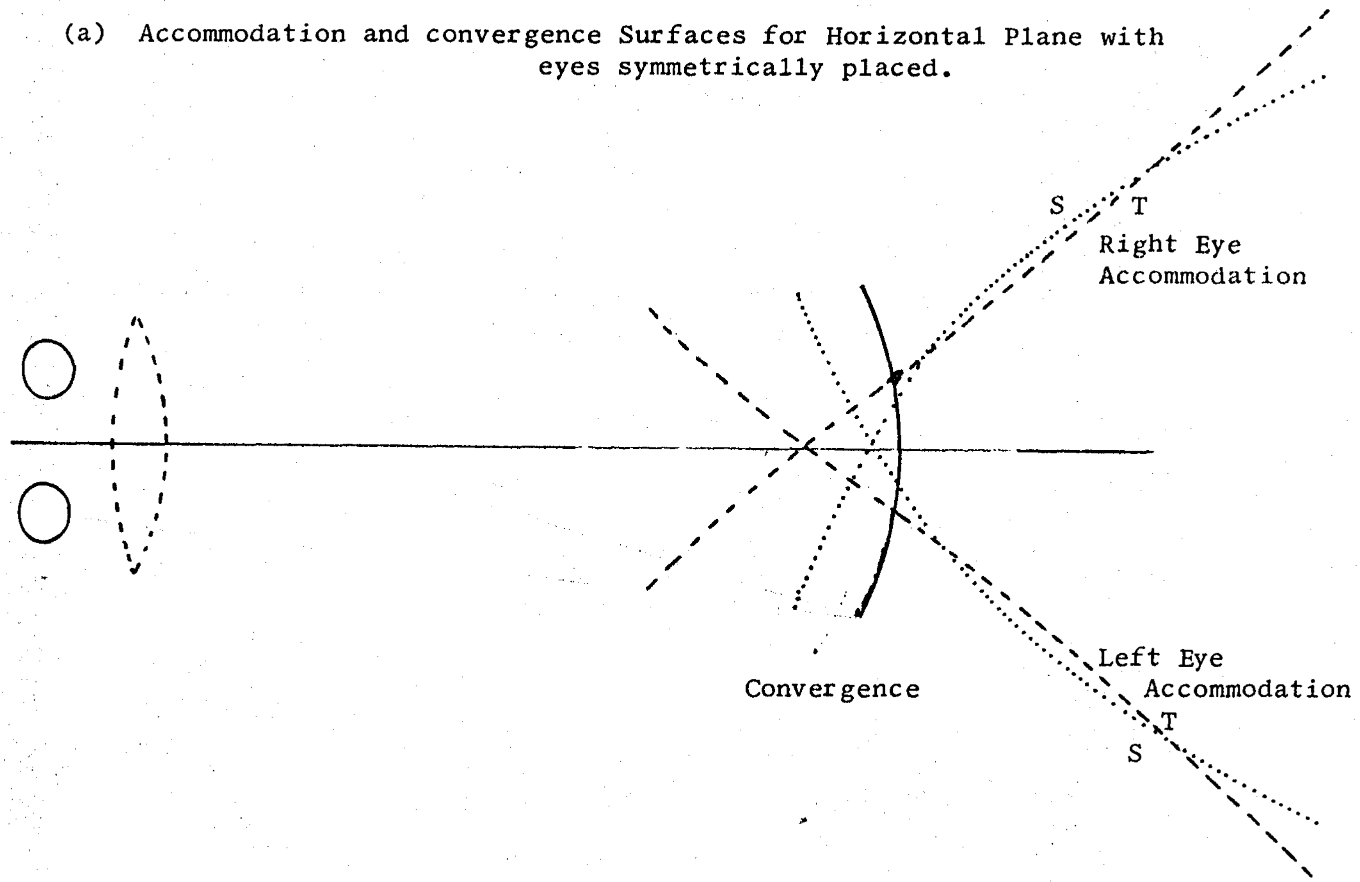
This limitation in field visible to both eyes (the binocular overlap) is a necessary 'aberration' of high-power systems where the strong curvatures of the lens elements limit their diameter so that the left eye looking through this limiting aperture sees more of the right hand side of the scene whereas the right eye sees more of the left hand side.

In his description of the Baird-Atomic design Anderson baldly states a field curvature of 1/8 dioptre. The drawing indicates no field-flattening lenses and one can only assume that this flat field is obtained by the introduction of over-correct astigmatism.

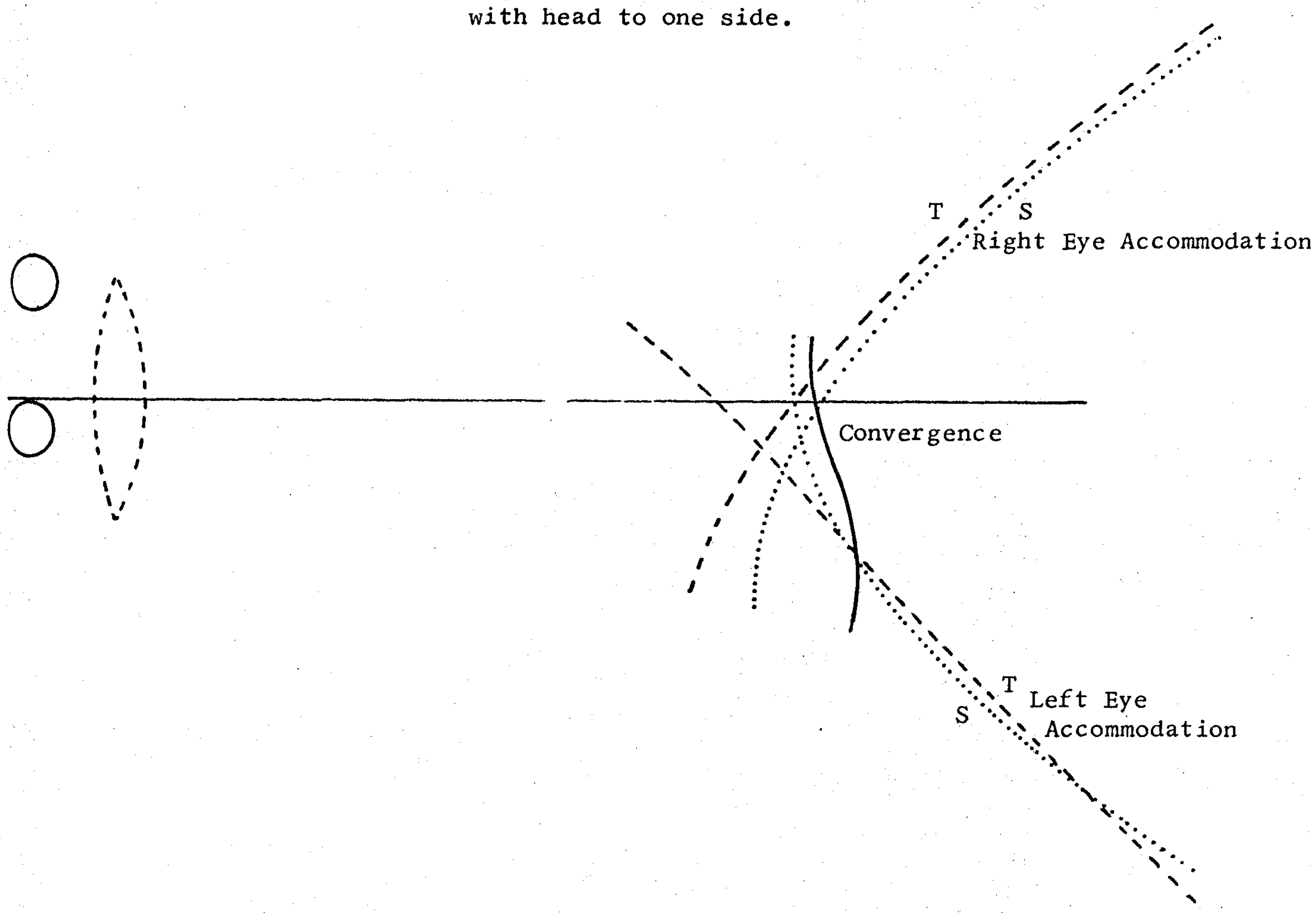
The Pilkington P-E Ltd., design of Rogers echoes the comments of R.E.Hopkins (1946) discussed in section 2.2, that "astigmatism should be elimated as far as possible and that a large amount of field curvature (4 to 8 dioptres) is preferable to introducing as much as 2 Dioptres of astigmatism." From his association with this lens the writer is aware that its astigmatism is generally as low as 0.2D. rising to a maximum of 0.8D.

FIG.9 REPRESENTATIVE ABERRATION CURVES

(a) Accommodation and convergence Surfaces for Horizontal Plane with eyes symmetrically placed.



(b) Accommodation and convergence Surfaces for Horizontal Plane with head to one side.



2.4 Visual Aberration Analysis

From the foregoing the major aberrations of high-powered biocular magnifiers which affect binocular vision are:-

Parallax Error

Reduced Binocular Overlap

Astigmatism

Field Curvature.

Distortion as defined by the fifth Seidel term does not directly influence the binocular vision of the observer. All four of the aberrations are dependent on head position, particularly when this is shifted sideways. In the major use of these lenses, that is as magnifiers used in night-vision systems, it is found that the required vertical field is considerably less than the horizontal field. Thus for the purposes of this study a considerable simplification can be obtained by concentrating on the aberrations and visual responses in the horizontal plane only. This allows all four aberrations to be drawn on one graph and their change with sideways head movement to be indicated by one further graph.

Fig.9, therefore, shows representative aberrations of a binocular magnifier for two head positions. The locations of the two pupils are shown on the left while the viewing distance indicates the eye relief and dioptre setting of the system. The parallax error is seen to be complex as the accommodation distances for each eye are equal only on the axis. At other areas some anisometropia is present. In the presence of astigmatism this is not easy to define, but obviously a difference between the convergence surface and the accommodation surfaces for the two eyes means that both of them are liable to a focus error of a magnitude which may be different for each eye. As is considered more fully in Chapter 3 this sort of error reduces the performance of the eye although an uncertainty of accommodation of about 0.3D has been found in normal viewing. For the present study parallax error is taken as the value which apertains at the centre of the field.

The restricted length of the convergence surface specifies the reduced binocular overlap incurred by the curvatures and diameters within the lens. Although it might be felt that this is relatively straightforward to define, it may be that the increasing parallax aberration towards the edges of this overlap region give a physiological overlap which is smaller than the mathematical value. Conversely, a binocular overlap which has its edges 'shaded out' by other aberrations may be more acceptable than one with sharply defined edges which, being well within the total field, are distracting to the observer. Again for the present study the simple value obtained by ray tracing will be used.

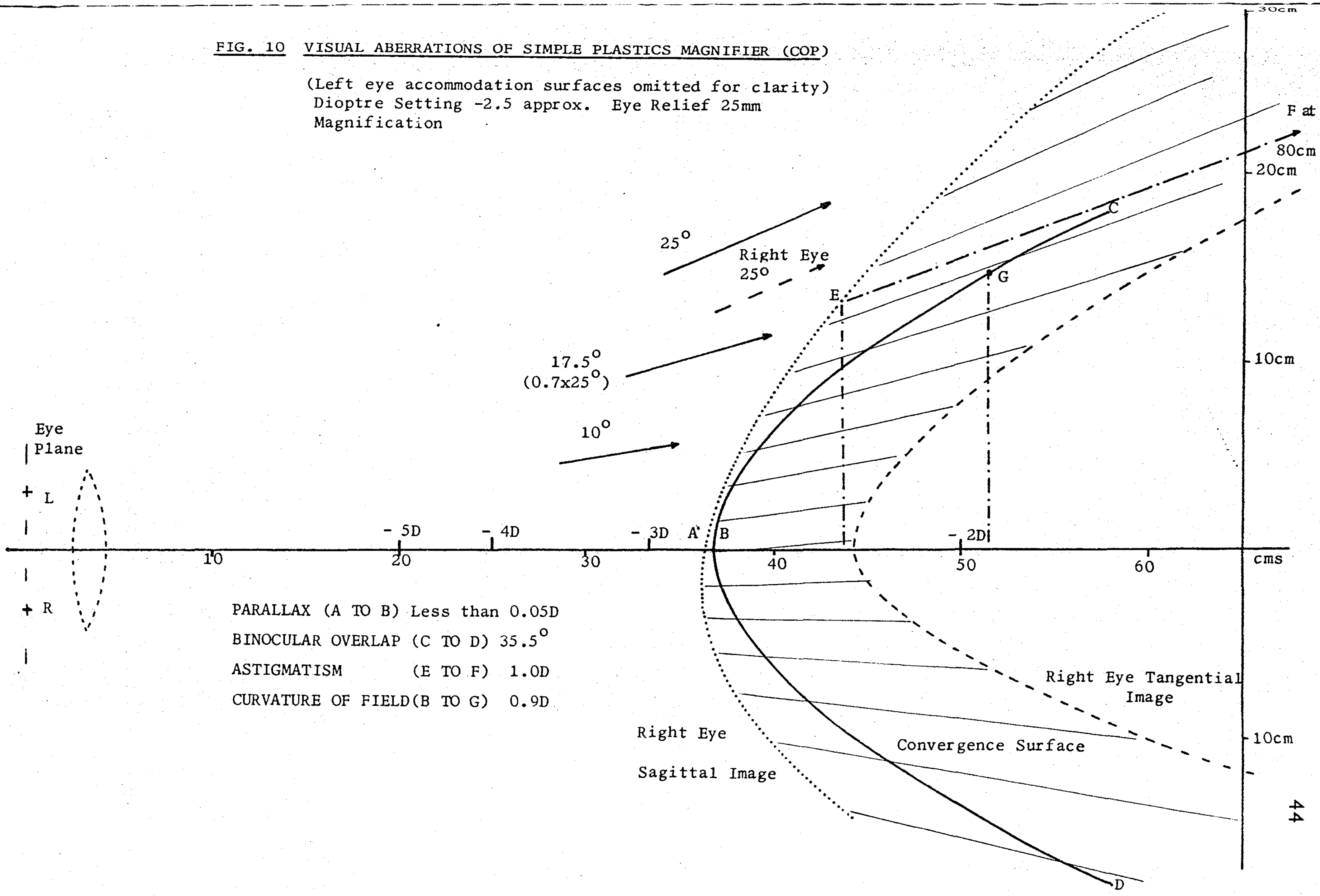
Astigmatism is shown by the two curves for each eye which locate the sagittal and tangential images. If 'corrected' this may be zero in places. Although its sign may change, it is still a longitudinal separation of the vertical and horizontal images (in the horizontal plane under consideration) and so a representative figure may be taken as the modulus value which includes the error over 80% of the field.

While the curvature of field is immediately apparent from Fig.9 its definition depends to some degree on the extent of the binocular field. If this is extensive then the curvature of field may be defined most simply by that change of dioptric setting between the centre and a point at 0.7 of the full field angle as given by the convergence surface. If the convergence surface does not extend that far a value related to the accommodation surfaces must be chosen. From a physiological point of view the field curvature value should reflect the muscular changes required of the observer to search the field. His subjective assessment of the curvature may be far from correct as distortion may influence his perspective sense to give an apparent curvature which is considerably different from the actual curvature.

Although all four of these aberrations have a value associated with them which can be measured in linear terms, the effects of them on the visual apparatus is inversely proportional to the viewing distance. Thus, while the graphs of Fig.9 are scaled in linear dimensions the visual aberrations are best stated in dioptres and degrees. When the head is shifted sideways the major change is with the orientation and location of the convergence surface. The values for astigmatism become different fòr each eye while the curvature remains roughly the same.

FIG. 10 VISUAL ABERRATIONS OF SIMPLE PLASTICS MAGNIFIER (COP)

(Left eye accommodation surfaces omitted for clarity)
Dioptre Setting -2.5 approx. Eye Relief 25mm
Magnification



2.5 Visual Aberrations of Particular Magnifiers

In order to obtain graphs such as Fig.9 for particular magnifiers a computer program was designed which performed optical ray traces through the lenses and then calculated accommodation and convergence surfaces for given eye positions. An interpupilliary distance of 64mm is assumed. Although it is a simple matter to obtain curves for any head position the following descriptions are restricted to the 'on-axis' case and in the experimental work a head restraint was used to obtain the condition.

2.5.1 Simple Plastics Magnifier (COP)

A simple single-element magnifier of e.f.l. 75 millimetres was obtained and its optical parameters measured. The apparent distortion when using this lens had been made very low and as a consequence very little correction was possible of the four binocular aberrations described in the previous section. Fig.10 shows the accommodation and convergence surfaces for an on-axis head position and a dioptre setting of -2.5D (given by a defocussing of approx.15mm). While considerable amounts of astigmatism and field curvature are present the parallax for the sagittal image is good and the binocular overlap extensive. On the basis of the previous section the aberrations can be quantified as shown in the figure.

2.5.2. High-Powered Magnifier (SLAB)

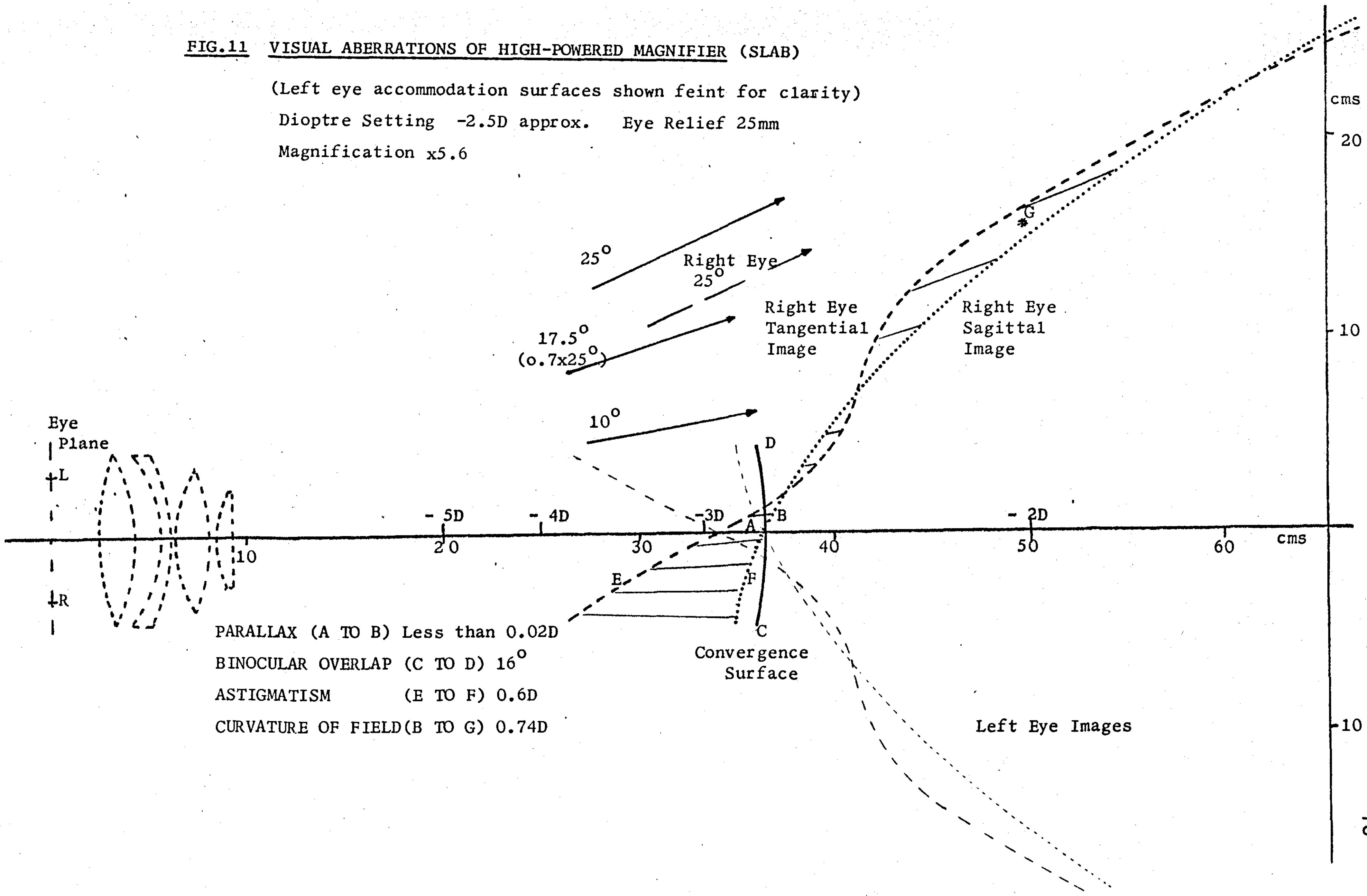
In order to obtain a 50^{o} field of view from a 40mm format, Rogers (1972) developed the lens design described in 2.2. The very high numerical aperture that is necessary means that steep curvatures are required which introduce higher order aberrations and also limit the component size. The obtainable

FIG.11 VISUAL ABERRATIONS OF HIGH-POWERED MAGNIFIER (SLAB)

(Left eye accommodation surfaces shown feint for clarity)

Dioptre Setting -2.5D approx. Eye Relief 25mm

Magnification x5.6



binocular overlap is somewhat reduced and the control of astigmatism becomes difficult. However, the residual level of astigmatism obtained is generally better than the simple lens. In defining the curvature of field a problem arises as the binocular field curves differently from the monocular. In order to let this value reflect the muscular changes required in searching the field a value based on the accommodation surfaces must be used.

From Fig.11 it is seen that the values for the four binocular aberrations are approximately as indicated. As is usual with lenses the area of greatest error occurs when the eyes are looking through the peripheral regions of all the elements. This occurs not at the limits of the total field but at the limits of the binocular overlap.

It is not suggested that these descriptions are comprehensive. Obviously, a more complex analysis can be undertaken, but this does not appear to the writer to be particularly worthwhile until at least some idea is obtained of the likely visual interactions with these aberrations as broadly described.

CHAPTER 3

ABERRATIONS AND VISUAL RESPONSE

3.1 Introduction

When an optical display system exhibiting some or all of the aberrations described in the previous chapter is used by a normal observer, his visual apparatus is capable of a number of different adjustments, both voluntary and involuntary, as he makes use of the equipment. These effect the clarity of the images on his retinae and the quality of his perception of the displayed information. These stages of vision are obviously closely related and together determine how well the purpose is achieved. This latter third stage may be termed visual performance as an overall description of the observer's utilisation of the displayed information, and as such is related to human factors studies.

These three areas form a useful framework in which to place a discussion of previous work as little of this is related directly to optical displays, and most must be taken from its original context and specifically applied to the problem. A further area, clinical experience, may also be included in this framework.

In recent years the measure of clarity or acuity has become more quantified from both objective as well as subjective methods of experiment. In a recent review of this subject Fry (1971) refers to the "optical performance of the human eye," and concerns himself in the main with optical transfer functions of the optics and retina. Rose (1948) refers to sensitivity performance, and Campbell (1965)(1966) (1967) (1968) variously to visual resolution, visibility, visual acuity and optical quality. Essentially these expressions relate to the ability of the visual apparatus to recognise simple objects such as discs, letters, gratings, etc., which is generally called "visual acuity."

When displays are considered, the value of a given system is usually measured in terms of the amount of information it can convey. Although "visual performance" is used in this connection, Biberman (1973) gives the title "Perception of Displayed Information" to a recent book on this subject. The word "perception" generally conveys a broader meaning to the visual sense than "acuity." In their use as night vision aids biocular magnifiers may become the only visual link between the user and the outside world. The visual space sense in the presence of aberrated information is therefore important.

The word "performance" strictly relates to the execution of a task. In studies of night vision aids, the measurement of the user's score when executing some visual task with the system is called "visual performance." This is particularly the case with paced tasks where the lack of stimuli to ocular adjustment may extend the response time to information even when it is well within the acuity of the observer. In such experiments it is generally found that the training and experience of the observer have a considerable influence on his performance. This is largely because the need for the observer to look in the object's direction has been added to the other requirements. Here, the voluntary oculomotor facilities of the observer's visual apparatus are being employed. When optical systems such as magnifiers are interposed between the displayed information and the observer, the aberrations of that system require that the observer not only looks in the correct direction, but to do so with the right state of accommodation, and for binocular vision, with the right convergence and cyclo-rotation to achieve fusion. A considerable amount of research work has been done on vigilance of observers, but this is not of immediate concern for this study. Although poorly designed equipment may affect the user's vigilance, this is of the nature of a second-order interaction, and as Vigilance varies considerably from person to person, and indeed from moment to moment, a study of magnifiers must first consider relatively simple situations requiring no great mental effort on the part of subjects.

When considering how the human visual system is likely to react to aberrations, the experience of ophthalmic practice should be valuable. This falls roughly into three areas:-

(i) the measurement of the required correction
(ii) the design and fitting of the spectacle lenses
(iii) the subsequent effect on the vision of the patient.

One large difference stands out. The patient has, or believes he has defective vision. In the case of magnifiers used by military personnel it is most unlikely that the observer's vision will be significantly different from emmetropic. A further difference lies in the fact that most spectacles are worn continuously while the period of use of magnifiers may vary from minutes to hours. This means that more pertinent data may be available from corrections prescribed for intermittent use such as reading glasses, or two-power systems such as bi-focals. Psychologically the provision of spectacles to a patient with defective vision is important to that person who may therefore make more effort to accept residual aberrations than will a potential customer of optical equipment, be it for a military or civil purpose. Thus, although clinical reports may be useful, it is extremely difficult to draw more than the broadest conclusions from them.

Thus the main areas of concern remain visual acuity, visual perception and visual performance. It is necessary to review each of these aspects of visual response under two headings, their measurement with displayed information and their interaction with ocular adjustments. Finally, the way in which visual aberrations interact with ocular adjustments is considered and general conclusions drawn.

3.2 Visual Response related to Displayed Information

Of all measurements related to how well a subject can see, the measurement of visual acuity at the fovea is of primary importance. For purposes of sight testing the use of the Snellen chart is widespread, as are similar targets such as the Landolt C (or broken ring). The acuity is expressed in terms of some critical dimension of the minimum size of target recognised. In the case of the Snellen letters the stroke width is considered the critical dimension while for the broken ring the size of the gap is used. A further system uses two bars separated by a distance equal to their width, and having lengths equal to three times their width. They are often called Koenig Bars, although arrays of these are referred to as Cobb Charts.

The need to specify the minimum detail discernable occurs also with optical systems, particularly photographic and television equipment.. The U.S. Air Force uses a three-bar target array of diminishing sizes. A further system, the Ignor Limansky Chart uses four-bar targets, while a system in use for British Military equipment uses five bars.

Grating patterns have been used to measure visual acuity, and the increasing number of bars indicated above is an attempt to measure the acuity in terms of a single spatial frequency. With optical systems the border-line case is the "resolving power" or the limit of resolution, and is commonly expressed in terms of the maximum number of cycles per millimetre in the image that can be resolved. When applied to the eye it is usually expressed in cycles per degree or milliradian.

The border-line is not sharp and the reducing size of the retinal image shows a reducing contrast as well. Contrast is defined as the difference in luminance between an object (L_o) and its background (L_B) divided by the background luminance (L_B).

$$\text{Contrast} = (L_B - L_o)/L_B \text{ or } (L_o - L_B)/L_B$$

Alternatively, modulation uses the mean luminance as the divisor.

$$\text{Modulation} = (L_B - L_o)/(L_B + L_o)$$

A third value in common use is the Contrast Ratio

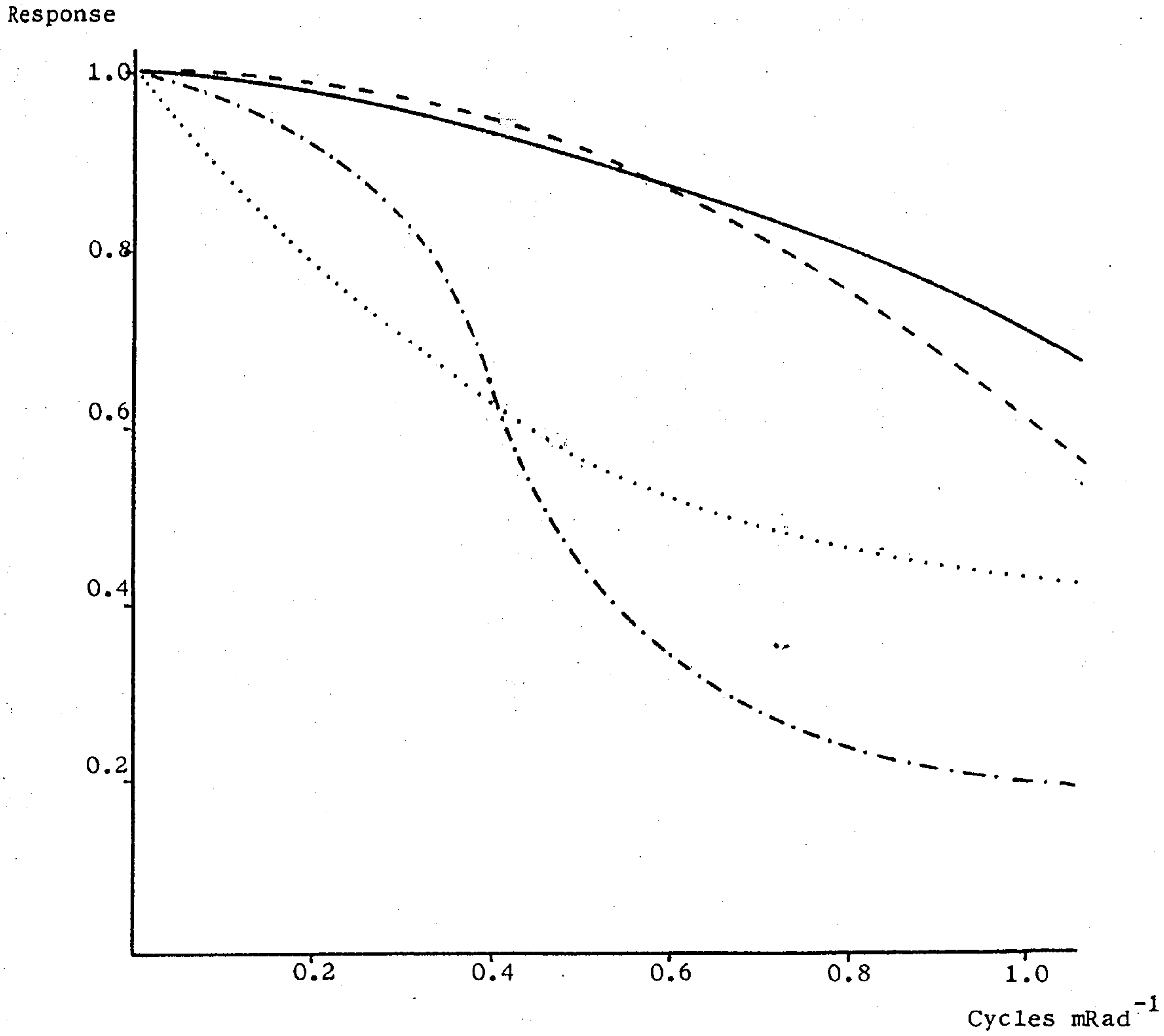
$$\text{Contrast Ratio} = L_o/L_B$$

As the contrast or modulation of the target itself is reduced the equipment or eye may fail to resolve it even though its size is large. Thus, threshold responses are a function of spatial frequency and contrast (Or modulation). The different expressions for these mean that at values less than about 0.1 the modulation figure is about one half the contrast value.

Experiments to determine the response of the eye in terms of spatial frequency and contrast or modulation have been extensive. Workers more interested in the variation with background luminance have sometimes used single-sized stimuli such as a disc subtending four minutes of arc (Blackwell & Blackwell) (1971), and taken results over a large number of subjects. Other work is often notable for the very small number of subjects used. Rose (1948) used a series of discs with varying diameters and contrasts making measurements

FIG. 12 VISUAL RESPONSE

- (after OVERINGTON (1973b))



Various eye mtf's compared at 2.5mm pupil

——————— Diffraction Limited

- - - - - - 'Best' computed from Ivanoff (1956)

·········· 'Optimally refracted' (green light), Campbell & Green (1965)

-·-·-·-·- 'Normal' eye, Westheimer & Campbell (1962) over background luminance values of 10^2 - 10^6ft. lamberts.

If a single or restricted range of luminance is used a more detailed investigation can be carried out. A moire system which gave triangular gratings has been used but most workers have used sine-wave or square-wave patterns. Differences in response between these have shown the existence of functionally separate mechanisms in the visual nervous system which respond to particular spatial frequencies (Campbell & Robson - 1968). In that work, the patterns (including saw-tooth profiles) were generated on a cathode ray tube. The viewing was monocular with the eye homatropinised. Contract thresholds were determined by the subject adjusting the contrast until the pattern was barely visible.

The values obtained by this method relate to the acuity of the total eye optics plus retina. Methods of separating these are useful as then the influence of pupil size and accommodation can be separated from retinal effects. In Fig.12 the response is based on contrast sensitivity which assumes that modulation of the output from the retina at threshold is constant from one spatial frequency to another so that the change in input signal required is due to the different amounts of demodulation introduced by the system.

In these investigations there are a large number of parameters which may effect the result.

The colour, form and mean luminance of the grating have specific effects. The accommodation, accommodative error, pupil size, adaptation and retinal illumination of the eyes also have particular effects. Most of this work has been done with the subject's monocular vision. It is known that the binocular threshold of vision is about 30% better than monocular.

Experiments with binocular contrast threshold have been related to photographic interpretation and image intensifier displays. This has been almost exclusively applied to directly viewed information such as photographs and large size C.R.T. displays. In the recent book "Perception of Displayed Information" the possibility of optical components between the observer and the information is completely ignored. Nonetheless the nomenclature and methods of this area have a direct relevance to the problem of magnifier design. The need to quantify the level of response had led to the adoption of three distinct sub-divisions - detection, recognition and identification. To these a fourth level is sometimes added - orientation, which lies between detection and recognition. These were first defined by Johnson (1958) as follows:-

Detection:	An object is present.
Recognition:	The class to which an object belongs may be discerned (eg: house, vehicle man, etc.)
Identification:	The object can be described to the limit of the observer's knowledge (eg: hotel, pick-up truck, policeman, etc.)

Almost the first requirement with such a description of vision is to relate it to physical parameters such as resolution, grain in photographs, illumination etc. Considerable work has been done in this field, and a major study by Scott (1968). led to the introduction of a Demand Modulation Function (DMF) which effectively specifies the minimum picture quality measured in physical parameters for a given object to be just seen by a normal observer. As such these concepts can be taken over into present magnifier designs by saying that the optics must not significantly reduce the ~~Transfer Function~~ Modulation of the object magnified. This may be useful with magnifiers for image intensifiers and small cathode ray tubes which are often two or three times worse than normal visual acuity. For magnifiers in industry viewing real objects for assembly or inspection the problem is more difficult. Here the work of Overington (1973) is more applicable although he restricts himself to monocular systems with the eye on-axis, and concentrates on the detection part of Johnson's criterion. He points out that the aberrations of the optical equipment and those of the eye may well assist each other. Thus, while it is possible that the general results of visual acuity measurements may be applied to biocular design their main value lies in the methods used which may be applied to the eye plus magnifier case.

When considering aspects of visual perception relating to the use of biocular magnifiers it should be remembered that a large proportion of biocular magnifier applications are for two-dimensional objects such as cathode ray tubes. The distortions of this presentation must be added to those of the magnifier which can provide variations in the third dimension before the total distortion apparent to the observer may be assessed. Just what is, and what is not "apparent" to the observer is not easy to define. The well known ability of subjects to see what they expect to see leads to optical illusions. This is indicated by current experience of some magnifiers where the heavily curved image is seen as flat and in experiments where size cues override vergence in distance judgements (Morgan - 1968), (Richards - 1969). The principle of the split-field steroscope (anaglyph) is where two pictures viewed independently by the eyes give rise to a sensation of depth when the eyes fuse the two images. This sensation is therefore derived from the convergence action, and not from the focussing action of the visual apparatus. This has been analysed to some extent by Fry (1969) who related the convergence surface to the perceived image surface directly, while the writer introduced in Chap.2 an intermediate stage so that the distortion in the object may be considered separately from the distortion introduced by the magnifier. The generation of a stereoscopic effect is not the intention of biocular magnifiers and previous work directed towards the measurement of stereoscopic thresholds is not immediately applicable.

The applicable work involves the investigation of apparent size and size-constancy effects both monocular and binocular as both types of vision occur with high-powered binoculars. Linked with these effects is that of depth estimation. Except where perspective cues are used to produce illusory depth, oculo-motor adjustments are involved immediately in this area and a discussion of specific papers is included in the next section.

In considering work on the measurement of visual performance the paper by Johnson (1958) referred to earlier is applicable as his "visual acuity" targets were used in performance measurements and, with some modifications, have been used subsequently in a large number of human factors studies of search-type displays. In these displays the major emphasis is on the time to obtain a particular response, and the interest lies in the search techniques and vigilance levels adopted by the observer.

As parameters of merit, response times and percentages of correct responses have both been used. The former is the time lapse from the presentation of the target to the observer's response while the latter is the asymptotic value calculated from the declining rate of response as the observer searches scenes containing targets of different difficulty levels. The latter test is most often used in photo-interpretation studies. In studies related to active situations where the time element is important, the former criterion is used. This may be divided between static tests where the target is presented, and the observer looks for it, and dynamic tests where the scene is changing. If this change is making the task steadily easier then the response times measured may be related to the probability test for a given difficulty of target, but the main difference between the static and dynamic cases lies in the pacing of the test as the former may be considered self-paced, while in the latter the observer waits until the target "comes to him."

Biberman (1973) points out that at least fifteen display variables have been shown to have significant, although often inconsistent effects on operator information extraction performance. He notes that individual experiments have tended to examine the effects of one, two or sometimes three such variables, but that due to the inherent interaction between them it is virtually impossible to quantitatively combine different sets of results, even when good experimental control has been exercised.

Thus, only the methods of these experiments may be considered for use with biocular magnifier studies, although the work on T.V. Displays (direct viewed) might be used to compare systems with large screens with systems employing small screens and magnifiers.

3.3 Visual Response and Ocular Adjustments

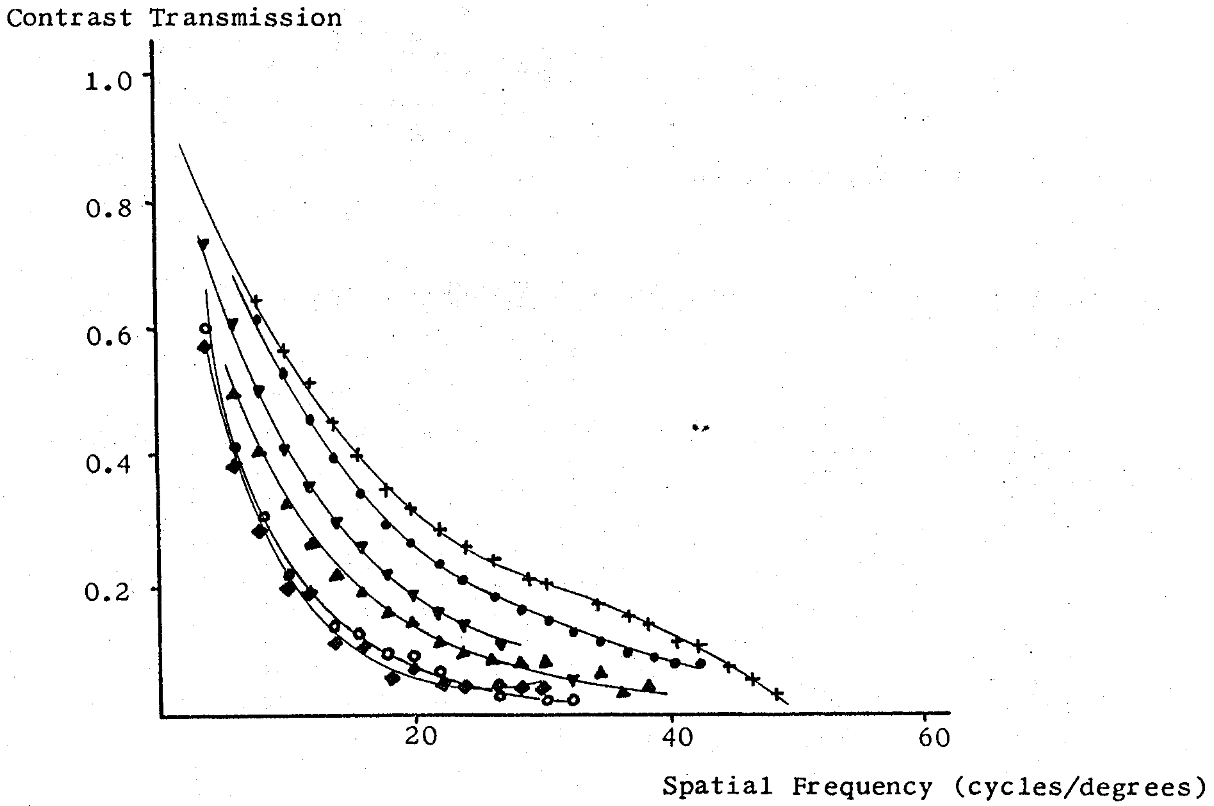
The triad response of the visual system comprises the inter-linked adjustments - pupil size, accommodation and convergence which together cover most of those ocular adjustments which are immediately important in a study of biocular magnifiers. The main purpose of the triad response is to maximise the visual acuity of the observer. The pupil size variation with illumination is generally the best compromise between the retinal illumination and residual aberration of the optical system, although this may not be so when a restricted field of view is observed. The near response of the pupil gives a greater depth of focus for near vision and the reflex nature of this action means that it still occurs even when viewing two-dimensional displays for which it is unnecessary. The effect of pupil size on visual acuity has been investigated by a number of workers including Campbell & Green(1965) and Arnulf & Dupuy (1960). The former maintained a constant retinal illumination, but only investigated three pupil sizes, 2mm, 3.8mm and 5.8mm. There is no evidence as to what further decrement larger pupils might show.

Subsequent work by Campbell & Gubisch (1966) investigated the optical quality of the human eye by recording the image on the retina of a thin line. The intensity profile of the line can be Fourier ~~analysed~~ transformed to give a modulation transfer function for the optical system of the eye.

Six artificial pupil sizes were used up to a maximum of 6.6mm, and the three subjects used had their natural pupil and state of

FIG.13 VISUAL RESPONSE AND PUPIL SIZE

- (after CAMPBELL & GUBISCH) 1966

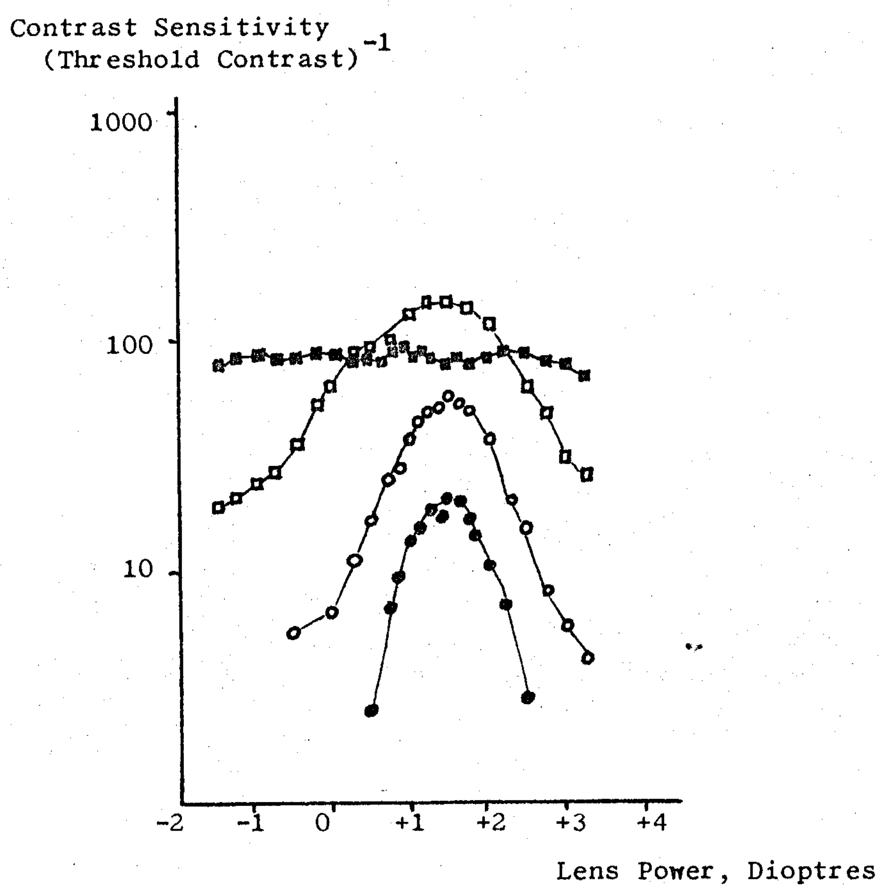


Modulation Transfer Function for various pupil diameters

- + 2.0mm
- • 3.0mm
- ▼ 3.8mm
- ▲ 4.9mm
- o 5.8mm
- ◆ 6.6mm

FIG.14 VISUAL RESPONSE AND ACCOMMODATION

- (after CAMPBELL & GREEN (1965))



The effect on contrast sensitivity of changing the refractive power of the eye of the subject. The eye was homatropinized and a 2mm pupil used.

● 30 c/deg, ○ 22c/deg, □ 9c/deg, ▪ 1.5c/deg.

accommodation paralysed with cyclopentolate hydrochloride. Their results are shown in Fig.13. These show that significant loss of contrast is occurring up to pupil sizes of 6.6mm. Thus, any unnecessary dilation of the pupil represents loss in the acuity of the subject.

Almost all recent experiments on visual acuity have been done on subjects with their accommodation paralysed. To investigate the effect of defocus on the visual acuity Campbell & Green (1965) measured this with a range of spectacle lenses in front of the homatropinized eye of their subject. Their results reproduced in Fig.14 are for a 2mm pupil, and show a symmetry about +1.5D which is non-zero due to viewing distance and refractive error. It is clear, however, that the rate of change of contrast sensitivity with the change of refractive power is greater at higher spatial frequencies. This has important ramifications where blur as a stimulus to accommodation is concerned.

The third part of the triad response - that of pointing of the eyes is generally assumed in the above experiments, where the extent of the test objects is generally large. To measure the effect of pointing error on visual acuity very small targets must be used if points close to the fovea are to be investigated. Millodot (1972) reviews this field and from the somewhat variable results concludes that a region of isoacuity exists of diameter between 20 and 30 minutes of arc. For a decrement of 10% a pointing error of about 24 minutes is required. However, this error is unlikely to occur with binocular vision without considerable eye strain (Chapter 4).

The role of ocular adjustments in visual perception was pointed out by Helmholtz who used examples such as the effect of vergence movements on apparent size, the variation in apparent size during accommodation, and the stability of the visual environment during active eye movements. Subsequent work has led to various "expectancy" models of perception in which the driving mechanism for ocular adjustment modifies the incoming sensory information. Considerable work has been done on the role of small eye movements on perception but at this stage it is thought that the aberrations of magnifiers may be assumed constant over these angles, and that no direct interaction between them will occur.

The dioptric settings of magnifiers usually place the image at a distance closer than one metre. Experiments on visual perception in this region have investigated the perceived size of simple objects by requiring subjects to adjust a control object to the same size. Harvey & Leibowitz (1967) found no significant difference in the accuracy of responses for monocular and binocular viewing. If the field of view was very restricted (little larger than the objects - 18° vertical by 1.5° wide) a considerable error occured above a 1metre viewing distance. In subsequent experiments Leibowitz, Shina & Hennessy (1972) monitored accommodation and with objects subtending 1° found good matching accuracy against actual accommodation distance up to about 1 metre. The accommodation cue appeared to be more important than any other up to this distance. Although no work has been found on size matching with non-normal accommodation/convergence stimuli it would appear that if an incorrect accommodation is adopted some error may be expected in size perception.

However, magnifiers are often used to present electronic representations of distant scenes such as television. Richards (1968) maintains that when planar, perspective cues are used to give the effect of illusory depth, size judgements are independent of oculomotor adjustments. However, his experiments were confined to relative size estimates of the corridor illusion with steady fixation and brief exposures of the scene compared to continuous free viewing. At no time were abnormal ocular adjustments required of the subjects.

With monocular viewing, Morgan (1968) reports experiments showing that apparent size overrides accommodation cues even at near distances. Two playing cards seen monocularly at 33cm and 66cm were reversed in position but also changed in real size so that their apparent sizes were maintained. Subjects could not detect the change in depth.

Most research work in visual perception is directed at increasing our understanding of the physiological and psychological processes at work. The specific situation with magnifiers requires the application of these methods to that condition and although previous work is invaluable in deciding the best areas of investigation it is not easy to use it to predict results.

Visual performance assessment, as indicated in the previous section often involves time dependent tasks. Thus, the interest in ocular adjustments now extends not only to how well they comply with the requirements for seeing clearly, but also how quickly they comply. Thus, the measurement of accommodation times by Campbell and Westheimer (1959 &1960) is of value. They found considerable variations in response time depending on the particular stimuli used. When this was only the blur of the image with monocular vision, reaction times of 0.3 seconds were found followed by up to 1 second to complete the response to a 2D stimulus. Obviously a delay in obtaining the correct adjustment should show as a performance decrement, but no studies are known which directly deal with this.

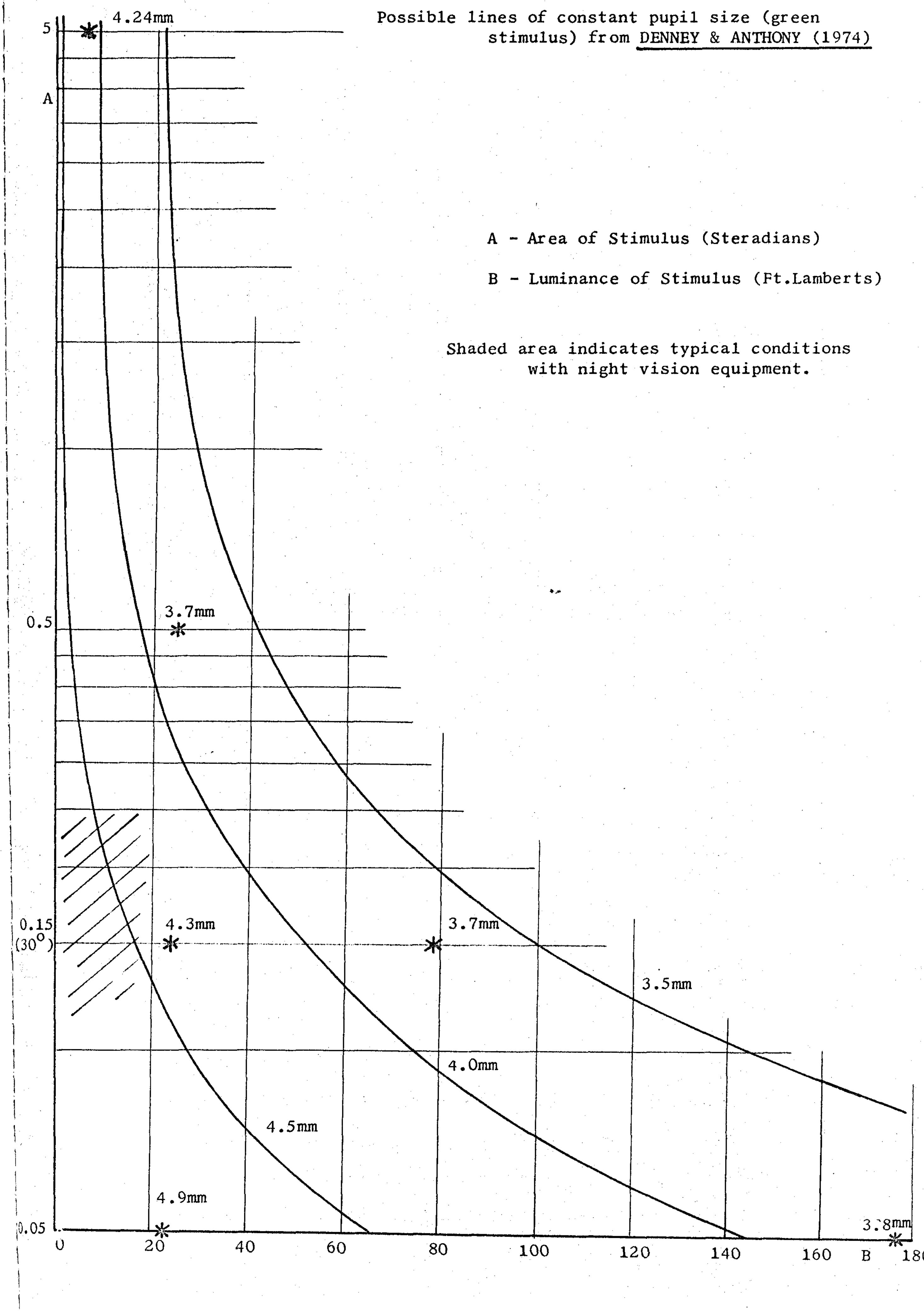
In the extreme case of aircraft pilots who need to look at their instruments as well as the outside world (about a 2D shift) the head-up display has been developed to project essential information at the same apparent distance as the outside world. Within the environment of an aircraft cockpit various convergence and accommodation responses are required of the pilot as he scans his instruments. Although many studies in eye movements have been carried out these usually relate to one eye only and do not measure convergence or accommodation. The accurate measurement of either over wide fields of view is very difficult. Using a photographic system Stewart (1961) carried out an investigation into jump vergence responses. He found that fusional movements at 10^{o} per second were much slower than fixational movements and somewhat slower than accommodative convergence movements, while the reaction times associated with all three were about 0.16 seconds. No work relating these oculomotor responses to visual performance has been found.

3.4 Ocular Adjustments with Visual Aberrations

When considering the likely reaction of the ocular adjustments to non-normal stimuli, it must be recognised that the oculo-motor system may rely on more than one parameter as a stimulus to action. Some actions are reflex while others are voluntary or have voluntary components and as such allow for training on the part of the observer.

The pupil response is entirely reflex, having a reaction time of 0.26 seconds. Its size is determined by adapting luminance. Groot and Gebhard (1952) suggest an equation for the case where the adapting field fills the total visual field. When the adapting field is reduced the size is modified. Although work has been done on very small fields, only Luckiesh & Moss (1934) have carried out work at field angles similar to biocular magnifiers. For a 30° circular field of 15ft. lamberts which is typical of a biocular magnifier, the equivalent luminance of an unrestricted (2π) field would be 0.45ft. lamberts which by Groot and Gebhard gives 4.5mm pupil. Luckiesh & Moss restricted their work to 35ft. lamberts, but their results show a non-linearity of 10% between these fields so that the predicted pupil size is nearer 4.0mm. However, the calculation of equivalent luminance, known as Crawford's Rule (Crawford, 1936) is inaccurate for large pupils. Palmer (1966) investigated the interaction of pupil size with optical instruments, having Maxwellian illumination via an eye ring. Where this eye ring was larger than the largest natural pupil, his results are applicable to magnifiers and show that for a field luminance of 14ft. lamberts pupil sizes of between 6 and 7mm were obtained. A short study by Denney & Antony(1974) on five subjects gave the mean values of pupil size against field

FIG. 15 PUPIL RESPONSE AND FIELD SIZE



size and luminance of the stimulus as shown in Fig.15. The stimulus was restricted to a green colour equivalent to the phosphor of an image tube by using a Wratten No.55 filter with a projector having an Illuminant 'A' source. Within this restricted range of parameters the lines drawn on the graph are only suggested by the results. Bouma (1965) did extensive work on pupil size with circular and annular adapting fields and fitted equations to his results, but as these were all obtained for his own eye (monocularly) no confidence can be placed in how representative they are. Bouma's equations are critically reviewed by Clark 1972 but without taking any further measurements. Clark also reviews the literature on binocular v monocular viewing and concludes that the latter gives a larger pupil size so that a stimulus about ten times brighter is needed to give a size equal to the binocular case. Bouma did carry out measurements while fixating the field off-centre. As the fixation point nears the edge and outside of the stimulus a considerable increase in pupil size occurs. This will cause changes in pupil size as an observer searches the field of a magnifier. The effect of accommodation changes (miosis) due to the curvature of field of the magnifier will be very much less. Obviously, specific experimental work over a number of subjects is required in the hatched region of Fig.15.

In general all investigations into these visual responses involve the manipulation of a stimulus as an independent variable, and a measurement of the response as a dependent variable under two sets of conditions. In the first condition the mechanism responding is free to make any response without, as far as is known, altering the stimulus conditions through sensory feedback and is called the 'open loop' condition. Alternatively, sensory feedback may be allowed given a 'closed loop' condition. In normal use, and with magnifiers, the 'closed loop' condition applies, although the sensory feedback may be modified by the presence of aberrations.

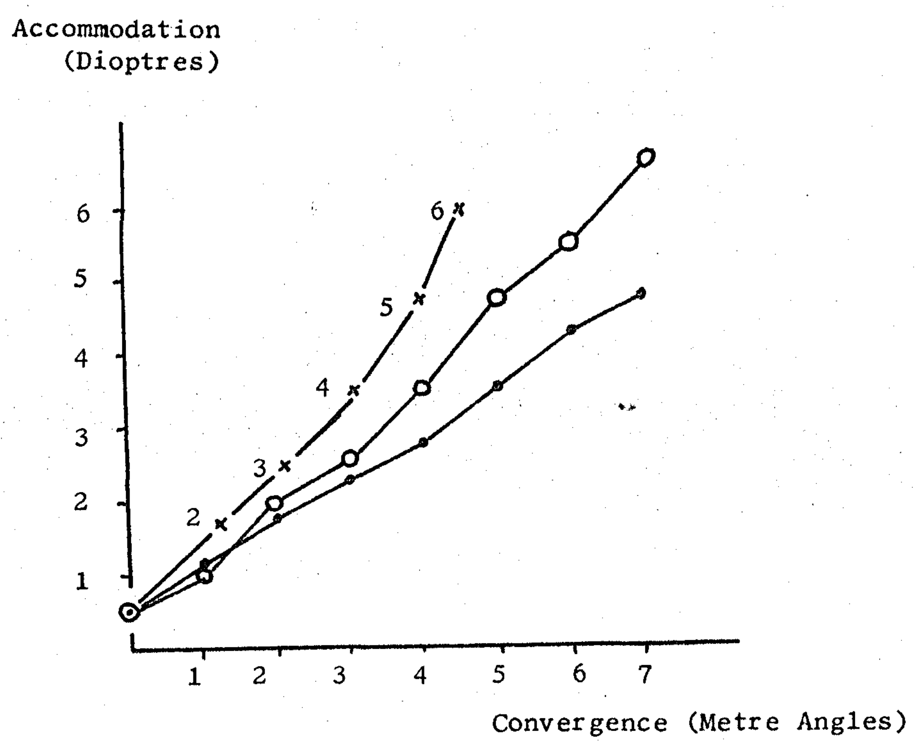
The stimuli to accommodation are more numerous than to the pupil, and are also subject to some controversy. The major problem concerns the interaction of accommodation and convergence. In normal binocular vision accommodation and convergence are adjusted together when viewing objects at different distances.

Fincham (1951) maintains that the most powerful stimulus to accommodation is the disparity between the images in the two eyes which leads to convergence, which in turn stimulates accommodation. The blur of the retinal image is seen as a further stimulus. Accommodation itself is a reflex action although becoming more voluntary for subject over 26 years of age.

Westheimer (1966) also classes accommodation as involuntary and characterised by an almost perfect correlation between the accommodative responses of the two eyes of a normal subject. It is also characterised by a dead zone of between 0.3D and 0.75D varying inversely with pupil size. Generally, an effective response does not occur unless the stimulus change is of this order of magnitude. The response tends also to lag behind the stimulus whether this be convergence or blur. Fincham & Walton (1957) examined both these stimuli in some detail, both 'open' and 'closed loop.' Fig.16 shows the normal response (open circles) is good over the 1.0D to 2.0D range but lags at stimuli nearer than this.

FIG. 16 ACCOMMODATION AND CONVERGENCE INTERACTION

after FINCHAM and WALTON(1957)



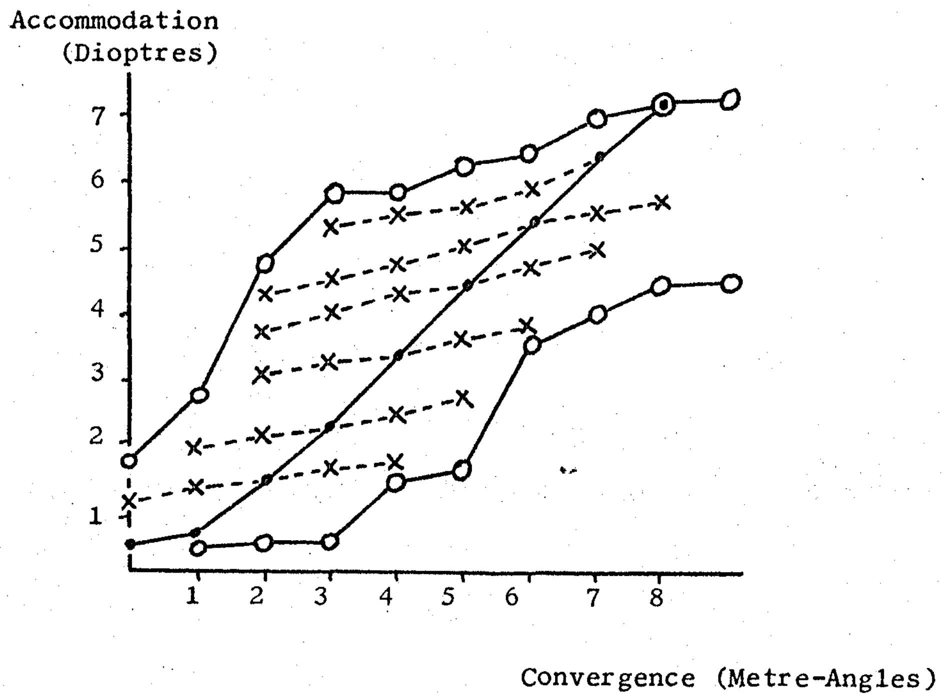
○ Normal Binocular Accommodation

× Accommodative Convergence (figures show Stimulus values)

● Convergence induced Accommodation.

FIG. 17 ACCOMMODATIVE RANGE

after FINCHAM and WALTON (1957)



Amplitudes of accommodation relative to a fixed convergence.

If the stimulus is only convergence (depth of focus made very large by small artificial pupils) the accommodative lag becomes worse (black circles). If the stimulus is only blur (monocular viewing) the accommodation of the viewing eye (crosses) lags to a slightly larger extent than normal.

All these situations apply to some extent in a biocular magnifier, and it would be helpful to have the data averaged over more than one subject! In the central binocular field of a magnifier the major stimulus to accommodation will be the convergence of the eyes necessary to achieve fusion. If this is incorrect the retinal vergence (blur) may act as a secondary stimulus to modify the accommodative response. Fincham & Walton (1957) again determined this for the same subject, and their results are shown in Fig.17. In this graph the solid circles represent the normal situation, while the crosses show the accommodative response to retinal vergence changes of 1D for each value of convergence. It is seen that with a 2 metre angle convergence the accommodative response can be increased from 1.5D to 2D by increasing the retinal vergence to 3D. Conversely the accommodative response can be increased to a correct value of 2D by increasing the convergence stimulus to about 5 metre angles, although this is about as much as the subject can stand as the open circles represent the limits of single vision. This latter action would be slightly better with younger subjects as the authors found that the slope of the convergence induced accommodation line changed from unity to almost zero over the age range 12 - 60 years.

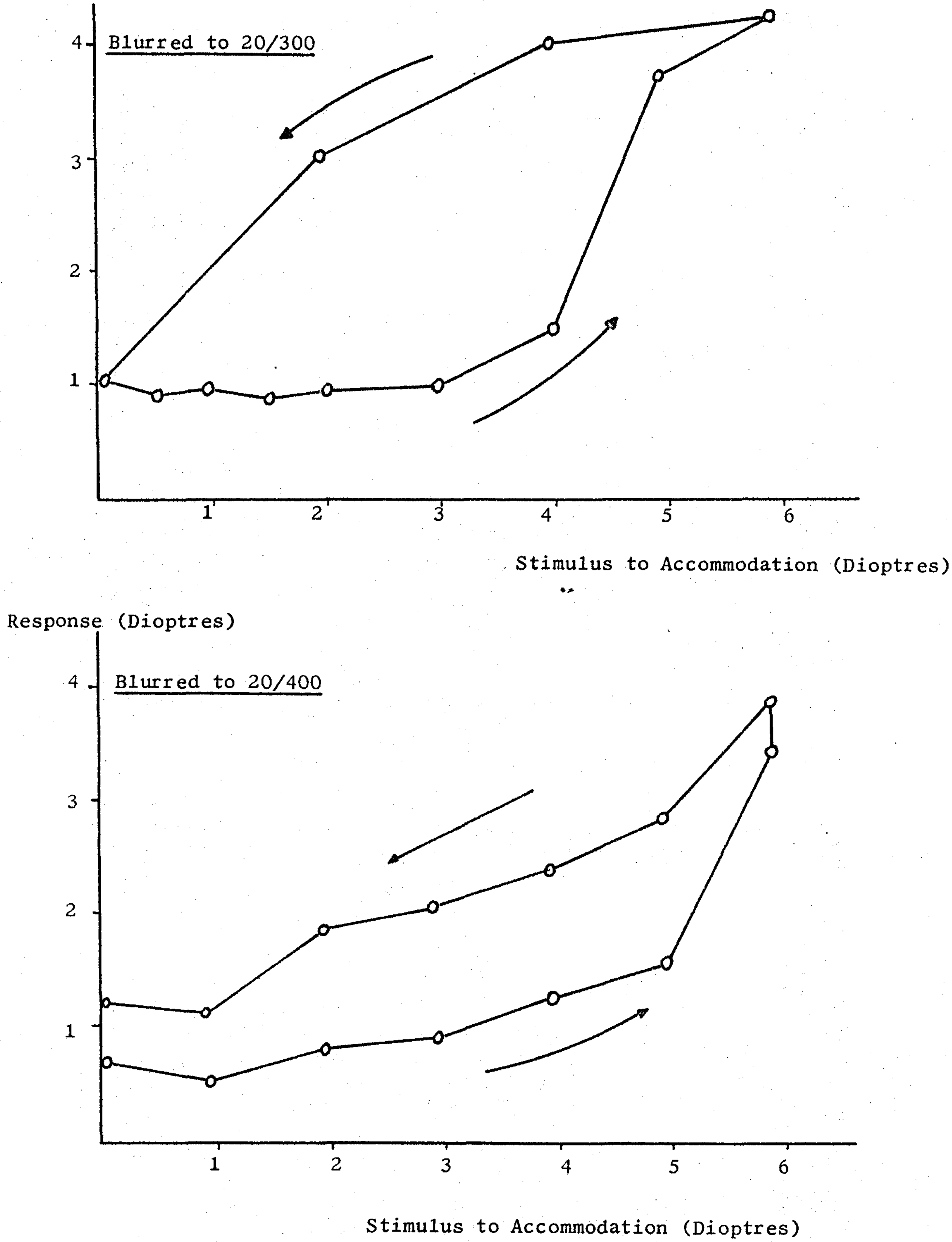
In areas of the magnifier where binocular vision is not available the stimulus to accommodative change can only be blur of the retinal image. In his earlier study Fincham (1951) pointed out that the blur of the retinal image was the same no matter in which direction the incorrect accommodation lay. However, the direction of the accommodative response is always in the correct direction for stimulus shifts up to 2D and for subjects up to 26 years old. He then found that this correctness was lost for 60% of the subjects when monochromatic illumination was used. In terms of biocular magnifiers used with image intensifier tubes it would appear that the green phosphor may constitute an aberration so far as the fine adjustment reflex of accommodation is considered. Whether a white light system would provide an improvement in visual performance is not certain when the 1.5 - 2D extent of chromatic aberration in the eye is remembered.

Possibly a greater hindrance to fine adjustment of accommodation in the binocular region and total control of it in the peripheral monocular region is the reduced visual acuity represented by the image intensifier as used with biocular magnifiers for night vision.

Heath (1956) reported that the precision of the accommodative response is a function of visual acuity, being poorer when the visual acuity is low. As the reduction in visual acuity was generated in one case by a ground glass screen interposed just in front of the targets, there is a strong resemblance to the image intensifier case. The binocular vergence cue was absent in these equipments, but the most interesting feature was that

FIG.18 ACCOMMODATIVE RESPONSE TO BLURRED STIMULI

after HEATH (1956)



Accommodative response to monocular stimulus having reduced spatial frequency. Arrows indicate the order in which the stimuli were presented.

the reducing precision showed up as an increased lag of accommodation. Fig.18 is reproduced from Heath's paper and shows the reluctance to change effect. The blurring to 20/300 represents a visual acuity limit which is fifteen times worse than normal vision. The magnified film of the experimental study corresponds to five times worse than normal vision.

The size of the reluctance effect is difficult to relate to other values of blur and of amplitude of the stimulus change coupled with the fact that the data is for one subject. However, the accommodative response time of a subject scanning to the edge of the field of view of a mgnifier having 2 dioptres of field curvature is likely to show considerable delay.

Other cues to accommodation have been studied, and although these are usually overridden by those of convergence and retinal blur, the absence or opposition of these may allow the others to have a significant influence. In particular, the influence of peripheral stimuli to accommodation is important when the eye can see the edges of elements of the magnifier which appear at different distances to that of the image. Anisometropic stimuli may occur in the image itself but this must be in the binocular region so the convergence cue will predominate. However, at the limits of the monocular fields the proximity of the field edge may introduce accommodative error. This was investigated by Hennessy and Leibowitz (1971) where subjects fixated a spot through various apertures while their accommodation was measured by laser scintillation. It was found that for apertures of 1^{o} and 4^{o} a considerable influence on accommodation occurred as the aperture was moved even though the spot remained stationary. Related to this is instrument myopia (IM) which has been found by many observers. Schober, Dehler & Kassel (1970) found that between 0.5 and 3 dioptres could occur with binocular viewing while an increase of 1.5D on these figures was found for monocular viewing. This figure describes the preferred setting of subjects using microscopes. The authors noted a considerable learning effect which reduced these values although this occurred over some months.

A common feature of the studies reported in this section is that oculomotor adjustments rarely rely on a single stimulus for their response. This makes it difficult to predict their reactions to the aberrations of biocular magnifiers although general conclusions may be drawn as a basis for study. Yet a further difficulty arises from the ability of the accommodative response to anticipate stimulus changes. Wildt, Bouman & Kraats (1974) presented a sinusoidably changing monocular stimulus to a subject and found cases where a considerable anticipatory affect could occur, which was related to training. In a high-power magnifier the curvature of field gives an accommodation stimulus which is fixed relative to field position. This should permit a considerable learning effect if the aberrations allow this.

3.5 Aberration limited Vision

In an attempt to relate chapters 2 and 3 it is useful to consider the aberrations of high-powered magnifiers indicated in the previous chapter and their likely effect on a normal observer.

The principal binocular aberrations listed were:-

1 Parallax

2 Limited Binocular Overlap

3 Astigmatism

4 Curvature of Field

Three other aberrations, not specifically binocular, need to be considered.

5 Limited Total Field

6 Reduced resolution (Visual acuity)... considered as a feature of the object magnified rather than optical aberrations over each pupil.

7 Limited Colour Range.

The effect of these on each aspect of the Triad Response is as follows:-

The pupil size is not obtained from the adapting luminance but exhibits an increase due to the restricted field. Some varying miosis will occur due to the curvature of field.

The accommodation driven by the convergence cues in the binocular area may be incorrect in the presence of parallax error. The retinal blur induced may not correct this in the absence of chromatic cues and at the reduced resolution values. In the monocular region the curvature of field demands a shift in accommodation as the field is scanned. In addition to the reduced colour and resolution, the nearness of the monocular edge of field may stimulate an incorrect amount of accommodation.

Convergence will be immediately affected by parallax error as the retinal blur response of the accommodation may alter the fixation disparity value. Energetic visual search of the whole field results in frequent jumps between associated and (at least partially) dissociated vision. Depending on the strength of the observer's fusional lock this could lead to double vision and suppression where one or other of the monocular fields is ignored.

The remaining aberration - astigmatism - remains somewhat enigmatic. Obviously a loss of visual acuity results but what effect this has on the oculomotor adjustments is more difficult. The convergence will achieve fusion on vertical line foci rather than horizontal and the decrease in the resolution will hamper the accommodative response. Unfortunately for this study astigmatism as an ocular defect is straightforwardly corrected and no work is known relating loss of visual response to its value.

Considering the visual response in its three areas it is seen that stimuli which generate a larger than necessary pupil size effectively reduce the visual acuity. Stimuli which give incorrect focus adjustments also reduce visual acuity. Visual perception will be influenced by the accommodation-convergence relationship although the extent of this with perspective representations as objects is unlikely to be large. Visual performance on the other hand is likely to show degradation due to the reduced visual acuity associated with incorrect oculomotor adjustments and also with the likely increase in the response times of these adjustm ents when faced with abnormal or conflicting stimuli. That these stimuli may cause visual fatigue in the observer is considered in the next chapter together with the possibility of adaptation and learning on the part of his visual apparatus.

The optical design of biocular magnifiers needs a mathematical expression which combines values of various parameters into a single value. This value can then be associated with a particular design. When changes in the design alter the value the direction of its shift can be taken as an improvement or degradation over the original design. This allows computer-based auto-design programmes to optimise designs. As will be appreciated, the mathematical expression contains the essence of the whole technology behind the design effort and, in the case of objective lenses, has been the subject of many years work and difference of opinion.

As a starting point with visual lenses the central physiological feature is the triad response and the stresses that the magnifier incurs in this. An initial expression for this single value or merit function could be the reduction in visual performance primarily related to an acuity task. This may be based mainly on the accommodation error but the extent of this error will not only vary with each field point but also on the field point at which the observer was looking immediately before. Thus a random or standardised search pattern and speed must be assumed before such a concept can be meaningful. Even then the best one can hope for is some sort of probable mean error over a period of time.

CHAPTER 4

VISUAL ABERRATIONS AND FATIGUE

4.1 Introduction

Some people suffer visual stress due to defects in their visual apparatus. Others have it thrust upon them due to difficult visual tasks, inadequate illumination or incorrect correction of refractive errors. In this study we are primarily concerned with persons having normal vision and any eye strain arising from the use of biocular magnifiers must be attributable to those magnifiers and not to defects in the user's vision.

However, optometric (ophthalmic) procedures have two main purposes:-

(1) to provide for clear vision, and
(2) to provide for comfortable vision,

and in the study of patients suffering visual discomfort, various attempts have been made to induce similar symptoms in normal subjects and so their work has an important bearing on this study. Almost all cases of eye strain can be relieved by relaxing in a darkened room (Heaton, 1967). The symptoms reappear some time after visual work is resumed. It is essentially a time-dependent phenomenon, and as such it is difficult to distinguish from fatigue.

Dubois-Poulsen (1969) points out that a solution to the problem of fatigue has been sought indirectly in the description of symptoms, in the study of presumed causes, in the calculation of output and rarely in a physiological study with the result that we do not have a physiological test for visual fatigue. Bartley & Chute (1947) suggest the following distinctions in terminology:-

Fatigue:-	Subjective feelings of aversion to continuing an activity,
Impairment:-	Physiological change in tissue which reduces its ability,
Work Output:-	Overt ability measurement.

R.H.Seashore (1951) describes these three factors as semi-independent variables. He adds that psychologists are often astonished by the extent to which the human organism can continue to perform adequately under extremely unfavourable conditions. Hovey (1928) used student learning tasks with and without continuous distraction and found no significant difference. Warren & Clark (1937) deprived subjects of sleep for 65 hours and found that although they had to struggle to stay awake, their work output on a variety of psychological tests showed little or no decrement.

The important word above is struggle, for the effort applied to the task by a subject is likely to have a greater influence on work output than either fatigue or impairment unless these reach chronic levels. However, chronic fatigue is much more likely to follow prolonged periods of unpleasant emotion rather than the expenditure of physical exertion which may even obliterate the fatigue. Because of the compensatory efforts made unconsciously by the subject, it is unlikely that work performance measurements will in themselves indicate what fatigue or impairment is experienced in using a specific piece of equipment to perform a particular task, although one might hope to obtain some empirical relationship between them over a restricted range of external parameters.

The above remarks regarding general fatigue and allied phenomena apply in the main to vision. However, a larger number of people complain of eye strain than any other strain when doing normal everyday tasks. The majority of patients locate the discomfort in the eyes, and usually relate this to the performance of near visual tasks rather than distant. The major symptom is the headache, but Heaton (1967) defines eye strain as the symptoms experienced by a person who strives to see. Duke-Elder (1949a) goes further, "In health the use of the eyes ought to be a sub-conscious function - eye strain may be defined as the symptoms experienced in the conscious striving of the visual apparatus to clarify vision by ineffectual adjustment."

The striving and the failure are essential ingredients for discomfort. Dubois-Poulsen (1969) makes the point that small defects are more serious than large ones. The eye stops fighting against large defects, but does not give up the fight against small ones. The abandonment of binocular vision in favour of using one eye only, and suppressing the other, tends to relieve eye strain.

The concept of striving to see suggests that visual discomfort and eye strain are muscular in essence. The muscular mechanisms of vision are sub-divided into those which point the eye - the extrinsic or extra-ocular muscles, and those within the eye controlling the pupil - the sphincter and dilator muscles, and controlling the accommodation response - the ciliary muscles. A further related group of muscles provide the protective mechanisms, blinking and lacrimation, which may respond symptomatically to visual discomfort.

In his chapter on eyestrain Heaton (1967) lists 11 pieces of evidence against the ciliary muscle being involved in eye strain and 10 against the extra-ocular muscles. For the former he quotes experiments to fatigue the muscle by ergographic experiments which failed to generate eye strain. Other efforts to fatigue the near point generally resulted in near-vision improving. He also points out that there is a constant fluctuation of accommodation of the order of 0.3D to counter reports that errors of much smaller magnitude cause eye strain. For the latter case Heaton quotes Lancaster (1932) that the extrinsic muscles have a vast reserve of power 200 times that required to move the eyeball. He quotes cases of hetrophoria with eye strain where prisms which increased the work load on the muscles cleared the symptoms.

Heaton goes on to concentrate on the psychological aspects of eye strain, but although he is able in this way to raise objections to ocular muscles being the exclusive cause, there is no question in the minds of many authors that the muscles are major contributors with sensory, nervous and cerebral factors also being involved, while the critical psychological factor appears to be whether the subject continues to strive for good vision.

Thus, the studies of visual fatigue concentrate on investigating muscular effects while including also the sensory mechanisms which provide the error signals to the muscles. Work on the actual nervous innervation of the muscles is much less common.

In relating normally healthy eyes to the mismatch conditions which may apply when using biocular magnifiers, it is likely that muscular difficulties will have the most immediate effect. If the mismatch also introduces sensory difficulties these may also contribute. The duty times allowed in experimentation over sufficiently large numbers of subjects will preclude any measurements which are aimed at long term effects. In fact, the phrase "visual discomfort" is a better description of the sort of effects likely to occur in periods up to one hour. For this study where the overall interaction between biocular magnifiers and the user's visual apparatus is being investigated the requirement is for some measure of visual discomfort which can be applied during or after use of the magnifier by each subject. Specific work on eye strain has been studied so that its relevance to visual discomfort with optical aids might be ascertained and, if possible, some suitable discomfort monitoring method obtained.

4.2 Fatigue of Visual Muscles

4.2.1. Protective Mechanisms

The act of blinking may be voluntary or involuntary. Unless the attention of the subject is drawn to it, it remains largely involuntary and is found to remain unaltered over a wide range of illumination intensities and in complete darkness. Luckiesh & Moss (1938) in very carefully controlled experiments found that average blink rate increased with time from 20 to 30 per minute when reading for one hour periods. If the size of the type was reduced, the average rate increased. A similar increase was found when 0.5 dioptre lenses were introduced. These figures were obtained as average values over 81 subjects. Other work by McFarland etal (1942) failed to show any consistency of results. When Bartley studied fixation fatigue (4.2.4.) he abandoned blink rate as a useful measure.

In the study reported in this thesis a preliminary trial was carried out with subjects viewing a film which had short blank lengths at 100 ft. intervals intended to facilitate phoria measurements (4.2.4.) without having to stop the projector. On monitoring the blink rate of subjects using a biocular magnifier it was found that their normal blink rate dropped to very low values during the time they were watching the film and rose to high values during these rest periods.

It was reckoned from this that the blinking action was no longer completely involuntary, and was therefore abandoned as a measure of discomfort for visual tasks having an interruption sequence. Subsequent experience suggests that interrupted tasks may not relate very well to normal use (Chap.6, Experiment 2). As a non-interfering method of monitoring an activity of the subject, blink rate measurement should not be completely ruled out.

Although subjects with eye strain often complain of hot burning eyes, it is difficult to see how this or their state of lacrimination may be measured with any accuracy.

4.2.2. Pupilary Behaviour

Measurements of pupil diameter on office workers by Luckiesh and Moss (1933) showed that this increased between morning and late afternoon. The study was done on nine subjects over 22 days, and the mean increase was 6.3% on diameter with a probable error of 1%. However, individual subjects showed variations on this figure of -1.8% to +17%. As the measurements require very good adaptation to a consistent level of illumination, the time for each one must be some minutes. It would seem unlikely that this method will yield usable results for subjects using magnifiers for periods much shorter than an eight hour day.

A different sort of experiment was carried out by Bartley (1942) in an attempt to deliberately fatigue the sphinctor and dilator muscles which control the diameter. This was done by a flashing light stimulus of variable frequency. At one flash per four seconds the pupil response could follow the changing illumination and no discomfort was experienced. As the frequency was increased, most subjects reported discomfort at 1 - 2 flashes per second. Bartley found that at this frequency the pupil was failing to respond completely or accurately to the stimulus. At 6 flashes per second the pupil was unable to respond at all, and the subjects reported no discomfort, although the flashes could be clearly seen.

This pattern of discomfort lends credence to the idea that strain occurs when the visual system is trying but failing to perform satisfactorily. In this case Bartley relates the discomfort to conflict between the two muscles relating to contraction and dilation of the pupil.

Halstead (1941) found that when these muscles were immobilised by drugs the discomfort with the middle rate flashes did not occur. This places the fatigue with the muscular actions rather than the sensory and nervous control of them.

4.2.3. Accommodation & Refractive Error

Although many cases of eye strain have been successfully treated by the provision of correcting lenses for ametropia, it has proved extremely difficult to cause fatigue of the ciliary muscle experimentally. Donders in 1864 first discussed accommodative asthenopia as a considerable factor in the incidence of eye strain. Duke-Elder (1949b) lists three types of dynamic failing:-

(1) Insufficient accommodation (sub-normal)

(2) Ill-sustained accommodation (failure to maintain a good level)

(3) Inertia of accommodation.

Insufficiency of accommodation has been measured from time to time, but the others only rarely, The simple measurement of the near point (nearest object location for distinct vision) has been measured before and after work and a deterioration found, but other tests have shown an improvement. Ocular ergographs which alternately bring an object towards and away from an observer have been used, but with mainly inconsistent results. Dubois-Poulsen (1969) remarks that very short relaxation from the task entirely relieves the symptoms. In attempting to measure the inertia of accommodation the same author provided reading material alternating between locations 5 metres apart. Equal apparent size was maintained and the shortest time of alternation was found for reading to continue. This lengthens considerably after the subjects had spent some time on an ergograph. The author notes that not all workers are in agreement with these results. Berens & Stark (1932) reported a study of 195 subjects in which 30% improved, 30% deteriorated and 40% exhibited no change in their near point. They used a card with small letters in an ergographic manner but the excursion was from 3D to within the near point.

Later Berens & Sells (1944) did further work on patients attending their clinic with complaints of ocular fatigue or other symptoms of asthenopia. This selection of subjects limits the applicability of their results to the general population. However, they were able to show that after 30 minutes on an ergographic task the mean near point of their 57 subjects had increased. However, the differences found were about one third the standard deviation of the measured values and so such a test of fatigue where the task comprises different magnifiers is unlikely to be able to discriminate between them .

A lot of the information supporting muscle fatigue as a basis for eye strain really arises from clinical experience of patients who suffer this disability. Astigmatism is known to be a source of visual fatigue complaints in as much a the correction of even quite small amounts is found to relieve the condition. Presbyopia is regarded as a major source and in particular the early stages of this. Later when the patient accepts the condition and no longer tries to overcome it, the symptoms disappear.

This point about acceptance or non-acceptance by a subject of his visual performance seems to relate back to Duke-Elder's definition of eye strain as the striving to improve clarity by ineffectual adjustment. The accommodation of the visual system in focussing for different distances has a basic similarity to an observer using a modern example of night-viewing equipment. The large aperture objective lenses required by passive image intensifier systems means that the depth of focus effect may be felt at distances up to 200 yards or more. Members of Pilkington P.E. staff engaged in demonstrations of such equipment report informally that users tend to fall into two classes:-

(1) Those who focus up the system for a given distance or on a star, and then leave it alone, and

(2) Those who seem constantly to be adjusting it.

These comments apply particularly to people having only slight experience of this type of equipment.

Also important from a fatigue aspect is the subjective appearance of the scene in such equipment where the magnifier power is commonly such that the limiting resolution of the intensifier is of lower spatial frequency than the aided eye. Thus, the scene appears blurred. As discussed in Chapter 3, the mechanism of accommodation is generally accepted as being a servo-controlled system with the retinal blur as a major if not the only error signal. The apparently low screen response means that the accommodative response can never reduce its error signals to the value to which it is accustomed. Essentially, the system is tending towards open loop with a continuously high error signal. If such a system is liable to fatigue there does not seem to be a better way of causing it short of the ergographic methods described earlier. If the scene to be observed has a field curvature effect so that different parts of it require different accommodative responses, a search of the scene becomes an ergographic task. The presence of astigmatism can only exacerbate the situation.

Accommodation measuring equipment in the form of infra-red optometers has been available for many years, and could be used to monitor a subject using a magnifier. However, no study of accommodative fatigue with objective accommodation measurement is known to the writer.

The possibility that subjects can block or reduce the sensory error signal by 'accepting' in some way the limitations of the equipment, is perhaps very likely. As in the cases of presbyopia, described by Dubois-Poulsen, this acceptance should lead to a diminution of fatigue symptoms or to an apparent learning effect while using magnifiers.

4.2.4 Vergence and Pointing Error

Difficulty in performing eye movements often produces fatigue, or to put it more cautiously, patients complaining of visual fatigue are often found to have some limitations in this oculo-motor function. Although the most apparent of these is heterotropia where one eye fails, turning in some other direction, and the image from that eye is suppressed by the brain, this suppression, if complete, results in monocular vision, and in general, an absence of fatigue. A much more common condition is where the pointing directions of the eyes at rest are different from those required in use, and muscular effort has to be expended to give fusion.

The rest directions are determined by disassociating the eyes, that is one eye looks at a scene which is completely different to that viewed by the other eye. The relative pointing of the eyes now has little significant effect on what the subject sees, and the eyes are considered to adopt an orientation relative to each other for which least effort is required from their extrinsic muscles. The difference between the relative convergence of the eyes when dis-associated, and that when fused binocular vision is obtained, called heterophoria, is commonly measured at distant vision conditions (over 6 metres) and near vision conditions, 0.33 metres. Where the eyes converge at rest to more than the necessary value this is called esophoria and where less, exophoria. For near vision conditions, exophoria is rather more common, while esophoria tends to be associated more with eye strain.

The rest directions may be different in the vertical orientation as well as in the plane of the eyes, and this is referred to as right or left hyperphoria, depending on which eye is uppermost. Difference between rest and use rotation of the eyes is called cyclo-phoria. This condition occurs infrequently, and then usually in association with appreciable degrees of horizontal or vertical inbalance. The visual discomfort commonly accompanying this condition is usually relieved when these other phorias are corrected.

It is possible by placing prisms in front of the eyes to match the required pointing of the eyes with the dis-associated pointing for any given viewing distance. These are described in terms of whether their bases are "in" (towards the nose) or "out" (or up or down) and their deviating power in terms of "prism dioptres" (cms shift at one metre distance). "Base-in" prisms in front of the eyes mean that they need not converge to the normal extent for a given viewing distance. When correcting refractive error, the lenses prescribed by opticians can also be decentred so that they contain effective prisms. Relief from eye strain symptoms can often be obtained by matching, at least partially, the required pointing with the phoria of the patient. In the case of high esophoria the provision of base-out prisms should ease eye strain symptoms, but often this improvement is short-lived and the symptoms return as the deviation increases. The practice of orthoptics usually tries to exercise the muscles and train the patient in the use of his eyes.

Mayou (1968) reviewing this field, maintains that more than defects of muscle balance are involved in these cases. She points out that orthoptic treatment succeeds in some cases, and fails to give more than temporary relief in others, not withstanding that the dis-associated phoria as measured is virtually unchanged.

This may be that the rest position of the eyes is not necessarily related to any conflict in the motor mechanisms when the eyes are in use. Hofman and Bielschowsky (1900) reported many years ago that pointing inaccuracies occurred with eyes which were apparently achieving fusion. This was demonstrated by providing the eyes with separate pages of print which were identical except for one having a short vertical line in the centre, while the other had a short horizontal scale. Although subjects achieved single vision with the print, it was found that the line intercepted the scale at differing places.

An extensive study of this was made by Ogle (1949) who called it "fixation disparity" and found it to be a commonly occurring phenomenon related to the ocular pointing mechanism making use of Panum's fusional areas to relax its precision. He found, however, in measurements on over 200 subjects that the dis-associated phoria exhibited was virtually independent of the fixation disparity. Ogle and co-workers have not related fixation disparity to eye strain to any great extent, but Brock (1961) maintains that the rest position of the eyes is far less likely to reveal causes of eye strain than the fixation disparity.

He claims that the inaccuracies of the pre-setting action of the eyes determine the fusion compulsion necessary to achieve single vision. For clinical use he designed a test in which the small area of dis-associated vision (the line and scale) was extended from the 2^{o} for Ogle to about 30^{o} - 40^{o}. This means that his measurements are somewhere between the extremes of associated and dis-associated vision, and as such are not directly relatable to either values. His claim that these relate more to eye strain is presented forcefully, although the basis is much more that of clinical experience rather than controlled research.

These two concepts of associated and dis-associated pointing error can both be defended as relating to eye-strain symptoms in patients. When the process of generating eye strain by introducing pointing error is considered, very little successful work has been done. In fact, Carter (1965) reported experiments carried out some years earlier where subjects were selected as having normal binocular vision (good sensory fusion) with no significant visual discomfort. Heterophorias on nine subjects and fixation disparities on thirteen subjects were measured before and after placing base-in and base-out prisms before their eyes and 15 minutes later during which time the prisms had been worn continuously. In almost every case the heterophoria, although showing a large change to begin with, at the end of the quarter hour returned to about the same value as before the test. The experiment was carried out with various prism -dioptre values from 10 base-in to 32 base-out divided between the eyes.

On removal of the largest base-out prism, only one subject was able to obtain motor fusion immediately. The other 12 were esotropic with diplopia for periods of two minutes up to four hours.

Longer periods of wearing the prisms obtained similar results. Throughout the experiment there were only a few reports of visual discomfort. There was considerable indication that the adaptation phenomenon was dependent on sensory fusion. The subjects who exhibited esotropia following the removal of base-out prisms were slow to recover single vision. If this effect were induced before sleep it was there on waking eight hours later.

Against these reports of adaptability without discomfort by the extra-ocular muscles, there must be placed two studies which did generate some visual stress. The earlier of these comprised the apparently simple task of fixating to a point <u>between</u> two fixation points. These were two white discs in an otherwise dark field.

Bartley (1942) reports that subjects found this task exceedingly difficult. Eye movements, although ordinarily voluntary, under these conditions became almost uncontrollable. All the observers could do was to avoid going outside of the black area and reaching the discs. It was found that over five minute periods discomfort and irritation developed, giving rise to fluttering of the eyelids, blinking and postural shifts of the body. Bartley maintains that these effects are due to the conflict in the reciprocal innervation of the extrinsic muscles.

In studies of the visual suitability of head-up displays Gold (1970,1972) found that when these superimposed a display on the outside world with vergence errors between the eyes, visual discomfort was experienced by the pilots who were used as subjects. The experimental arrangement comprised a telecentric viewing which presented images from a cathode ray tube to each eye alternately but well above flicker fusion. This allows binocular disparities to be generated electronically by switching the CRT display into different locations as each eye is exposed.

At the same time a background scene could be seen by the subjects upon which the CRT information was superimposed. After a 15 second view of a given binocular disparity subjects were asked to rate his level of visual comfort in one of the following categories.

CATEGORY	VISUAL COMFORT LEVEL
1	Excellent
2	Comfortable, short of Excellent
3	Mildly uncomfortable
4	Severely uncomfortable
5	Doubling less than 50% of the time
6	Doubling more than 50% of the time

Three subjects were used in the first series of tests and six in the second but unfortunately only the former contained measurements made without a structured background. This represents the case where a subject is looking into a magnifier without any other stimuli against which to compare his vision. Gold found that horizontal disparities of 9 minutes of arc and 18 minutes (convergence) would reduce the reported comfort levels to 2 & 3 respectively when the outside world view was present. When a plain background was used these increased significantly to over 37 minutes and over 69 minutes respectively.

Thus, again it is seen that the eyes are much more susceptable to stress when there is a conflict in the visual scene.

4.2.5. The Triad Response

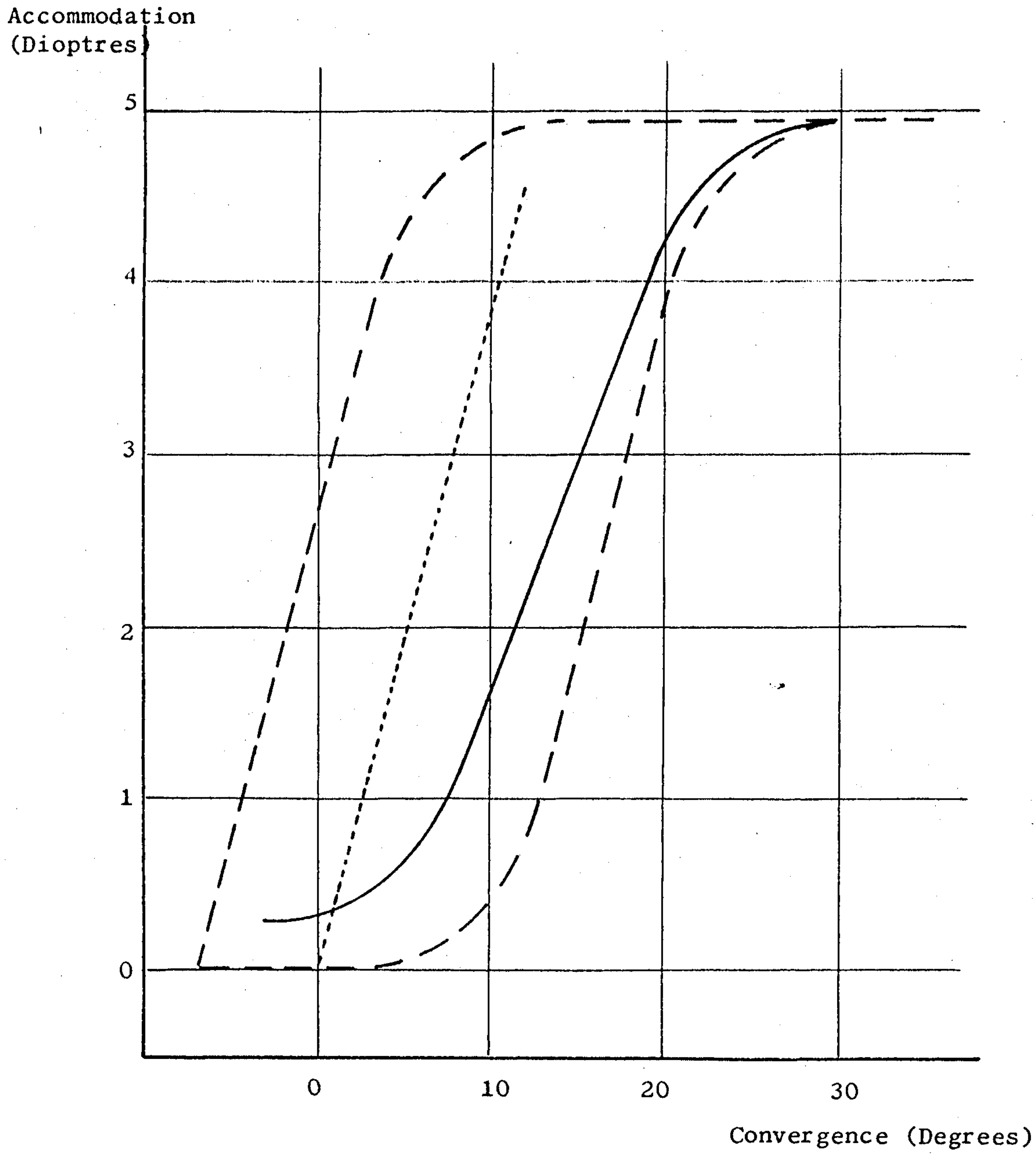
As this term comprises the related muscular actions of convergence, accommodation and pupillary response, it is clear that fatigue of this has been partially covered already, particularly in the experiments of Carter where the prisms worn changed the convergence and not the accommodative situation. However, the relationship between accommodation and convergence, although abnormal, was at least fixed for the period of the test.

It has been shown that with biocular magnifiers the convergence surface may be different from the accommodation surfaces such that the stress on the triad response may vary as different field points are fixated. Although the extent of a patient's fusional reserves are generally measured by an ophthalmic optician, there seems to be no general data available on average values over the normal vision population. Balsam & Fry (1959) showed a general diagram (Fig. 19), which indicates the acceptable range of variation and clinical practice usually restricts any effects due to spectacles to the central third of this.

This diagram can be redrawn in magnifier co-ordinates (Fig.20) which allow an appreciation of the relatively large variations accepted in ophthalmic practice. The scales have been made similar so that a 'reality line' can be drawn. It is then seen that the phoria line is removed from this line which lies near the centre of the single vision envelope.

FIG.19 CONVERGENCE / ACCOMMODATION RELATIONSHIP

after BALSAM & FRY (1959)

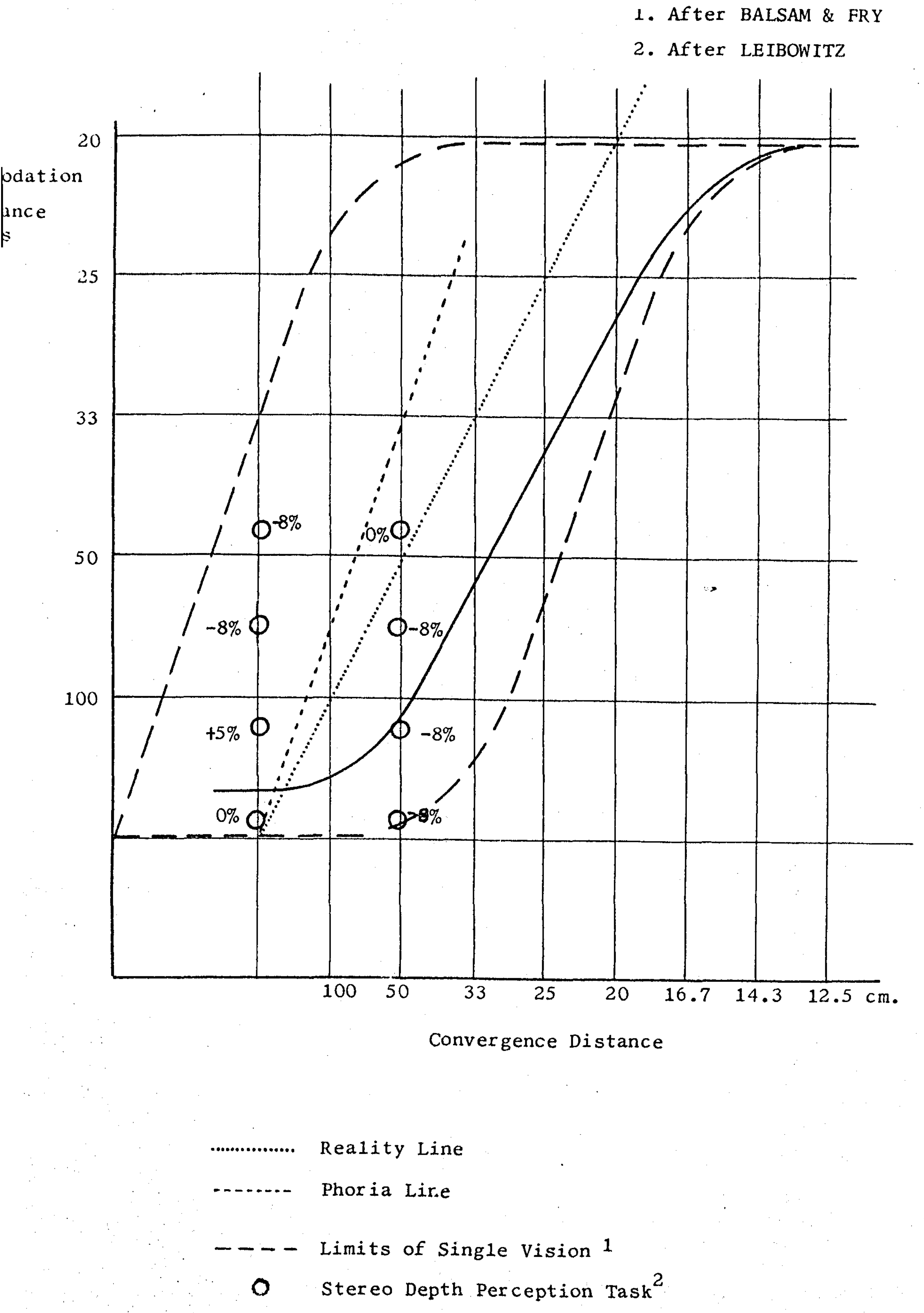


-------- Phoria Line

———— Convergence Accommodation

— — — — Envelope of Relative Convergence Curves for single Vision

FIG. 20 BINOCULAR PARALLAX PARAMETERS



It might be suggested that if a magnifier gave a visual parallax aberration which required an accommodation and convergence which lay within the dotted envelope all will be well.

Several factors militate against this. For a start, the locus of the envelope is an informed estimate rather than the result of many investigations and variations between observers are considerable. Secondly, we do not know the contours of acceptability within the envelope. Leibowitz et.al. (1971) made measurements on a difficult stereo depth perception task at various accommodation and convergence values. Although most results off the reality line were worse than those on it, some incompatible viewing conditions showed an improved performance. Thus, the possibility arises that better performance at other visual tasks may occur at points other than on the reality line. However, if the area of parallax error is shifted from this it would probably result in a higher incidence of discomfort over a representative group of users.

As spherical aberration producing parallax error is difficult to control over the fast lenses which constitute high-power magnifiers it is essential that suitable limits of it should be determined. Whether these limits will be denoted by an maximum allowed drop in performance or the onset of visual discomfort in the users is a major concern of the experimental part of this study.

4.3 Sensory Fatigue Tests

Although the largest fatiguing effect of visual aberrations in biocular magnifiers is likely to be on the muscular mechanisms of the eye, consideration should also be given to sensory fatigue, either as suitable monitor of eye strain, or as being induced by some action of the magnifier.

Bartley & Chute (1947) lists threshold fatigue, fixation-disappearance, colour fatigue, adaptation and flicker detection under this heading. Only the first and last of these is not directly related to a very particular visual activity. McFarland, et.al(1942) investigated a possible deterioration in threshold response. Although they were able to relate this to general fatigue, there is no evidence that the reduction they found was linked with the performance of a visual task. The work by Spencer & Cohen (1928) on visual threshold and fatigue obtained a correlation of 0.78 between a person's threshold and how long he had slept the night before. Again, this is not directly related to any visual fatigue using optical instruments.

In studying the effects of driving fatigue, Lee & Hammond (1942) measured the critical fusion frequency of the eye and found that this was depressed following exposure of the eye to a flickering light. The exposure periods were five minutes and a reduction in the c.f.f. of about 3 cycles per second was noted over 5 subjects. After two or three exposures the original value was obtained after recovery times of up to one hour. They applied this measurement to lorry drivers finding a slight, but consistent tendency towards lower critical frequency with increasing hours of driving.

These reductions were in the order of 2 cycles per second after five or ten hours of driving. With some groups an improvement was found after ten hours. Arnold, Busch & Wachholder (1953) were able to show three stages of fatigue - an increase in c.f.f. then a reduction, and finally a new increase by compensation. Although such a test might be convenient to do, Dubois-Poulsen (1969) holds little hope for this from the studies reported claiming that the effects of sympathetic stimulation, secretion of adrenalin and mental concentration influence the figures to too great an extent.

4.4 Other Fatigue Tests & Symptoms

Tests for fatigue based upon concepts in psychology are common, but usually relate to general fatigue rather than specifically visual discomfort. Although the use of biocular magnifiers for observing displays over many hours will obviously fatigue the users, general fatigue tests are so various in their results that they require sizeable groups of subjects for statistical analysis. The use of these tests to differentiate between alternative optical design solutions to the magnifier design problem cannot be considered likely to produce valuable results.

One test related to visual perception uses the fluctuation of optical illusions employing reversible perspective. Tussing (1941) found that the open cube illusion gave an average fluctuation of 19.5 per minute before a general fatigue exercise. This involved pulling a machine about 500 feet involving the expenditure of about 0.36 horse power. Afterwards the rate of fluctuation had increased to 28.8 per minute. Tussing concludes however, that variations in these results render the device inadequate as a fatigue index for individual prediction.

In this study of visual fatigue caused by biocular magnifiers, such a test may be useful in determining the effects of apparent distortion, not only by making before and after measurements, but by applying the tests via the magnifier.

Heaton (1967) lists the symptoms of eye strain with the headache as the commonest. If an objective measurement of ache intensity was available, or even a subjective system allowing inter-subject comparison, its value would be enormous. The nearest measurements to this are the various electrical potentials obtainable from electrodes on the scalp. Lippold (1970) has found that alpha rhythms are related to oculo-motor activity. The possibility exists that the strain of responding to non-normal stimuli may be reflected in the strength of the rhythm. As yet research in this field is very exploratory and no generally supported conclusions have been found to justify its immediate application to the use of magnifiers, although its study under abnormal conditions of vision may show useful relationships for future applications.

4.5 Fatigue & Visual Performance

The effects described in the previous sections often derive from experiments where the actual visual performance of the subjects under the strain conditions is not measured. At other times the work output is confused with the fatigue and measured solely as an index. Very little work exists to link the visual performance ideas described in Chapter 3 with the work output values used in the experimental part of this study.

The situation of a person operating a machine or driving a vehicle using information presented via a binocular magnifier may be investigated from a Human Factors standpoint. While such an approach is valuable in determining the conditions for best performance it is not sufficient when an understanding is required as to why performance changes occur.

The purpose of this study is to link visual aberrations with total visual performance using ocular adjustments as the connection. Whether these adjustments are normal or abnormal and whether they help or hinder the visual performance are the pertinent questions.

A conceptual framework is required on which to base a discussion of possible effects. Unfortunately the descriptive terms used in fatigue studies often prejudge the issue by their very meaning and it is difficult to avoid this. However, in addition to the proposed definitions of Visual Aberrations and Visual Response contained in the previous chapters the following scheme is suggested.

Visual Discomfort	Subjective State of Eyes
Visual Discomfort Indicators	Lacrimation, Blink Rate, α-rhythm, etc.
Visual Impairment	Changes within sections of the visual apparatus affecting the ability to see :- Pointing error, Blurring, Phoria Shifts, etc.
Visual Impairment Indicators	Acuity Tests, CFF, Motor Response Times, Near Point Values.
Visual Compliance	Alteration of ranges or rest states of adjustments of visual apparatus.
Visual Task Performance	Work output values over periods of time.
Visual Performance	Seeing ability of eyes under specific conditions of discomfort and impairment.

The use of the word impairment tacitly assumes that the changes produced will be deleterious. If one could measure this quantitatively the possibility of obtaining a negative value must be accepted. On the other hand the term compliance denotes an improving action. Possibly negative compliance can occur. The immediate question is whether impairment and compliance are likely to be the same action in opposite directions.

Although this equivalence may, in subsequent work to this, be found to be valid, it seems to the writer that the impairment term may be related to the adoption of an incorrect adjustment. by the ocular apparatus; while the compliance term relates to the adoption of a new adjustment compared to those used in normal vision. Thus, impairment is the difference between the demands of a situation (such as a biocular magnifier) and the adopted ocular adjustment while compliance is the difference between the normal adjustments used by the eyes and the new adjustments adopted. In a simple one-dimensional case it may be that impairment reduces as compliance increases. However, as the visual system has a number of adjustments available to it, the likelihood is that future discussion and debate will require both concepts.

From the literature reviewed in this chapter it is obviously not possible to make specific predictions regarding the reaction of the visual system to a biocular magnifier. Although the normal observer can and will make adjustments to obtain the best vision possible he may experience visual discomfort if either the adjustments he makes do not give sufficiently clear vision or if conflicting stimuli to adjustment are present. From the other point of view it is reasonable to predict that subjects experiencing no eye strain during normal use will not experience any with biocular magnifiers provided their adjustments with the device give clear vision.

CHAPTER 5

EXPERIMENTAL WORK

5.1 Experiment Policy

Before the theoretical study reported in the previous chapters was complete, the experimental approach had to be decided so that equipment manufacture and in particular, visual task preparation could be put in hand. The lack of similar previous work was a difficulty only to be expected when the first high-power biocular magnifier was reported two weeks after the start of this study. The first magnifier of the series made by Pilkington P-E Ltd., with which the writer has been associated, was built approximately six months after the start of the stüdy.

As briefly indicated in section 1.3 of Chapter 1 a large number of aberrations and other criteria can influence the response of an observer to a given magnifier. Although the considerations of Chapters 2 and 3 help to indicate which criteria may be the more important these were not fully researched at the time when the experimental policy was being formulated. Their inherent complexity did suggest that experimental work on real magnifiers might be difficult to interpret. The alternative course is to simulate specific aberrations or criteria by the use of separate prisms or lenses in front of the eyes. Although more standard results and better guidance from previous work might be expected with this approach considerably more difficulty would then ~~ocurr~~ occur in applying the results to the magnifier case.

It was therefore decided that real magnifiers would be studied initially in the hope that results from these would demonstrate what visual discomfort effects and visual performance values were to be associated with differing magnifiers or whether differences between subjects would have a larger masking effect.

With this last consideration in mind it was recognisied that the visual task should not involve vigilance as this is prone to considerable variation not only between subjects but also with the same subject at different times. Although some relation between the visual comfort of a magnifier and the vigilance of the user might be expected, the initial interest must centre on his visual response. This rules out a task based on the 'detection' concept of Johnson (1958) referred to in Chapter 3 as this is very sensitive to vigilance. However, 'recognition' requires some training of the subjects and unless this is comprehensive a continuing learning effect may occur during the time each subject is being used. As different magnifiers must be presented in a sequence this could lead to a masking effect. The same situation occurs with an 'identification' task. Thus, the 'orientation' task was chosen even though this is less common in human factor studies.

Although a simple static task could be constructed in which small objects appeared in the subject's view through the magnifier, concern was felt that even well motivated subjects would not be able to maintain a steady level of attention for very long. In this hypothetical race between boredom and visual discomfort it was felt that the latter would require at the very least 20 minutes on each magnifier if the work reviewed in Chapter 4 was any guide. The search for an interesting task led to a simulation of the driving task for which many biocular magnifier designs are intended. In this the objects appear to approach the subject and so become easier to see. The moment at which he can indicate the orientation of the object is therefore related to the apparent spatial frequency and contrast at that moment although the accuracy of this is limited by the reaction time of the subject and his decision strategy. Whatever the visual task these inaccuracies remain when a total subject response is used.

Because such a taks simulates a possible use of the magnifiers it is reasonable to use these seeing times as a monitor of visual task performance. This must not be affected by any measurements of visual discomfort or visual impairment. Thus, these latter aspects must either be measured by tests of very short duration or restricted to 'before and after.'

It was felt initially that the measurement of any physiological effect would need more than two values if any change with time was to be examined in sufficient detail. If measurements were to be made during the task time of say 20 minutes their duration must be very small compared with this. A time of 15 to 20 seconds is a reasonable guess.

Of the possible visual impairment monitors reported in previous work most would take a longer time than 15 seconds to obtain two or three readings. Visual acuity, threshold or critical flicker frequency are not likely to yeild accurate values if rushed. Oculo-motor response times would be suitable but it is difficult to see how a subject can transfer from the magnifier under test to the monitoring equipment in the time allowed for the measurement. The possibility of making such measurement <u>via the magnifier</u> is very attractive but the wide variety of magnifiers investigated precluded such an approach in this study.

Other possible measurements include blink rate, pupil size, heterophoria, α-rhythms and fixation disparities. Although some initial measurements were done on blink rate it was rejected as a suitable parameter for this study due to doubts that it was completely involuntary (Chapter 4). Although α-rhythms were considered and discussed the general concensus of opinion was that results relatable to optical aberrations were very unlikely. Pupil size is very prone to extraneous influences and careful adaptation is required.

As the main interest lay in the stress on the triad response it was decided that a monitor of horizontal heterophoria would be a suitable test which could be located just below the magnifier. The subject could drop his eyes to this very quickly and obtain two or three readings in the time available. Being a dissociated test it would not introduce any fusion contours different from the magnifier and it could be applied at a viewing distance equal to the dioptre setting of the magnifiers in the test.

Although fixation disparity is claimed to have a closer connection with clinical eyestrain, this demands an associated test which would effectively interrupt the viewing of the scene through the magnifier. Against this must be set the clinical unreliability of near-point hetrophoria. However, in this case, the interest is in <u>changes</u> of the rest position with subjects having normal or corrected vision.

The remaining decision concerns an indicator of visual discomfort. Here it was acknowledged that no satisfactory test of visual fatigue or discomfort is known. For this initial study it was decided that a series of questions be asked of each subject after their period on each magnifier to ascertain their subjective state of vision. In later experiements this was augmented by a Visual Comfort Rating chart (after Gold (1970)). Subjects were also encouraged to comment on their vision during the trials but few did this.

The experimental equipment therefore comprises a visual task film and a system for viewing the film via various magnifiers, an electronic timing system on which subjects can indicate the orientation of objects on the film, and a Maddox wing or similar test for near heterophoria. The preparation of these is described in the following sections of this chapter, beginning with the experimental rig which carried all the components to form an observation station at which the subjects performed the visual task.

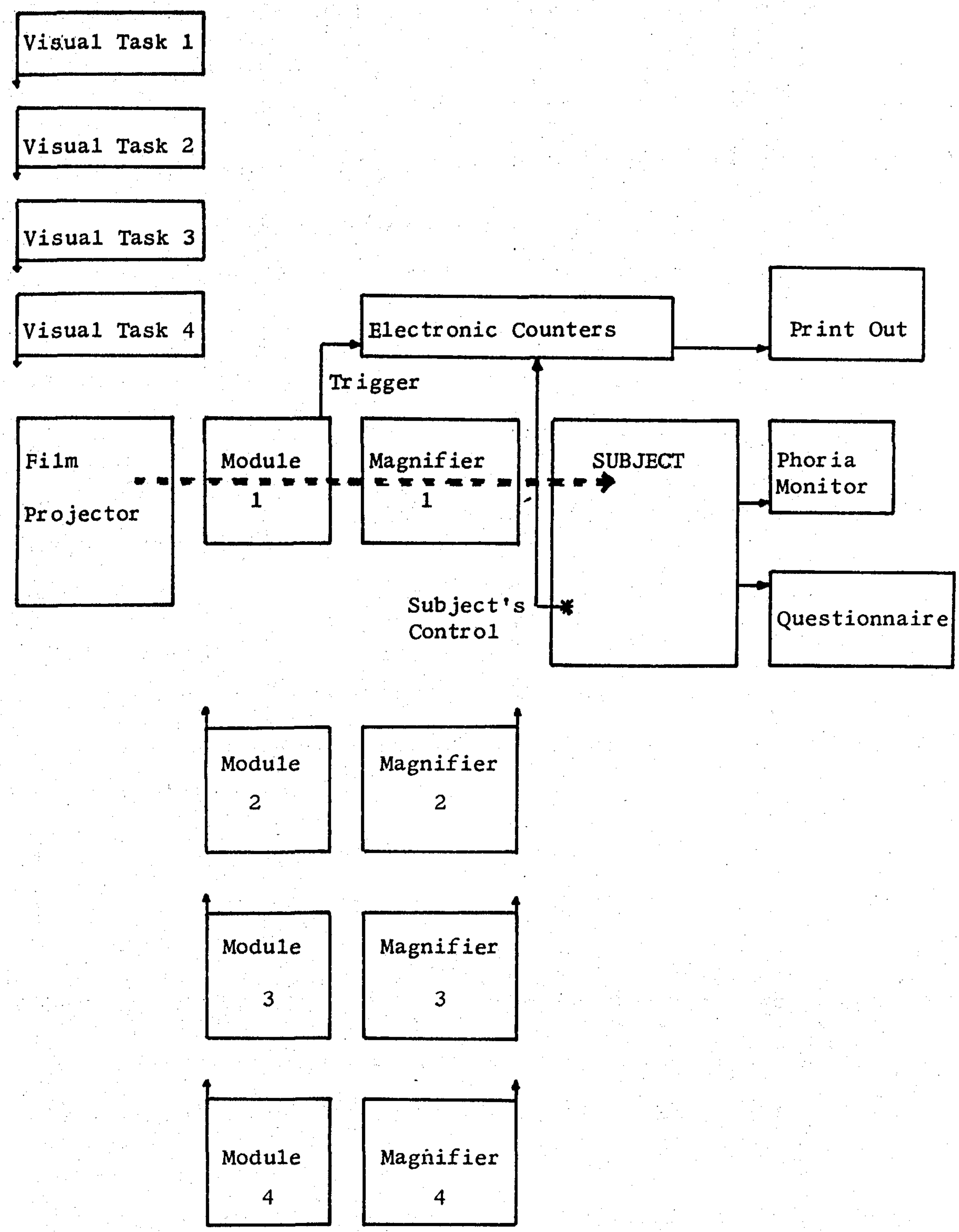
5.2 Observation Stations

During the course of this work two arrangements for supporting the component parts where utilised. The need is for a stable platform on which a 16mm film projector may be mounted. This must project a suitable image for the magnifier being studied. The subject must have a location from which to use the magnifier while sitting comfortably. A method by which the subject indicates the orientations of the objects that he sees must be conveniently available to him as must the test for muscular balance. As subjects will be used on different magnifiers it must be possible to alter the system relatively easily to accommodate the new magnifier. Thus, a block diagram of the systems is as given in Fig.21.

Obviously such a system depends on the range magnifiers chosen for investigation and the space requirements of the modules needed to give the magnifiers a suitable image. The decision to investigate real magnifiers was based on the need to come to grips with the general problem as early as possible. However, this was coupled with a fear that 'noise' on the results caused by subject differences, unstable motivation, etc. would mask small differences between magnifiers and therefore, as a first experiment, magnifiers with as widely differing properties as possible should be investigated.

The basic high-power magnifier developed at Pilkington P-E Ltd., has been described in Chapter 2. It provides a 50^{o} field of view from a 40mm format by virtue of a focal length of 43mms. At its dioptre setting of -2.5D it has a power of x5·6 approximately. Obviously, a similar field of view could be provided by a low-

FIG.21 BLOCK DIAGRAM OF EXPERIMENTAL ARRANGEMENT



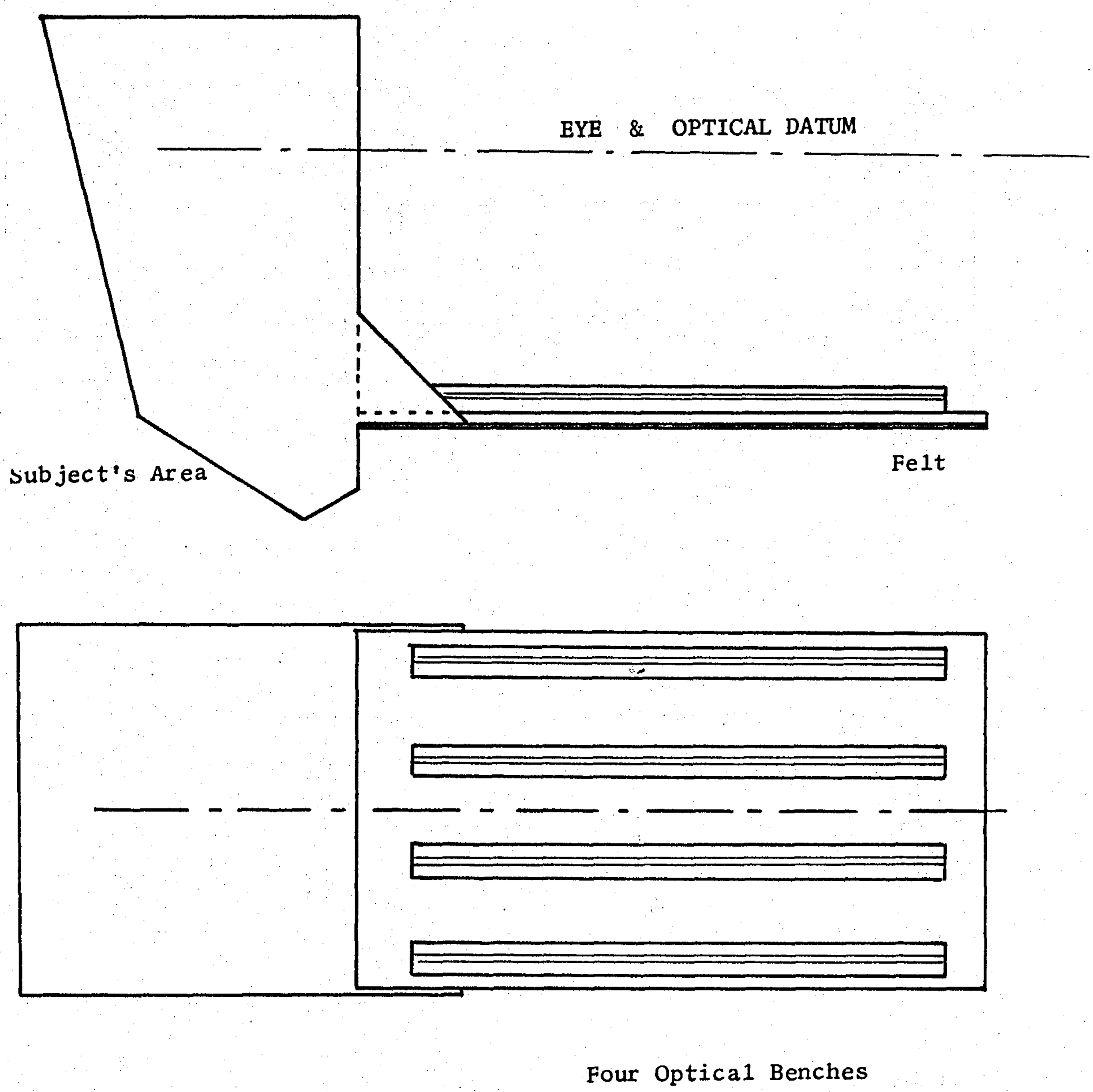
power magnifier looking at a larger format. Furthermore, a unity-powered magnifier could be defined for this dioptre setting by looking at a format of sufficient size 50cms from the eye through a piece of plano glass. This 'magnifier' together with the others is described in section 6 of this chapter.

With these considerations in mind and also the need for a portable system if subjects from other locations were to be used a simple system was constructed according to the drawings of Fig.22.

A simple two-part construction was adopted to form the base for the experimental arrangement. This comprised a 'half-cubicle' in which a subject could sit and from which hung a black cloth behind the subject so that no stray reflections would distract him. This cubicle could be hung on the end of a felt backed base which would be supported on an ordinary office desk or table. This base carried four one metre optical benches of triangular section, so that equipment could be located and replaced with a fair degree of precision.

It was decided that precision sufficient to ensure exact registration and focus on relocation of each magnifier arrangement would only be obtained at great expense. The initial means of overcoming this assumed that the light path carrying the visual task information to the screen in front of a specific magnifier could at some point be collimated. This would then form the junction between the fixed projection part of the system and the replaceable magnifier modules. A degree of inaccuracy in location would then not have a major effect on the quality and location of the image seen via the magnifiers. This approach was not possible with the full-size system as the

FIG. 22 OBSERVATION STATION - ONE



projection lens needed to be of wide-field if a reasonably compact station was to be obtained. No pair of lenses were commercially available to give this.

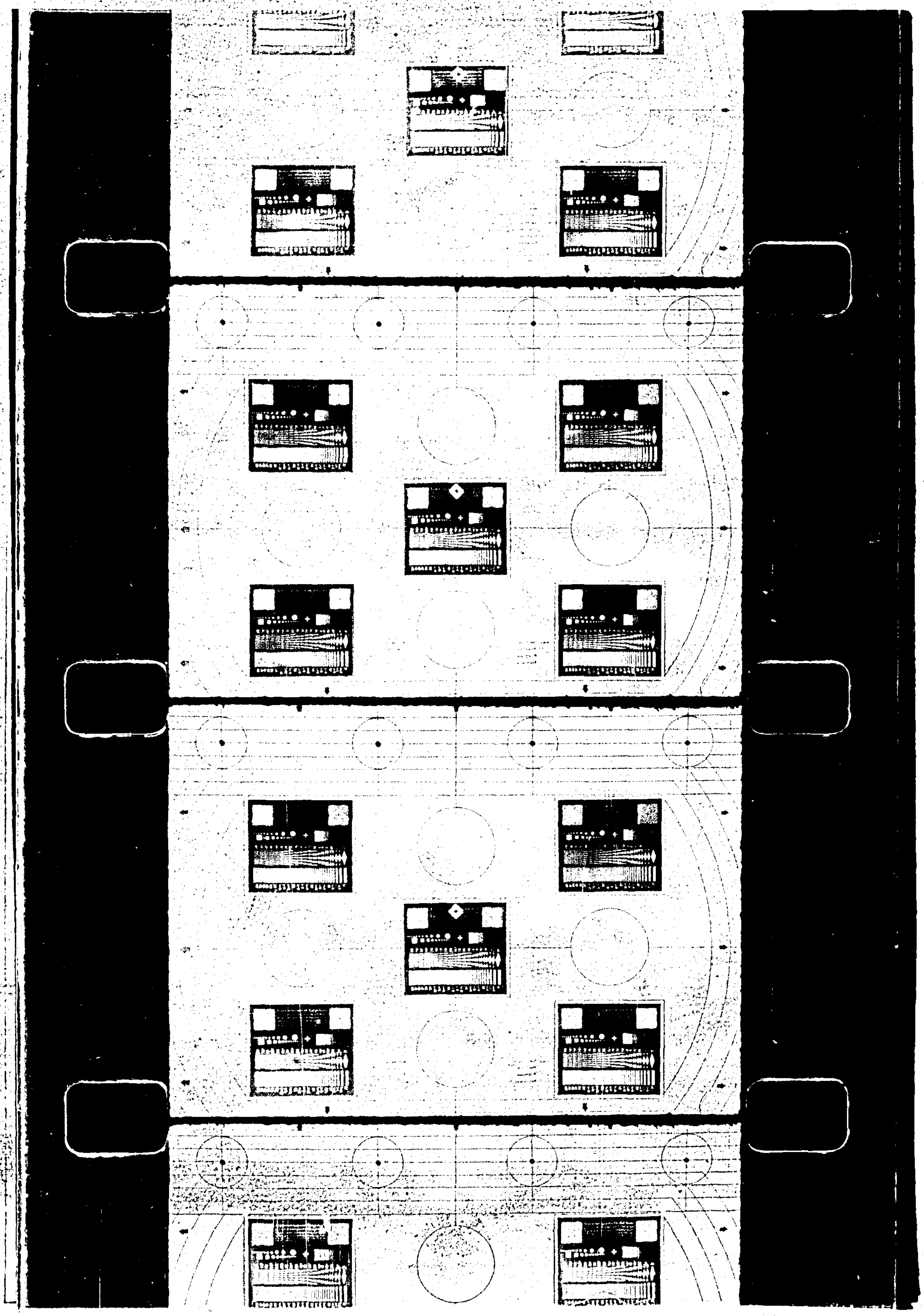
An alternative approach was adopted in that a lower precision system was utilised with finite conjugate beams and a registration film was prepared which allowed fine adjustments to be made relatively easily. The extra time for setting up following a re-arrangement of magnifiers was accepted as a necessary evil.

The opportunity was taken when designing the registration film to include frames from a standard photographic test chart - Fig.23. This allowed the system to be adjusted for lateral position and for longitudinal focus. It also allowed the overall resolution limits of each system to be monitored, although this function was not as precise as desirable. However, it did show up the major differences between the different systems and allow these to be reduced to relatively small values. The effects of any residual differences are considered in Section 6 of this chapter.

The use of 16mm film for the visual task is dictated by the need to obtain realism and maintain the interest of the subject as discussed earlier. This means a 16mm film projector must be built into the arrangement. In the first instance an old R.C.A. projector was obtained and early trials on this showed up problems of viewing film at 50° - the field of view of most magnifiers. It should be remembered that most 16mm film is viewed at a subtended angle of about 25° at the most - that is a 6 foot screen at 12/15 feet. A television set is commonly viewed at a subtended angle of $10 - 15^{\circ}$.

FIG 23 REGISTRATION

Registration Film



When viewed at 50^{o} subtended angle, that is 6 feet away from a 6 foot screen, any instability in the projection becomes overpowering. In a search for fatigue differences between magnifiers it is essential that the projection of the task does not conceal these. Thus film jitter and flicker must be reduced as much as possible. It was found that no commercially available projection has more than a three-bladed shutter, while technical film analysers are generally limited to 16 frames per second.

It was found that a large part of the projection jitter of 16mm film arises from the location accuracy of the sprocket holes in the film stock rather than in the projector. This is largely due to the photographic system which utilises one stock for the camera (the negative) and another for the projection (the print). The possibility of reversal film being used is unrealistic when film wear dictates a number of prints to cover the magnifiers of interest with sufficient subjects.

A further requirement of the projector was that it should be self-threading as the optical arrangement required supports and hardware very close to the projector lens which precluded the opening of the gate. A Bell & Howell projector was finally chosen.

With this projector a solution to the short-throw projection problem for the unity magnifier was available. A ½" efl, 50^{o} lens incorporating a 90^{o} bend was obtainable and this was purchased. Using this the 20" format was filled at maximum brightness as the lens had an aperture of F/1.4. The much smaller format of the other magnifiers (40mm & 87mm) precluded this lens being used as the conjugates required for this image size were well outside its range for good definition.
A further 2" efl projection lens was used for this. Although this

FIG 24 OBSERVATION STATION ONE WITH STOG MODULE

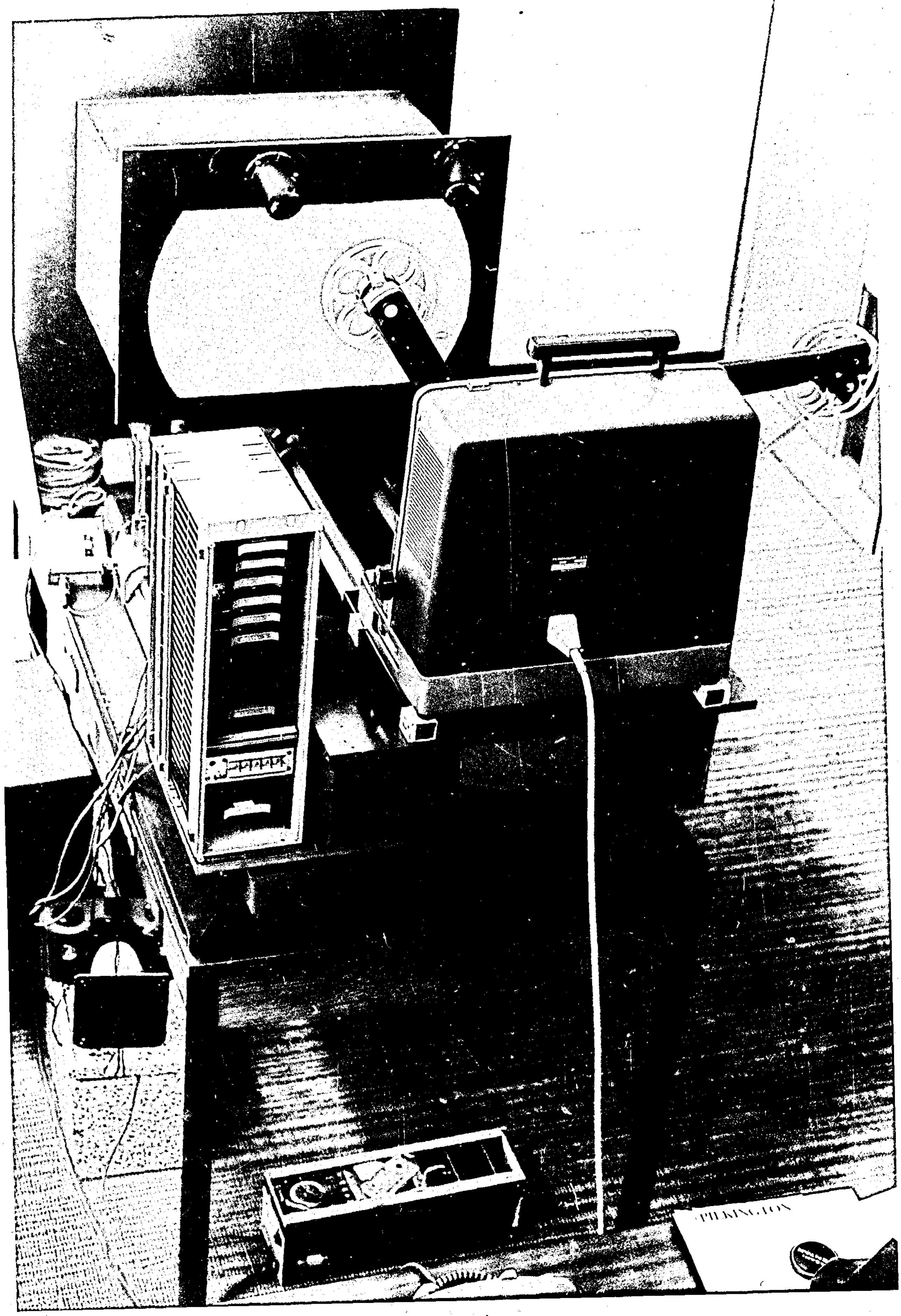


FIG 25 OBSERVATION STATION ONE WITH COP MODULE

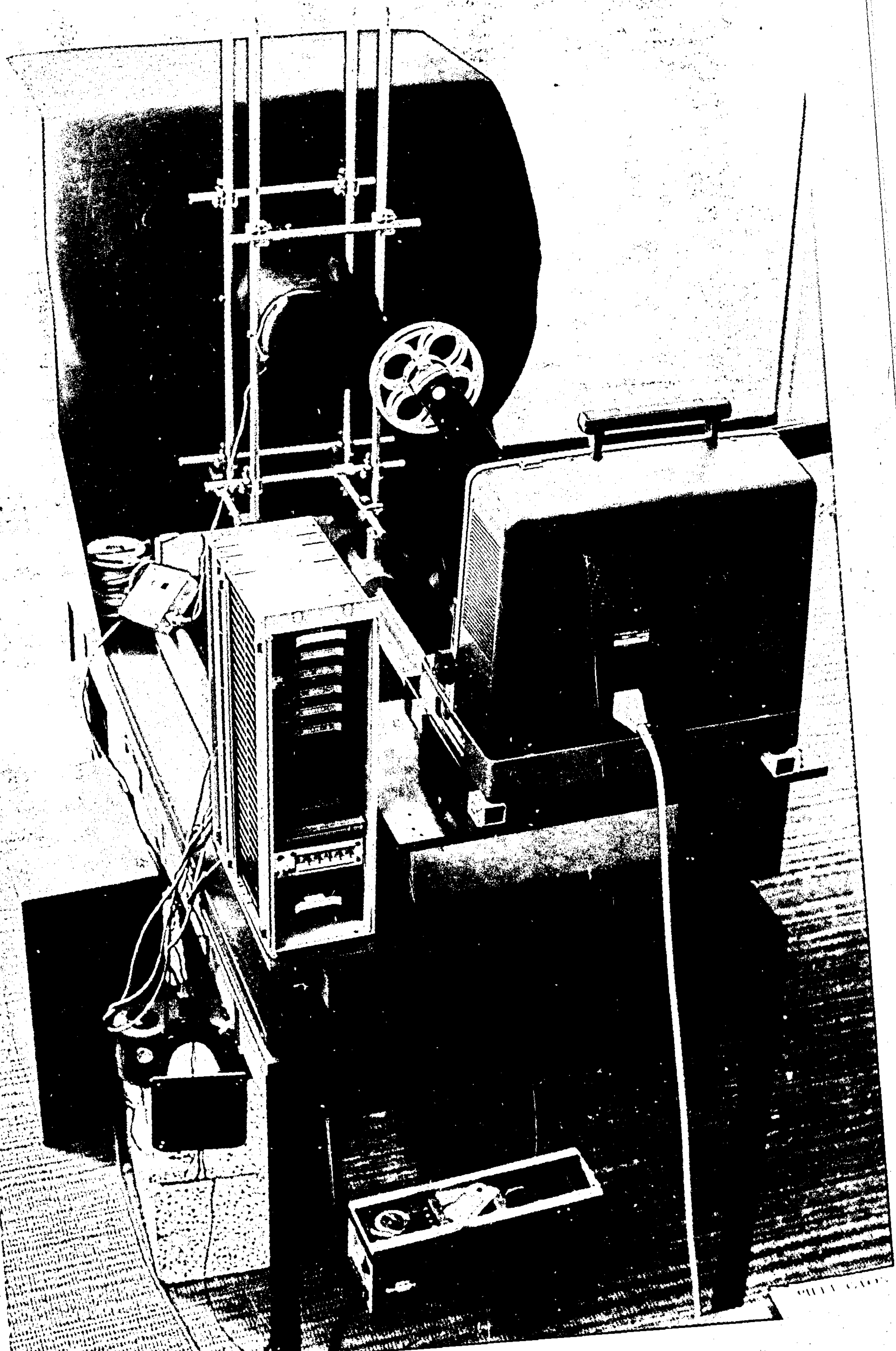
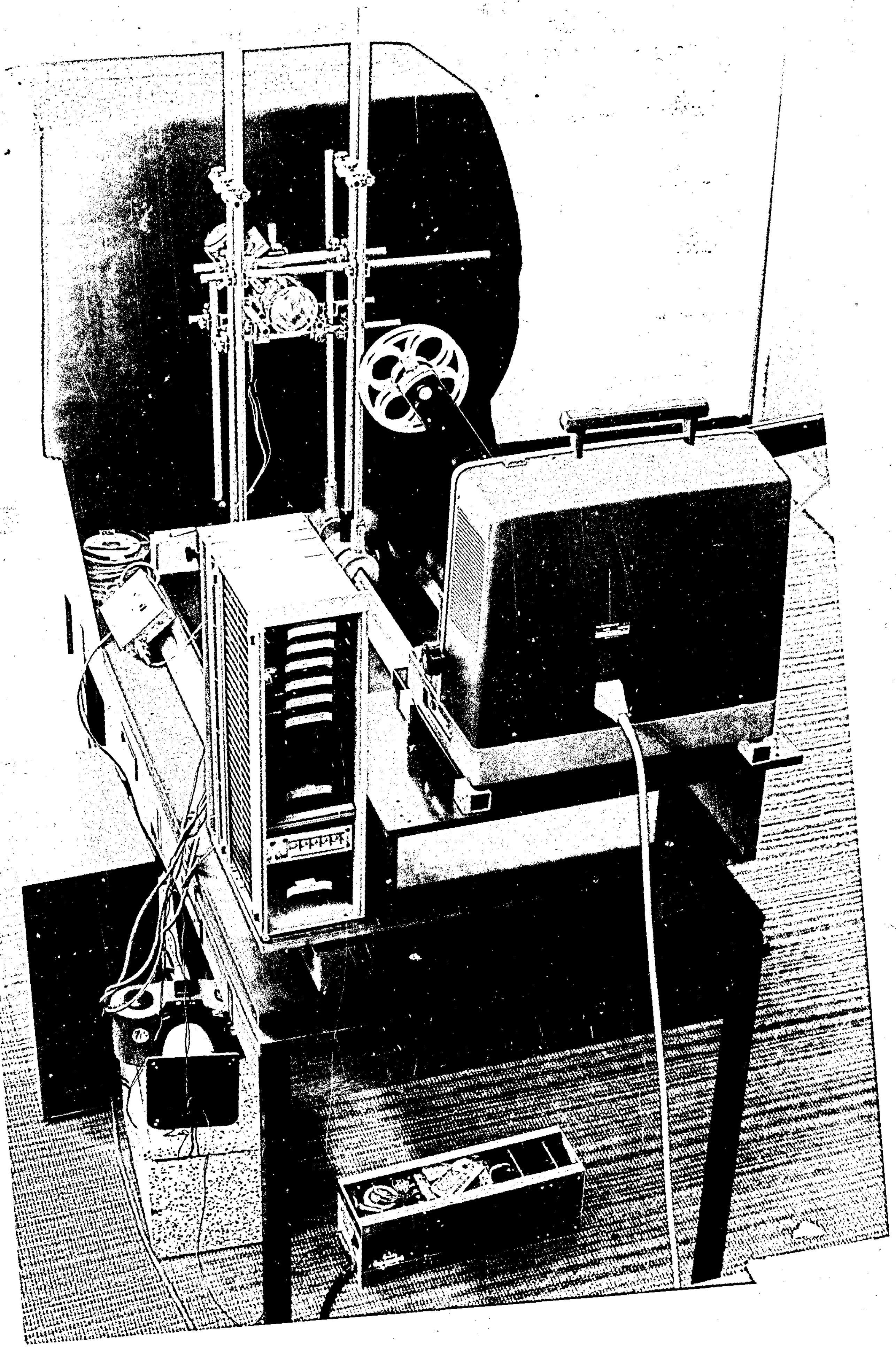


FIG 26 OBSERVATION STATION ONE WITH SLAB MODULE



could introduce spurious differences between magnifiers, precautions were taken as described in Section 6 of this Chapter.

Thus, the overall experimental system is as shown in Figs. 24,25 & 26. The light baffling has been removed for clarity in these pictures. The projector is carried on two optical benches and can slide to pre-determined locations for given magnifiers. Magnifier modules can be located so that the actual magnifier protrudes into the subject's area and can be used by him. The provision of the subject's controls and triggering system is considered in Section 4 of this chapter. The subject's area was not made totally light proof but the area behind the subject was draped with a black curtain so that no distracting reflections from the magnifier lenses would occur. An adjustable office armchair was used by the subjects who ranged from 5'4" to 6'7".

This station was used for EXPTS 1, 2 & 3. A modified station was built for subsequent experiments with a higher platform than that obtained from ordinary office tables. This station allowed better control of the ambient light level around the subject, which was still not completely dark but maintained constant throughout each trial. The design was much simplified by the use of only one type of magnifier. Thus, the projector only needed to be moved for cleaning. With the highest-powered magnifier the projection lens may be well stopped down while still providing more than sufficient light into the 40mm image format. The outer parts of the lens were then available to drive the triggering system and also provide a monitoring image which had a more critical focussing requirement which is assessed in Chapter 6, section 5. Views of this system are given in Fig.27 with curtain & masking removed as is the brow pad for centering the eyes.

FIG 27 OBSERVATION STATION TWO WITH SLAB MODULE

5.3 Visual Task Preparation

Progress on visual task films was very slow to begin with. Contrary to expectations, the films taken from moving road vehicles were subject to far too much vertical motion, so that the sighting of objects was very difficult and became very variable. In this study the visual task is not intended to tax the subject to any great extent. A task demanding a very high level of concentration from the subjects will show large variations between them and with the same subject at different times. The purpose of this study is to discover whether subjects see clearly and comfortably when using these magnifiers. Any task demanding concentration on the subject's part to follow film motion due to the suspension of the road vehicles carrying the camera is likely to show up only large differences between magnifiers.

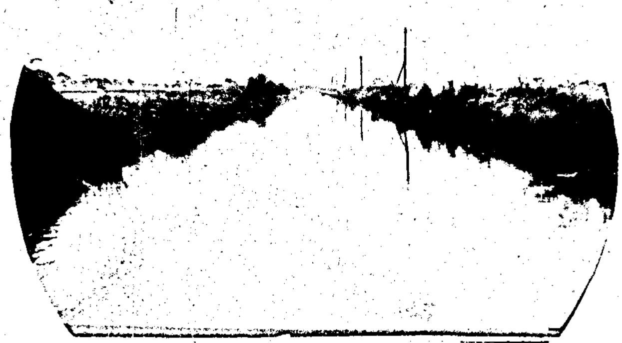
A series of films were taken from a variety of road vehicles ranging from a Mini with soft tyres to a Ford Executive. With all these a vertical motion of 3^{o} to 5^{o} was evident and rendered the films unacceptable. The 50^{o} field of view was too wide for any available optical means of image stabilisation. Other mechanical means were considered but it was felt that at the shorter ranges the vertical motion was contributing just as much to the image motion as the angular motion on the suspension for which these devices would compensate alone.

During these trials various object types and size had been used. It was found that objects of total dimension less than 20cm were not seen very often, even when filmed under high contrast conditions. Initially crosses and squares were used for objects and subjects were instructed to press the appropriate button when they could recognise which type of object was approaching them. However, a number of

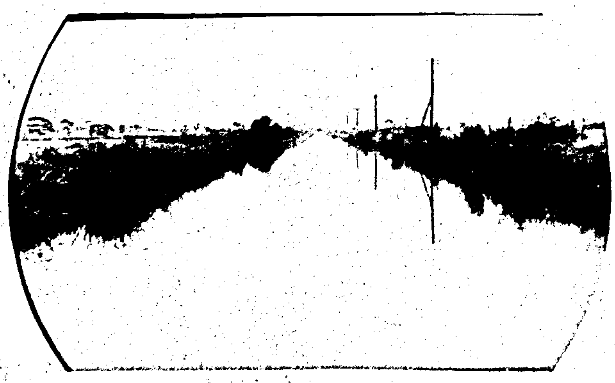
FIG 28A VISUAL TASK

Approach of Typical Object

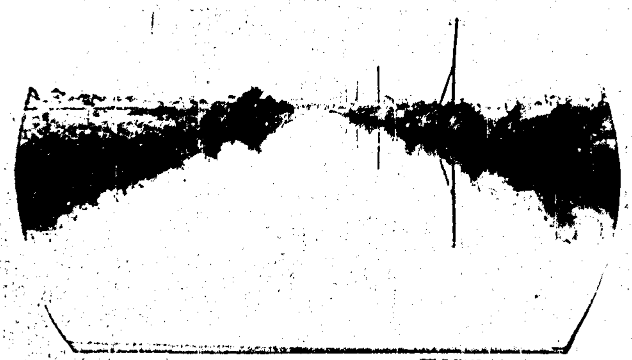
at 0.5 secs. before trigger



at 1.0 secs after trigger

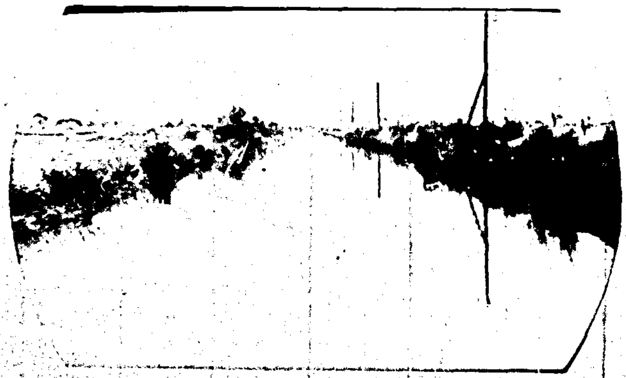


at 2.5 secs after trigger

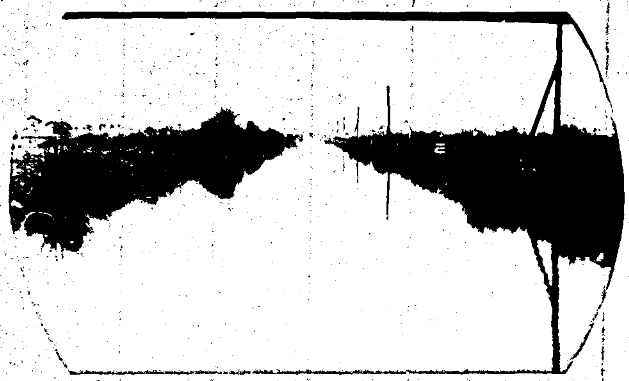


at 4.0 secs after trigger

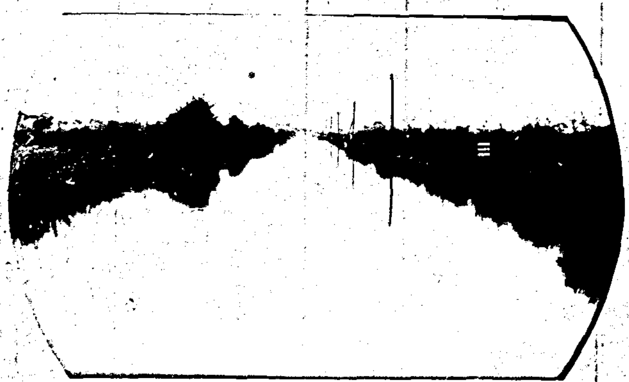
FIG 28B VISUAL TASK continued ....



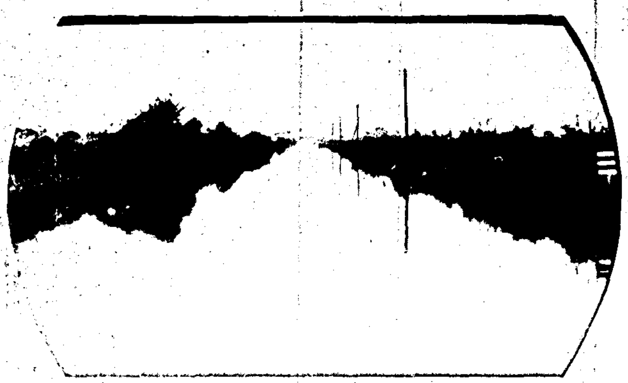
at 5.5 secs after trigger



at 7.0 secs after trigger

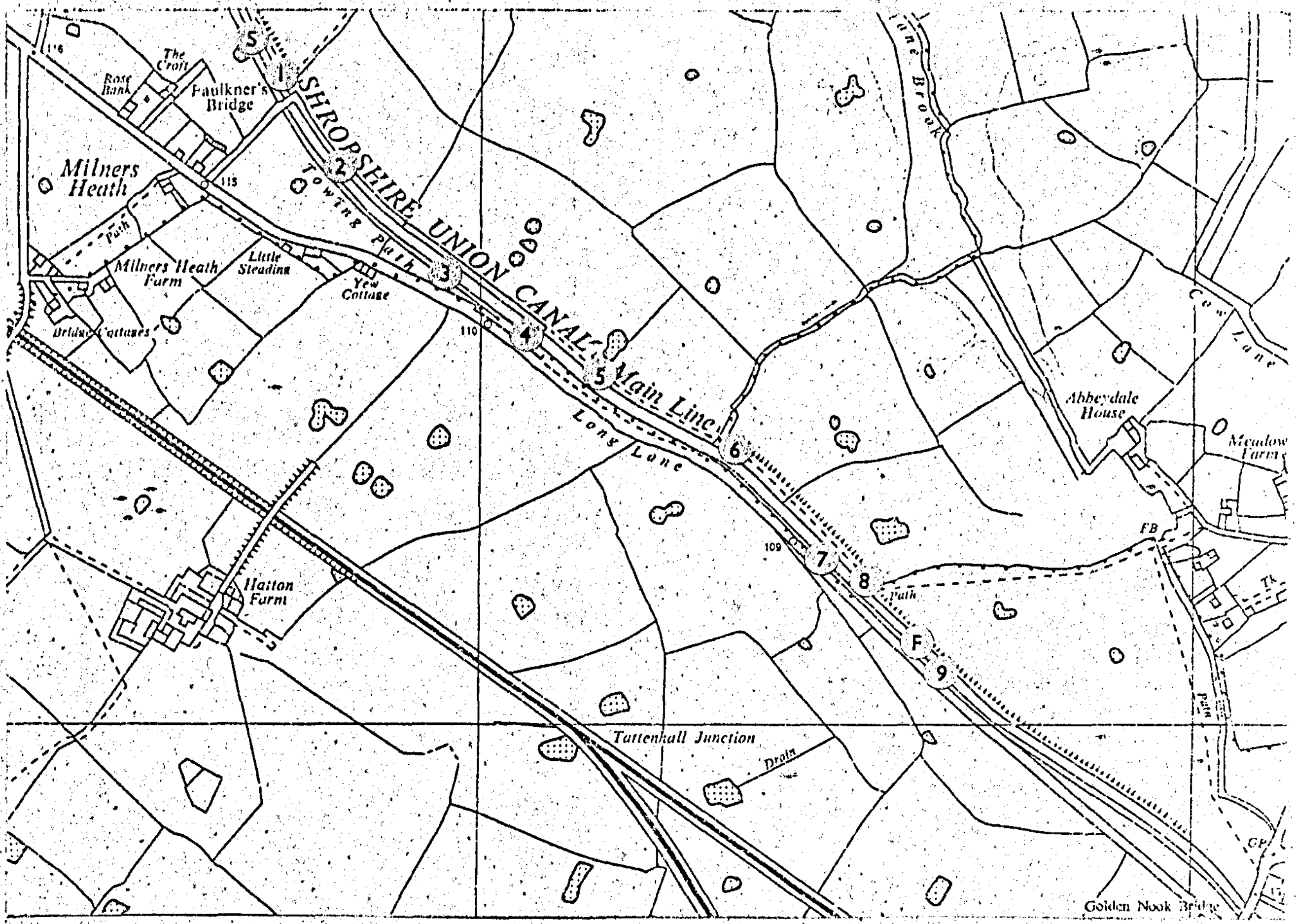


at 8.5 secs after trigger



at 10 secs after trigger

FIG. 29A LOCATION OF OBJECTS



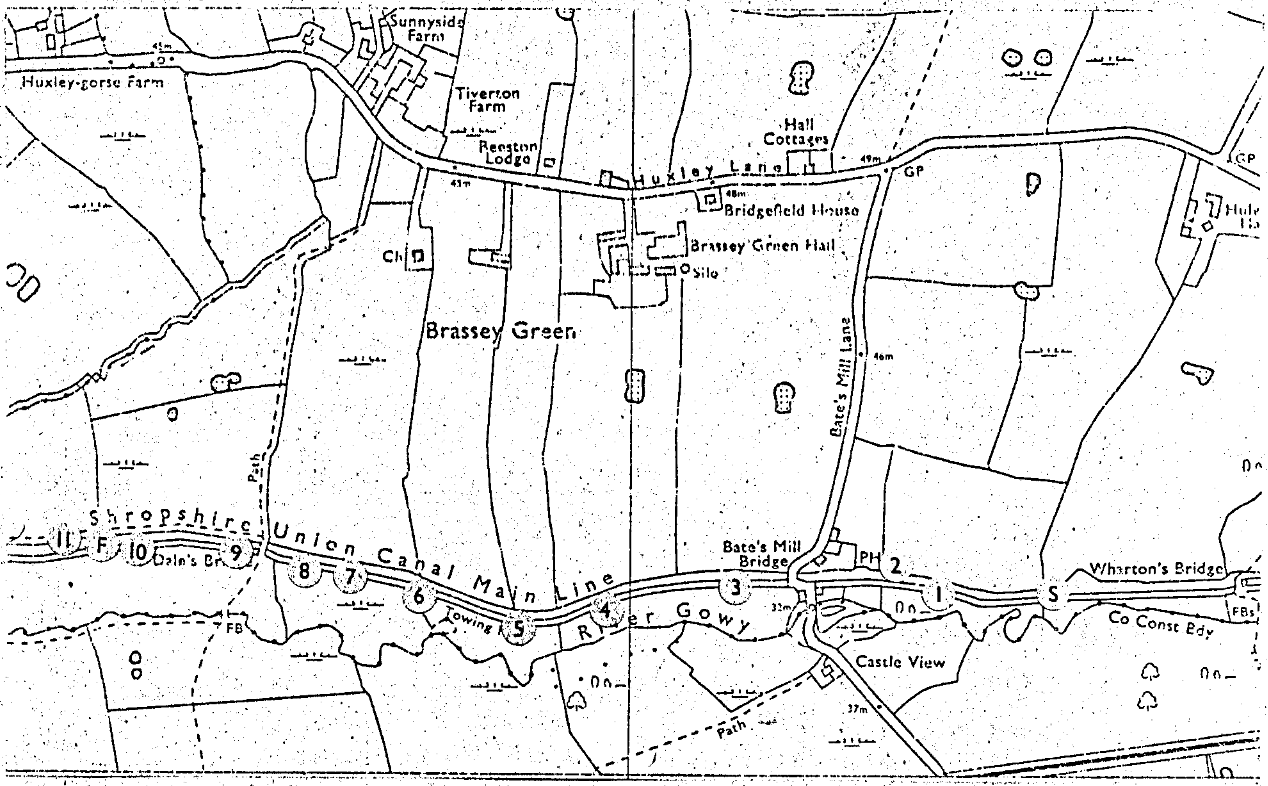
FILM 1 SECTION 1 (First Half)

Object No.	Type	Time (Min.Secs)
START		0.00
1	Hl	0.10
2	Faulkner's Bridge	0.13
	Hl	0.28
3	Hr	0.57
4	Vr	1.15
5	Hl	1.37
6	Vl	2.00
7	Vr	2.22
8	Hl	2.33
FINISH		2.43
9	Vr	(2.44)

KEY

V	Vertical Object
H	Horizontal Object
l	left bank
r	right bank
S	Start
F	Finish

FIG. 29B LOCATION OF OBJECTS



FILM 1 SECTION 4 (First Half)

Object No.	Type	Time (Min.Secs)
START		0.00
1	H1	0.18
2	Vr	0.30
Bates Mill		0.42 ←
3	H1	0.54
4	H1	1.15
5	H1	1.31
6	V1	1.50
7	H1	1.58
8	V1	2.08
Dales Bridge		2.15 ←
9	H1	2.19
10	V1	2.35
FINISH		2.45
11	Vr	2.48

1 min 33 secs gives 25 feet per second.

KEY
- V Vertical Object
- H Horizontal Object
- 1 left bank
- r right bank
- S Start
- F Finish

people found difficulty in remembering which button applied to which object. For other films vertical and horizontal bars had been used and a simple joystick arrangement was used so that subjects could move the knob downwards for vertical bars and across for horizontal bars. Because of the success of this the objects for the final series of films were given this format.

The writer is indebted to Dr.B.Wheeler of the Signals Research & Development Establishment for the suggestion that a canal barge be used as the mobile camera platform. Initial trial films showed this to give very good image stability. The stretch of canal chosen for the main filming was situated in Cheshire, and suffered only from being somewhat wide. Trials in overcast daylight had indicated that 50cm objects would not be too large, and so about 30 of these were made and attached to posts of various lengths. A 36 foot narrow boat was hired and measurements indicated that the boat's speed at $\frac{3}{4}$ throttle was 2.75 miles per hour. A filming speed of 4 f.p.s. was chosen so that the apparent motion to the subject viewing the film at 25 f.p.s. would be equivalent to about 17 m.p.h. The camera was mounted in the prow of the boat. Using ordnance survey maps at 6 inches to one mile, the locations and form of objects were determined using random number tables. Because of limitations in the timing system it was necessary to modify these on a small number of occassions as two similar objects very close together could not be differentiated.

A total of 16 usable films were obtained and a sequence of frames at one second projection intervals is shown in Fig. 28A & 28B. Maps of object type and location for film nos.2 and 14 are shown in Fig. 29A and Fig.29B.

The speed of the filming boat was slightly different in each direction due to the slight current, but calculations on a number of films showed that an effective speed of between 16 and 17 mph was obtained.

The filming runs were carried out over four separate stretches of canal with two runs in each direction. Each run took nearly 100 ft. of film which provides $2\frac{1}{2}$ mins. of projection time. Between eight and eleven objects were used on the canal, but only eight of these are actually monitored by the timing system of the experiment.

The 16 x 100 ft. films were spliced up into two 800 ft. films, having four sections of 200 ft. Thus, each section comprises five minutes of visual task time having sixteen objects. Equal numbers, overall, of vertical and horizontal objects were used and equal numbers were placed on the left and right hand banks of the canal. The total visual task library is shown in the chart where V & H specify Vertical and Horizontal while L & R indicate Left and Right Hand Banks of the canal. (Fig.30)

In order to use these films as measurable visual tasks, an indication of the type of location of objects is required to be passed to the measuring equipment so that the subject's response can be measured against it. For this the extra size of the film format was utilised. The 30^{o} and 50^{o} required for the magnifiers used 6mm by 10mm of the 7.5mm by 10mm format of the film. On the negatives the extra 1.5mm was clear.

A marking up system was adopted in which the frame located 10 secs previous (250 frames) to the last frame carrying the object, was marked with indian ink in this clear area. For horizontal objects

FIG. 30 BASIC VISUAL TASK STOCK

(X indicates object not used)

Film 1

Section 1 (Made on Stretch 1 travelling West and Stretch 1 travelling East)

H_L	V_R	H_L	H_R	V_R	H_L	V_L	V_R	H_L	:	H_L	H_L	H_R	V_R	H_L	V_L	V_R	H_L	V_R
		X															X	

Section 2 (Made on Stretch 2 travelling East and Stretch 2 travelling West)

H_R	V_L	V_R	H_R	V_R	H_L	V_R	H_R	:	H_L	V_L	H_L	V_R	H_L	V_L	H_L	H_R	V_L
														X			

Section 3 (Made on Stretch 3 travelling West and Stretch 3 travelling East)

H_R	V_L	V_L	V_R	V_R	H_L	V_R	V_L	H_R	:	V_L	H_R	H_L	V_R	H_L	H_L	H_R	V_R	V_R	H_R	V_L
			X									X				X	X			

Section 4 (Made on Stretch 4 travelling West and Stretch 4 travelling East)

H_L	V_R	H_L	H_L	H_L	V_L	H_L	V_L	H_L	V_L	:	H_R	H_R	V_R	H_R	V_R	H_R	V_R	V_R	V_R	H_L	V_R
			X					X				X						X			X

Film 2

Section 1 (Made on Stretch 1 travelling East and Stretch 2 travelling East)

H_R	V_L	H_L	H_L	V_R	H_L	H_L	H_R	V_R	H_L	:	H_R	H_L	V_R	V_L	V_R	H_R	V_R	H_L	V_R	H_L
X								X									X			X

Section 2 (Made on Stretch 3 travelling East and Stretch 4 travelling East)

H_L	V_L	V_R	H_L	V_L	H_L	V_R	H_R	H_L	:	V_R	H_L	V_R	H_L	V_R	V_R	V_L	H_L	V_L
								X										X

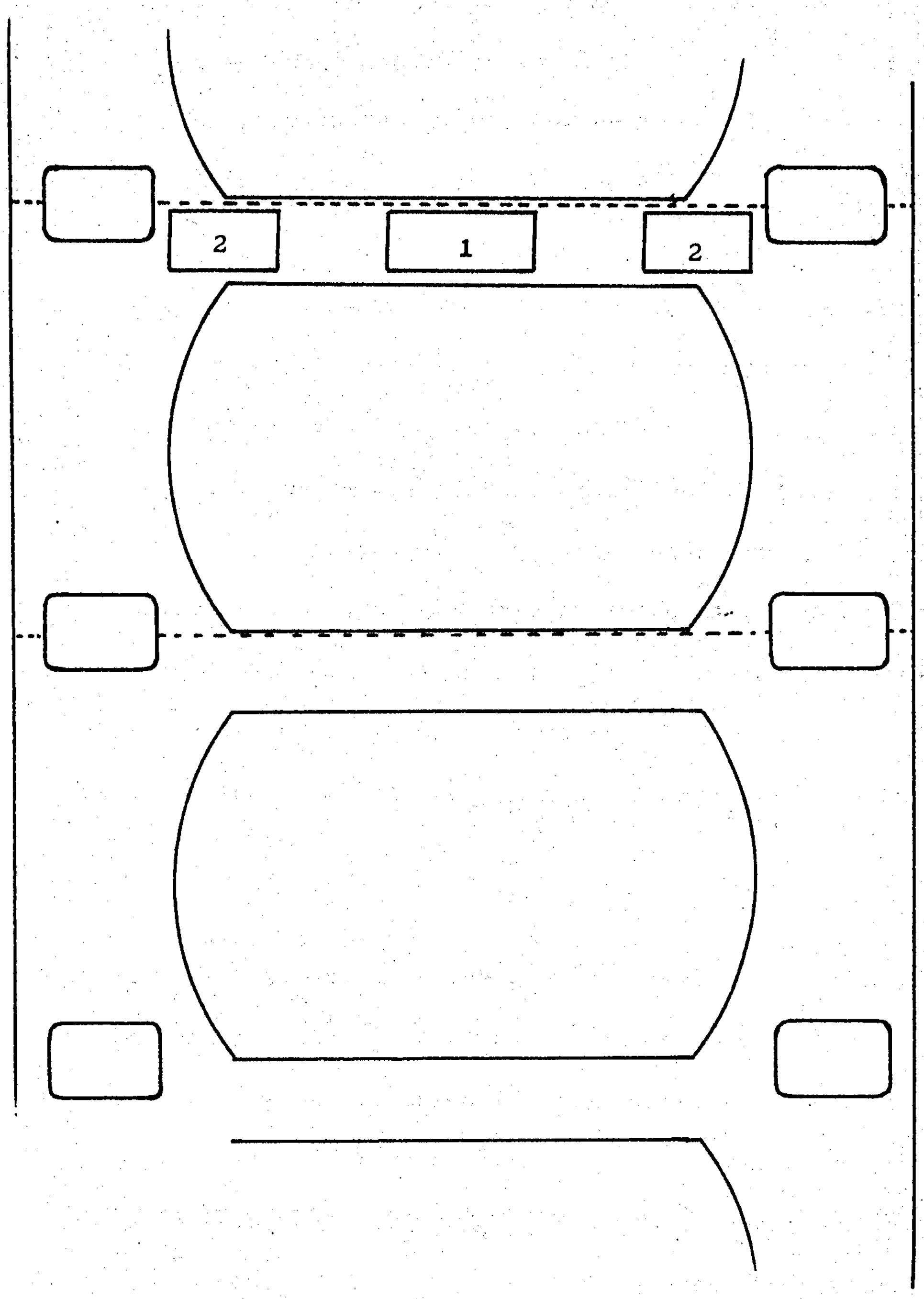
Section 3 (Made on Stretch 4 travelling West and Stretch 3 travelling West)

H_R	V_R	H_R	H_L	H_L	V_R	H_L	V_R	H_L	:	V_R	V_L	H_L	V_R	H_R	V_R	H_L	H_R	V_R	H_L
								X		X									X

Section 4 (Made on Stretch 2 travelling West and Stretch 1 travelling West)

V_L	V_R	V_L	H_L	V_L	H_R	H_L	V_R	V_L	:	V_R	H_L	V_L	V_R	V_R	H_L	V_R	V_R	H_R	V_L
		X											X			X			

FIG. 31 LOCATION OF TRIGGERING FLASHES



Flash at 1 for Vertical Objects

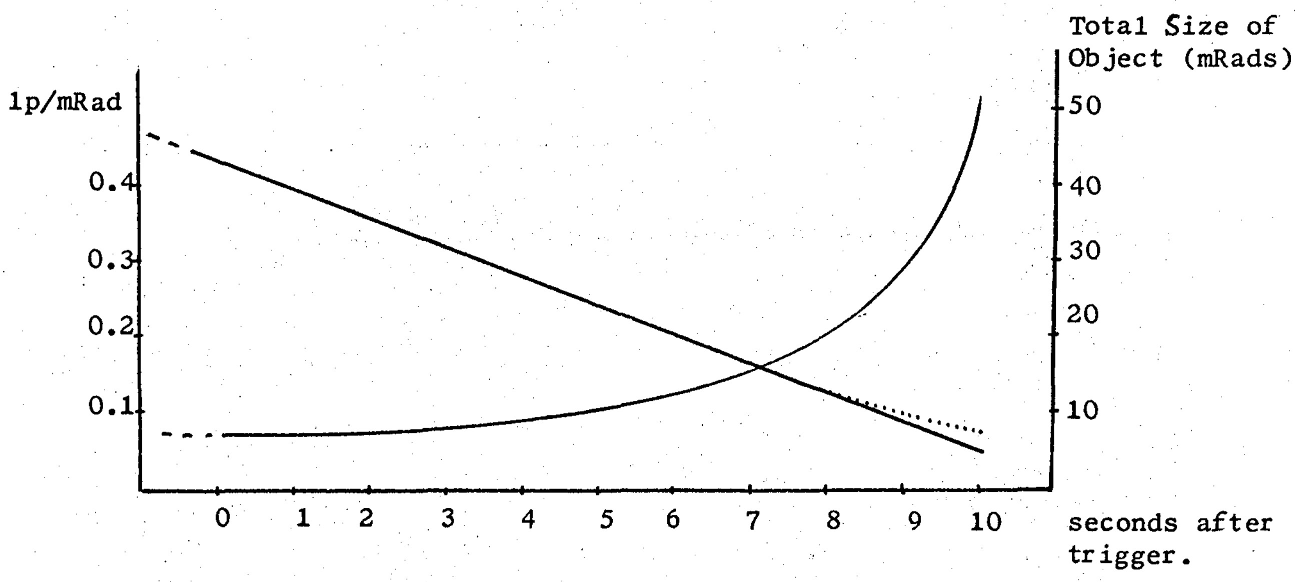
Flash at 2 for Horizontal Objects

two marks were located at the edges of the area. For vertical objects a single mark was placed in the centre. (Fig.31). When printed these marks produced transparent areas on particular frames in a region which otherwise was dark. The data system made use of the light flashes which occur on projection and the design of the magnifier modules precluded the subject from seeing them.

During the ten seconds the objects grow larger as they are approached. The chosen object size of 50 cm by 50 cm having two black stripes 10 cm wide gives a 2-bar object of five line pairs per metre or 1/200 lp/mm. This increases in size non-linearly with time but the resolution criteria is linear with time as shown in the chart, Fig. 32 which assumes an apparent boat speed of 7.5 metres per second. The resolution criteria is given in line pairs per mRad., while the dotted line indicates the slight difference generated by objects being on the banks of the canal and not directly in the path of the boat.

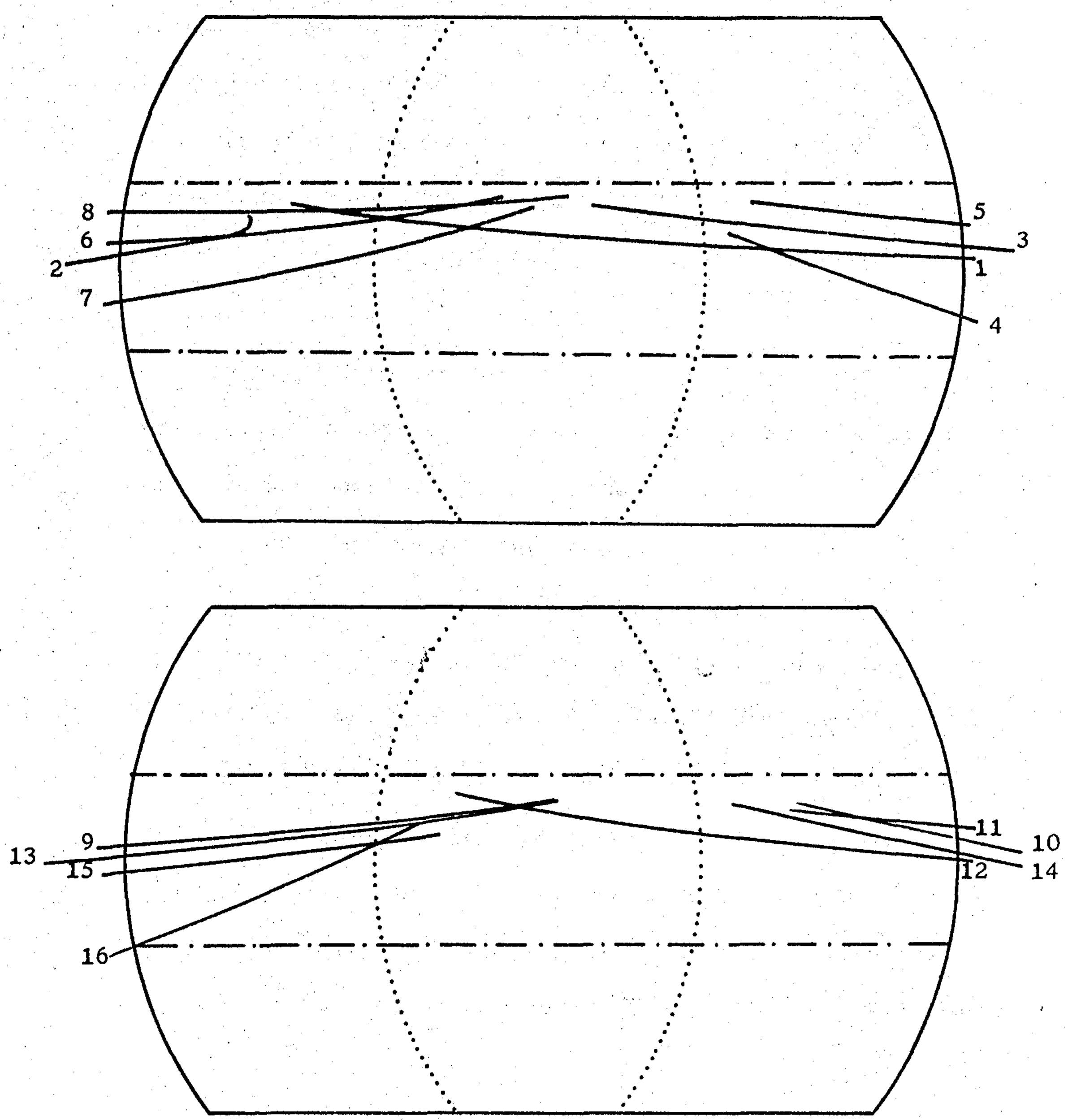
When the actual path of the objects is traced on the format of the film (Fig.33) the limited use of the field of view is demonstrated. Two attitudes may be taken to this restricted coverage of the field. It may be argued that the task represents a simple driving operation along a track when the majority of visual cues are located in a narrow horizontal band. This is inherently recognised in the choice of 50^{o} horizontal by 30^{o} vertical as the field for driving devices. The counter argument maintains that in other conditions all parts of of the field become important. However, a restriction to a "ribbon" field does allow a less intractable assessment of the interaction between the performance curves of the magnifier and the horizontal horopter of the eyes. The charts (Fig.33) show that the loci of

FIG.32 OBJECT SIZE AND FREQUENCY VALUES



.... Variation due to object being off-set on bank of canal

FIG.33 LOCI OF OBJECTS ON FILM



Numbers indicate objects for film 1 section 3

Horizontal broken lines indicate ± 5° vertical field

Curved dotted lines indicate limits of binocular field.

the objects used in the visual task film are generally within the central 10^{0} of the field of view. The camera was aligned with the horizontal, but the use of only the lower 6mm of the 7.5mm available format on 16mm film gives an effective downwards tilt of nearly 4^{o}. As most objects are below the horizontal line of sight they traverse the central 10^{o}.

It is important to remember that the intention of the visual task films is not to measure the vigilance of subjects using them. This factor varies considerably with motivation and training of the subject, and when the purpose lies in differentiating between magnifiers the inclusion of other variables only adds noise to an already noisy situation. Obviously, differences between subjects are important, but when visual fatigue and performance are being tested it is preferable to present a relatively straight-forward but interesting task. Thus, the objects can normally be detected before their markings can be resolved while the apparent forward motion of the observer commands his attention. Few subjects admitted boredom even after the fourth 20 minute viewing session.

5.4 Electronic Triggering and Experimental Design

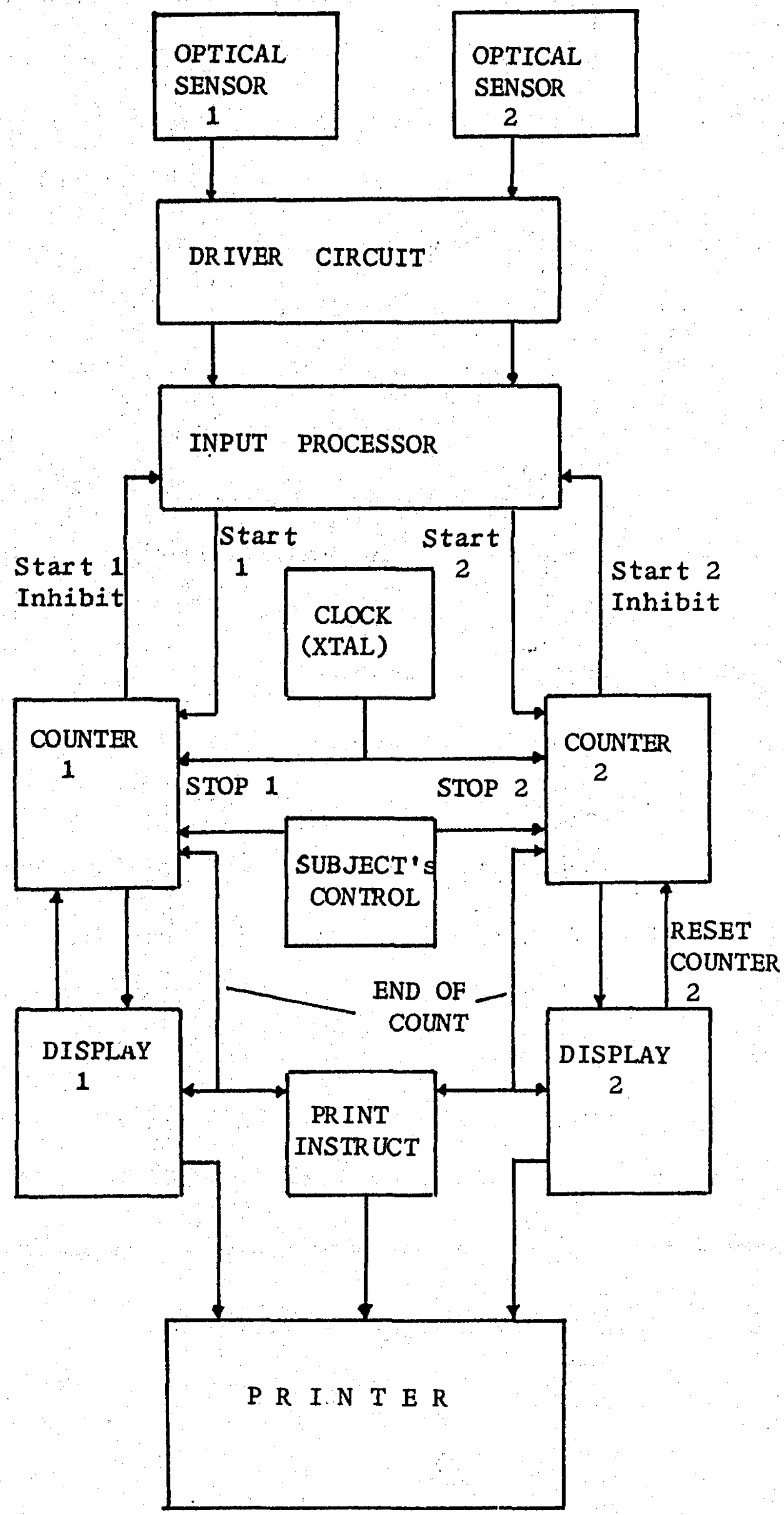
The electronic timing system is a simple arrangement to provide a consistent indication of the location of each object at the moment when the subject indicates what orientation it is. As described in the previous section light flashes are obtainable from one of the two locations above the reduced viewing area of the film format. Two photo-diodes can be placed in these locations and when one of them receives a flash it connects its own counter to a master clock giving 100 pulses per second. These counters are stopped either by the correct action by the subject or when they reach 9.00 seconds.

The subject's action involves the movement of joystick switch by their right hand. A downward movement of the stick stops the counter for vertical bar targets while a horizontal movement stops the counter for horizontal bar targets. The action with the joystick is indicated by lamps to the experimenter. When the action is correct or when the counters reach 9.00 seconds the count is indicated on a digital display and recorded by a printer.

The block diagram (Fig.34) shows the general layout. The optical sensor approach has proved sufficiently reliable although some problems were found with the large screen display due to insufficient illumination of the photo-diodes. With a projection speed of 25 frames per second the accuracy of 0.01 secs is spurious as, although each frame is projected three times by the three-bladed shutter, the object still approaches the subject in a series of 0.04 second jerks.

With such a visual task as has been chosen, each object is unique in its location, background, and conspicuity. Although some averaging of

FIG.34 TIMING SYSTEM & DATA RECORDING



these effects may be expected when 16 such objects are viewed over a five minute period it is obviously invalid to compare viewing times of different parts of the visual task films.

In the design of experiments where extraneous influences on the results cannot all be eliminated, the usual recourse is to arrange these likely sources of error in such a way that each will contribute equally to the specific areas under investigation. In this work these sources of error comprise the differences between subjects, the differences between films, the differences between a subject's first trial and subsequent trials. There may also be an interaction between a magnifier or film and the one preceding it.

With four magnifiers the order of viewing can be arranged in 24 ways. However, all these are not necessary as the performance of a subject with a given magnifier cannot be affected by the particular magnifier that follows it, nor can the effect be large of the particular magnifier more than one trial in front of it. If such a distinction is accepted, it is possible to devise a 4 x 4 array of magnifiers showing their order of viewing for four subjects such that each magnifier occupies a given position once only, and in which no magnifier follows a given magnifier more than once.

The array is:-

	1st Trial	2nd Trial	3rd Trial	4th Trial
1st Subject	1	2	3	4
2nd Subject	2	4	1	3
3rd Subject	3	1	4	2
4th Subject	4	3	2	1

(Array 1)

The next consideration involves the visual task material. Of the 4 20 minute visual tasks available, no given object has any particular relationship with any other, so each must be presented through each magnifier. Although it is possible to do this with the array given, it is not possible to locate each task into each trial once only.

The following arrangement shows the magnifier (first digit) and task (second digit) arranged so that each magnifier uses each task once.

	1st Trial	2nd Trial	3rd Trial	4th Trial
1st Subject	1.1	2.4	3.2	4.3
2nd Subject	2.2	4.1	1.3	3.4
3rd Subject	3.3	1.4	4.2	2.1
4th Subject	4.4	3.1	2.3	1.2

(Array 2)

If eight subjects are used, the use of tasks over the trials may be balanced in the following way, which uses the same layout:-

	1st	2nd	3rd	4th Trial
Subject 1	1.1	2.4	3.2	4.3
2	2.2	4.1	1.3	3.4
3	3.3	1.4	4.2	2.1
4	4.4	3.1	2.3	1.2
5	1.3	2.2	3.4	4.1
6	2.4	4.3	1.1	3.2
7	3.1	1.2	4.4	2.3
8	4.2	3.3	2.1	1.4

(Array 3)

This arrangement was used twice on the first experiment of 16 subjects (Nos.1 to 17 with No.6 excluded). An alternative 16 subjects array is as follows where each task is used with each magnifier. The first half of this array was used for subjects 26 to 33.

		1st	2nd	3rd	4th	Trial
Subject	1	1.1	2.4	3.2	4.3	
	2	2.2	4.1	1.3	3.4	
	3	3.3	1.4	4.2	2.1	
	4	4.4	3.1	2.3	1.2	
	5	1.2	2.3	3.1	4.4	
	6	2.1	4.2	1.4	3.3	
	7	3.4	1.3	4.1	2.2	
	8	4.3	3.2	2.4	1.1	
	9	1.3	2.2	3.4	4.1	
	10	2.4	4.3	1.1	3.2	
	11	3.1	1.2	4.4	2.3	
	12	4.2	3.3	2.1	1.4	
	13	1.4	3.1	3.3	4.2	
	14	2.3	4.4	1.2	3.1	
	15	3.2	1.1	4.3	2.4	
	16	4.1	3.4	2.2	1.3	

(Array 4)

Once again the lack of any relationship between one visual task object and another does not allow the performance of a subject at the beginning of a trial to be compared with that at the end of a trial. To facilitate this, each 20 minute task was divided into four sections of 5 minutes duration each. This meant that different subjects could view these sections in different orders. Again the ordering of four sections allows 24 possible sequences, but only four of these is needed to satisfy the condition that each section should appear in each location only once and follow another given section once only. The same arrangements are chosen as with subjects and magnifiers. The following array shows the section's arrangements were coded.

	1st Sec.Seen	2nd Sec.Seen	3rd Sec.Seen	4th Sec.Seen
Code 1	1	2	3	4
Code 2	2	4	1	3
Code 3	3	1	4	2
Code 4	4	3	2	1

(Array 5)

Thus, the visual tasks used for the 16 subject investigation were in Code 1 arrangement for the first four subjects, Code 2 for the next four, Code 3 for the third four and Code 4 for the last four. The subjects need not be used in the strict order of the array and the subject numbers show the actual designations given to them in order of their recruitment. Subject 6 was inadvertently given an incorrect arrangement so that his results were withdrawn. The sixteen subjects comprise 8 male and 8 female. The three figures under each trial/subject location indicate Magnifier,Task,Code.

		1st	2nd	3rd	4th		1st	2nd	3rd	4th	Trial
Subject	3F	1.1.1	2.4.1	3.2.1	4.3.1	12M	1.1.3	2.4.3	3.2.3	4.3.3	
	1M	2.2.1	4.1.1	1.3.1	3.4.1	11F	2.2.3	4.1.3	1.3.3	3.4.3	
	4F	3.3.1	1.4.1	4.2.1	2.1.1	10M	3.3.3	1.4.3	4.2.4	2.1.3	
	2M	4.4.1	3.1.1	2.3.1	1.2.1	13F	4.4.3	3.1.3	2.3.3	1.2.3	
	8M	1.3.2	2.2.2	3.4.2	4.1.2	15F	1.3.4	2.2.4	3.4.4	4.1.4	
	5F	2.4.2	4.3.2	1.1.2	3.2.2	14M	2.4.4	4.3.4	1.1.4	3.2.4	
	9M	3.1.2	1.2.2	4.4.2	2.3.2	16F	3.1.4	1.2.4	4.4.4	2.3.4	
	7F	4.2.2	3.3.2	2.1.2	1.4.2	17M	4.2.4	3.3.4	2.1.4	1.4.4	

(Array 6)

At the time of running this experiment it was felt that the equivalence of the two halves of the array would ease the computation, although in retrospect the more balanced arrangement of Array 4 would have been better.

As explained in section 5.3. the four visual tasks in these arrays are obtained from 16 by 100ft. films. Each film last 2.5 minutes so that each 5 minute section of the task comprises 2 films. Thus, for four tasks of four sections each, a total of 32 films would be required. The sixteen films were stretched to this by also showing them laterally reversed in the projector. Thus task 3 is task 1 in reverse while task 4 is task 2 in reverse. In the analysis of the results from the first 16 subjects it was found that no significant difference could be detected between the straight and reversed films.

This result means that the four codes can be covered in a balanced array using 8 subjects only as shown below. In this array the figures indicating Magnifier, Task and Code are followed by a further figure indicating the number of the trial.

	Trial 1st	2nd	3rd	4th
Subject 1 (26)	1.1.1.1	2.4.4.2	3.2.1.3	4.3.4.4
2 (29)	2.2.1.1	4.1.1.2	1.3.4.3.	3.4.4.4
3 (27)	3.3.4.1	1.4.4.2	4.2.1.3	2.1.1.4
4 (28)	4.4.4.1	3.1.1.2	2.3.4.3	1.2.1.4
5 (30)	1.2.3.1	2.3.2.2	3.1.3.3.	4.4.2.4
6 (33)	2.1.3.1	4.2.3.2	1.4.2.3	3.3.2.4
7 (31)	3.4.2.1	1.3.2.2	4.1.3.3	2.2.3.4
8 (32)	4.3.2.1	3.2.3.2	2.4.2.3	1.1.3.4

	1st	2nd	3rd	4th
TOTALS =	20.20.20.8	20.20.20.16.	20.20.20.24	20.20.20.32

(Array 7)

The bracketed subject figures give the actual subjects used in an 8-subject trial. When the columns are summed it is seen that the mean of results obtained in these locations show differences only due to the number of the trial each subject performed. If these locations are re-arranged, then the differences due to magnifiers can be obtained in the same way.

	1	2	3	4	Magnifier
Subject: 1	1.1.1.1	2.4.4.2	3.2.1.3	4.3.4.4	
2	1.3.4.3	2.2.1.1	3.4.4.4	4.1.1.2	
3	1.4.4.2	2.1.1.4	3.3.4.1	4.2.1.3	
4	1.2.1.4	2.3.4.3	3.1.1.2	4.4.4.1	
5	1.2.3.1	2.3.2.2.	3.1.3.3	4.4.2.4	
6	1.4.2.3	2.1.3.1	3.3.2.4	4.2.3.2	
7	1.3.2.2	2.2.3.4	3.4.2.1	4.1.3.3	
8	1.1.3.4	2.4.2.3	3.2.3.2	4.3.2.1	

	1	2	3	4
TOTALS:	8.20.20.20	16.20.20.20	24.20.20.20.	32.20.20.20.

(Array 8)

Thus the totals relate differences due to magnifier only.

For shorter experiments a four-subject array was devised as below:-

Subject	1st	2nd	3rd	4th	
1	1.1.1.1	2.4.4.2	3.2.3.3	4.3.4.4	Trial
2	2.2.3.1	4.1.1.2	1.3.2.3	3.4.2.4	
3	3.3.2.1	1.4.2.2	4.2.1.3	2.1.3.4	
4	4.4.4.1	3.1.3.2	2.3.4.3	1.2.1.4	
TOTALS	20.20.20.4	20.20.20.8	20.20.20.12	20.20.20.16	

(Array 9)

In fact codes designated for tasks 1 & 3 are independent of those for tasks 2 & 4 as these use different films. Although the arrangement in array 9 is not entirely balanced the lack of any bias between the same task projected laterally reversed means that the use of only tasks 1 & 4 in the 2nd trial is allowable. The limitations of an experiment involving only four subjects are likely to be due to the variations between subjects being very much larger than the looked for effect.

Previous to the recognition that insignificant bias was attributable to the film reversal, a four subject run was carried out on the array given below. This is not balanced as some difficulty was experienced at the time in obtaining subjects between task code changes which involve cutting and resplicing the films.

	1st	2nd	3rd	4th	Trial
Subject 1 (22)	1.2.1.1	2.1.2.2	3.4.3.3	4.3.4.4	
2 (23)	2.3.1.1	4.4.1.2	3.2.4.3	1.1.4.4	
3 (24)	3.1.1.1	4.2.2.2	1.3.3.3	2.4.4.4	
4 (25)	3.3.2.1	1.4.2.2	4.1.3.3	2.2.3.4	

(Array 10)

Results from this run will be discussed later, but the 5% significance level was of the order of one second which is considerably larger than the looked-for effects. Thus, the eight subject array number 7 was used for subjects 26 to 32. As is discussed in the following Chapter these subjects gave results which suggested a relationship between subject's muscular imbalance and performance on magnifiers having various prismatic errors (parallax). In order to investigate this further it was decided that a further eight subjects should be used so that the grand total of sixteen subjects would fall into four general categories of esophoria or exophoria. Within each category the four subjects would have different viewing orders so that the results averaged across each four would not be affected by the order of viewing.

As this effect had not been foreseen when the original eight subjects were used it was found that the chance arrangement of their muscular imbalances would not allow the 4 by 4 arrangement in all categories. It was therefore necessary to delete subjects 30 & 33 and replace with subjects 53 & 54 who viewed the magnifiers in a different order. (A further new subject was required as an equipment failure occurred during the trial with subject 31. Subject 44 replaced 31).

With this in mind the following 16 subject arrangement was planned (Magnifier, Task, Code, ~~Location~~ Trial).

		1st	2nd	3rd	4th	Trial
2Δeso to 1Δexo	Subject 1 (45)	1.3.3.1	2.2.4.2	3.4.3.3	4.1.4.4	
	2 (54)	2.1.3.1	4.2.3.2	1.4.2.3	3.3.2.4	(33)
	3 (44)	3.4.2.1	1.3.2.2	4.1.3.3	2.2.3.4	(31)
	4 (46)	4.2.2.1	3.3.1.2	2.1.2.3	1.4.1.4	
1Δexo to 4Δexo	5 (26)	1.1.1.1	2.4.4.2	3.2.1.3	4.3.4.4	
	6 (48)	2.3.1.1	4.4.1.2	1.2.2.3	3.1.2.4	
	7 (47)	3.2.4.1	1.1.4.2	4.3.3.3	2.4.3.4	
	8 (28)	4.4.4.1	3.1.1.2	2.3.4.3	1.2.1.4	
4Δexo to 7Δexo	9 (50)	1.4.1.1	2.1.2.2	3.3.1.3	4.2.2.4	
	10 (49)	2.4.3.1	4.3.3.2	1.1.4.3	3.2.4.4	
	11 (27)	3.3.4.1	1.4.4.2	4.2.1.3	2.1.1.4	
	12 (32)	4.3.2.1	3.2.3.2	2.4.2.3	1.1.3.4	
7Δexo to 10Δ exo	13 (53)	1.2.3.1	2.3.2.2	3.1.3.3	4.4.2.4	(30)
	14 (29)	2.2.1.1	4.1.1.2	1.3.4.3	3.4.4.4	
	15 (51)	3.1.2.1	1.2.2.2	4.4.1.3	2.3.1.4	
	16 (52)	4.1.4.1	3.4.3.2	2.2.4.3	1.3.3.4	

(Array 1[1])

The above arrangements allow mean performance values obtained across all subjects to be descriptive of each magnifier and to some extent of each 5 minutes on each magnifier. Although results were obtained for all these subjects, it was necessary to use new prints of the visual task films from subject 44 onwards. On initial examination of the performance of subjects 53 and 54 (done with subject 44 before the last eight) a bias was found due to poor film printing. Further printings were then obtained for use on subjects 45 to 52. These gave no significant bias when compared to subjects 26 to 33 but it was then necessary to use subjects 30, 31 and 33 rather than their replacements.

When the results were examined it was found that a second interaction between a subject parameter and a visual aberration of the magnifier was present. This concerned the inter-pupilliary distance (P.D.) of the subjects. This effect was larger than the expected phoria effect and tended to cancel it. It was found that statistically significant results could only be obtained by dividing the subjects into two groups of eight rather than four groups of four. Thus, the array 11 , although part of the experimental plan is not used in the analysis of results.

In the following chapter (Fig 52 page 213) the values of the subjects' P.D. and base phoria at 50 cms is laid out in a 4 x 4 square so that division in left and right-handed sections gives a difference in mean P.D. while division into upper and lower sections gives a difference in mean phoria. These groupings of subjects are thus:-

46	45	30	31
26	48	47	28
27	32	50	49
51	33	29	52
mean P.D. = 62.2mm		mean P.D. = 65.6mm	

46	45	30	31	mean phoria = 1 Δ exo
26	48	47	28	
27	32	50	49	mean phoria = 6 Δ exo
51	33	29	52	

The totals of the Magnifier, Task, Code and Trial designations of array 11, obtained for these subject groups are as below; by trial order and magnifier order.

	1st	2nd	3rd	4th	Trial
62.2mm	20.17.18.8	20.23.27.16	20.23.14.24	20.17.18.32	
65.6mm	20.23.22.8	20.17.18.16	20.17.26.24	20.23.22.32	
1Δexo	19.21.20.8	18.21.19.16	22.17.21.24	21.21.20.32	
6Δexo	21.19.20.8	22.19.21.16	18.23.19.24	19.19.20.32	

	1st	2nd	3rd	4th	Magnifier
62.2mm	8.21.18.20	16.19.18.20	24.19.18.20	32.21.18.20	
65.6mm	8.19.22.20	16.21.22.20	24.21.22.20	32.19.22.20	
1Δexo	8.19.17.18	16.22.23.21	24.18.17.19	32.23.23.22	
6Δexo	8.22.23.22	16.18.17.19	24.21.23.21	32.18.17.18	

It is seen that the balance is no longer perfect. Although a balanced order of viewing against magnifier order is maintained for the P.D. groups it is not possible to maintain even this for the phoria groupings. However, the imbalance is only one subject out of each eight and the results obtained from the subjects divided into 'order of viewing' groups do not show a strong interaction. (Chapter 6, Fig 51, page 211).

The other imbalances of film and code are regarded as less important as a further data reduction process had been devised to facilitate better comparisons across time. This calculated a mean viewing time over all sightings of a given object. The difference between a particular sighting and the mean for that object is then calculated to provide a value which is more independent of film and code. This process is described in Chapter 6.

In these experimental designs the major difficulty has been the double treatment aspect. Not only do subjects look through a particular magnifier during a trial, they also use a particular visual task. The need to order the tasks and magnifiers in a balanced manner can only be satisfied with standard greco-latin squares if one assumes there is no residual effect from the previous trial. (Cockran & Cox 1957). If the residual effect is to be eliminated by balance only single treatment arrays may be obtained from the literature. As a residual effect with the magnifiers is more likely than with the films which are nominally identical it was decided to use a latin square of the magnifiers which satisfies the conditions of balance for residual effects as specified by Patterson (1952).

These conditions, in the terms of this experiment, are as follows:-

I No magnifier is used by a given subject more than once.

II Each magnifier occurs in a given sub-trial an equal number of times.

III Every pair of magnifiers occur together for the same number of subjects.

IV Each ordered succession of two magnifiers is presented to the subjects equally often.

V Every pair of magnifiers occur together for the same number of subjects excluding the last magnifier seen by each subject.

VI For those subjects which use a given magnifier last the other magnifiers are used equally often.

VII For those subjects for which a given magnifier is used in any but the final trial each other magnifier is used last equally often.

Patterson states that a 4 x 4 array is the smallest that can be found. Of the 4 latin squares suggested by Yates (1933) only the one used satisfies the above conditions. (Array 1)

5.5 Choice of Subjects and Physiological Tests

In order to test out differences between magnifiers in their interaction with the visual apparatus of the user, it is necessary to check the normality of vision in the subjects used. Whilst not wishing to restrict the study to persons with perfect vision, it is important that subjects requiring, but not equipped with spectacles, should be excluded. Equally, those subjects with gross defects such as monocular vision or strabismus, should be excluded as this would normally exclude them from any military use of these devices.

To this end all subjects used in this study had been tested on the MAVIS Vision Screener. This semi-automatic system rapidly checks the major aspects of acuity and binocular balance at both far and near distances. Stereoscopic acuity is also measured. Acceptance criteria were abitrarily set at:-

Visual Acuity in each Eye:	N8 near	6/7.6 far
Binocular Balance Horizontal:	±6 Δ near	±5 Δ far
Binocular Balance Vertical:	±1 Δ near	±1 Δ far
Stereoscopic Acuity:	75 sec. near	100 sec.far

As was discussed in the last chapter, little guidance is available from the literature in the choice of a physiological parameter related to fatigue. In formulating the experimental policy the choice of lateral heterophoria measurements was decided as much by the simple apparatus required and the ease with which measurements could be made as by any rational progression from previous work. Although changes in heterophoria had no record as an indicator of general fatigue the feeling was that it had not been disproved in relation to aberration limited vision.

In order to obtain the maximum amount of information the effects of viewing time it was decided that the 800 feet of film providing the 20 minute task should have 20 sec. blanks at 5 minute intervals so that the phoria could be measured on an adjacent instrument during this time.

Phoria (or heterophoria) is the difference between the rest directions adopted by the eyes when vision is disassociated to those adopted when binocular fusion is obtained. Most people have some rest error of this nature, and orthophoria is relatively uncommon. Variation in the size of the error is usually found between distant vision (6 metres) and near vision (25 cm).

The latter is of greater interest in this case, but the typical magnifier setting gives an image at about 50 cms. Thus, the usual Maddox Wing test for near vision heterophoria was incorporated into a system operating at 50 cm, but compact enough to rest in front of the subject below the magnifier. In use the subject merely needed to tilt his head from the magnifier viewing position to look into the twin apertures of this device. Through these he saw a horizontal scale with his right eye and a single I-shape with his left eye. Both of these were bright objects on an otherwise dark field. The illumination sources for these objects were independently controlled, and the subject could only see the I-shape initially. On illuminating the scale the subject was asked to indicate the location of the I with respect to the scale. To avoid confusion the scale carried the digits 0 to 9 with 5 as the orthophoria condition. The scale numbers were in fact at 1cm intervals which at 50cms is equivalent to 2 prism dioptres. In other words the range -10Δ to $+10\Delta$ was used and found adequate for the subjects chosen.

Reference has already been made to the 4 x 5 minute structure of the visual task. Prior to this time the subject was instructed in the use of the triggering control, and the height of his chair was adjusted for comfortable viewing. The nature of the task was explained to them by reading a description as follows:-

1. This will take about 25 minutes. Your main job is to watch a film through an eyepiece. The film is taken from a boat sailing along a canal, but we have speeded it up so that you are effectively travelling at about 20 m.p.h. You may notice high speed cars on the road alongside, but your main job is to watch out for objects along the banks of the canal.

2. These objects are white squares 2 ft. by 2ft. having two black stripes. Sometimes the stripes are vertical, sometimes horizontal as in this picture. I want to know the moment you can see that it is a horizontal or vertical type. To do this I want you to use the knob you find by your right hand. You can press this down and move it along. All I want you to do is press it down when you see that the stripes are vertical and along when you see that they are horizontal.

3. As well as this I want to do a measurement on your eyes. If you look down you will see an oblong black box with two holes in it. If you look through these holes you should see a line of numbers. There is also an I-shaped object which may move about a bit. I can switch the numbers on and off. Can you see the I-shape and the numbers? Please look at the I-shape. When I switch on the numbers I shall want you to tell me which number is the nearest to the I or whether it is between two numbers.

4. Now look through the eyepiece again.

5. The most important thing is that you are sitting comfortably.

Is your chair the right height?

Is the back rest supporting your back?

Is your forehead central on the brow pad?

6. Now we are ready for the main test. When you see a horizontal object press the knob sideways. When you see a vertical object press the knob down.

7. From time to time the scene will go black. I want you then to put your eyes down to the lower equipment and tell me the number which is nearest the I-shape.

8. If you have comments to make during the time, please make them. If you get a headache or feeling of strain, let me know. If you want to give up let me know. If a head ache comes it may clear again - let me know that as well.

9. Try to work carefully and consistently without being overkeen or too intense. Try to ignore the sound of the equipment.

At the end of the task period the subject was questioned according to the questionnaire below:-

*1. How do you rate your present state of vision?

1.) Excellent

2) Comfortable

3) Mild Discomfort

4) Severe Discomfort

5) Double Vision at Times

2. Are your eyes hot, dry and watering?

3. Do you have a headache?

4. Were you bored by the task?

5. Do you feel your attention to the task was consistent?

**6. How do you rate this equipment with previous types?

7. Does your back or neck ache?

***8. Did you use one eye or change eyes from time to time?

* The check list was used from subject 26 on.

** Question 6 applied to the second and subsequent trials.

*** Question 8 was asked only after the monocular magnifier.

5.6 Magnifier Module Design

Although the observation station and use of 16mm film has been described it is necessary to describe the link between the projector and the magnifiers used in the experimental work. Even the lowest-power biocular magnifiers have a numerical aperture greater than that of the projection lens. Thus, a scattering surface is required in the plane of the projected image to fill the magnifier with light. The requirements of this scattering surface become more critical the higher the power of the subsequent magnifier. The requirements amount to uniformity of contrast transfer function and of illumination into the aperture of the magnifier. The first requirement is difficult to satisfy when magnifiers of different powers are being compared. If the magnifiers are of identical power, when the same scattering screen material can be used, only the second requirement remains important as gross variation in intensity across the angle scattered into will mean that subjects with larger interpupil distances may see a dimmer scene than those with closer set eyes.

The first problem means that comparisons across magnifiers using different screens must be done with care. The second means that even when the same screen is used comparisons between different subjects must take into account their different eye locations even when each subject uses a brow-pad to centre the head. However, the visual aberrations of a magnifier are themselves sensitive to interpupil distances so that it is advisible to choose subjects over a restricted range of this parameter.

The limitations of any comparison across magnifiers using different screens are reviewed later in this section after the descriptions of specific magnifier modules. The effects of subject parameters such as interpupil distance are reviewed in Chapter 6. Three modules were required for the first experiment to compare widely different magnifiers. Subsequent experiments used the third module modified.

STOG Module (Straight Through ordinary glass)

This module requires no magnifying lenses as the image is viewed directly at 50cm from the eyes. A plane piece of glass was included so that subjects would not see an immediate difference. This system requires the largest image and a screen size of 46.6cm diameter by 28cm vertical truncation was required to provide a 50° by 30° field of view at a viewing distance of 50cm. which is equivalent to a dioptric setting of - 2 Dioptres. A Harkness 'Translite' rear projection screen was used. A projector lens of 50° field of view was used which gave a throw of about 50cms as shown in Fig.24 with the black-out covering removed.

The open gate luminance viewed through the ¼" plano glass was found to be 165ft. lamberts. This reduced to 50ft. lamberts when a Wratten Green Filter No.55 is placed behind the plano glass to give the phosphor response of image intensifier tubes. These figures apply to the centre of the field. At the edge (horizontally) a reduction to 75% of central values was observed. With the task film running, a reduction to 35% of open gate values was observed. Thus, an 'in use' luminance of 17ft. lamberts was obtained, and this was considered comparable with image intensifier tubes under moderate to high ambients.

The value of 165ft. lamberts with open gate and no green filter was thus taken as a standard as the smaller screen sizes of the other magnifier modules would easily allow better than this and stops and filters could be used to adjust to this level. Two problems remained with this system.

The triggering photo-cells were not receiving sufficient intensity to operate the input processor of the electronic timing system. This was rectified by imaging the projection lens onto each photo-cell by the use of lenses as shown at the top of the module in Fig.24. The other problem was more serious and was due to the relatively wide aperture of the projection lens - f/1.4 and 0.5" efl. The axial motion of the film in the gate while not in itself exceeding the depth of focus of the lens, could, due to the very short back focal length of the lens, give a loss of focus when a splice passed through. Modifications to the focussing mechanism made this more stiff and a continuous watch on focus was maintained while this module was under test.

<u>COP Module</u> (Single Plastics Lens)

The aspheric plastics lens as described in Chapter 2 requires a screen format of 85mm diameter by 51mm truncated height. This gives a field of view of 50^{o} if the angle of view is derived from the extreme image location relative to the viewing eye position. The considerable field curvature and astigmatism of this lens makes it difficult to define the limits of the field exactly.

With this arrangement the central part of the screen is being viewed at an angle of 27^{o} by each eye. (Equivalent to f/1.1).

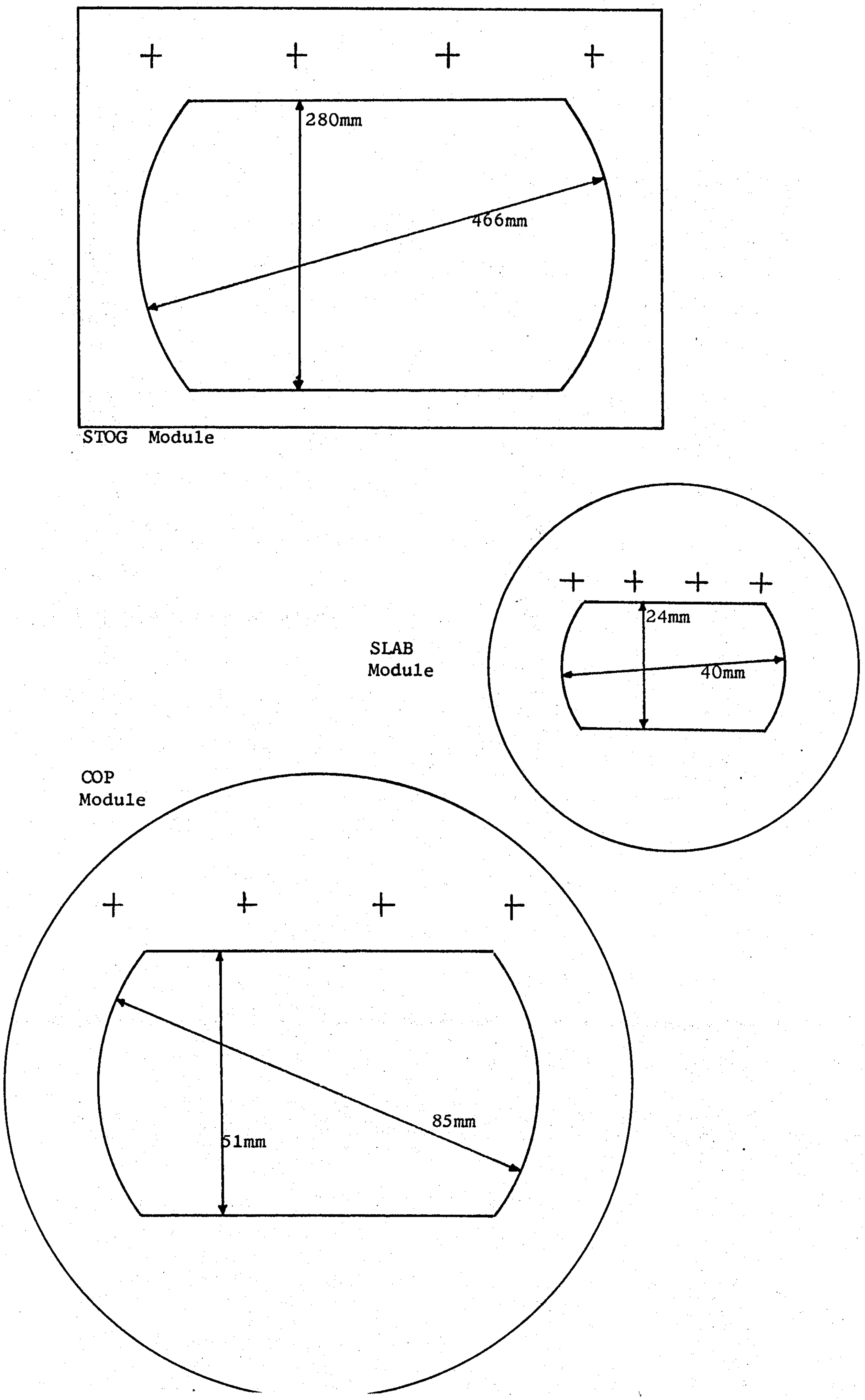
At this sort of aperture the thickness of the screen material becomes the limiting factor on its resolution.

In order to obtain the same limiting resolution on this screen as on the STOG system, a special high resolution screen was purchased from de Oude Delft which gave a similar limiting resolution to the STOG magnifier when the projection lens was used with a stop of 16mm diameter. This improvement in resolution is largely due to the reduction in light trapped in the scattering material which eventually emerges some lateral distance from its point of incidence. The apparent luminance of the screen with open gate and this stop size was 850 ft.lmbts. This was reduced to 165 ft.lbts. by using a neutral density filter of 0.71 O.D. (nominal) near to the screen. Both the neutral filter and green filter were placed only over the screen area so that the photo-cells received the full illumination and were able to trigger the electronic counting system satisfactorily.

SLAB Module

The screen problem with the COP system is even worse with the SLAB magnifier module which, as described in Chapter 2, requires a format of 40mm diameter by 24mm vertically truncated. It was found that the screen materials gave insufficient resolution when the projector lens was stopped down to 13mm diameter and that little improvement on this was obtained by smaller diameters of stop. It was decided to change the screen material to Polacoat 'Lenscreen' which was lighter and more robust than that used on COP and to vibrate this material to enhance the apparent resolution. This vibration was applied as a simple linear motion at 45° to the vertical and

FIG. 35 SCREEN FORMATS OF MAGNIFIER MODULES



horizontal objects used in the visual task films. A small Pye-Ling vibrator was used driven from a power oscillator at 50 Hz. The amplitude was arbitrarily set at about 1mm as no detectible change in resolution occurred at amplitudes above 0.5mm. The 13mm stop gave a screen luminance of 1400 ft. lamberts and a 0.9 O.D. (nominal) neutral density filter was inserted to reduce this to 165 ft . lamberts.

As the format required for a PPE Ltd., Monocular magnifier was identical with that of the SLAB magnifier, as this was designed to replace it, the same module could be used for both these magnifiers.

Comparison of Magnifiers

The three formats used in these modules are shown in Fig.35. The magnifiers as initially suggested, were intended to provide as wide a range of visual aberration levels as possible so that the extent of observer interaction with visual instruments of this type could be assessed over a broad front. The problems encountered in obtaining equalisation of screen resolution cast some doubts on this approach. Essentially, the screen and projector lens became part of the magnifier when these are different for each type. The effective resolution at the centre of the field was visually assessed with the registration film to be 35 lp/mm on the film. This was consistent across all modules to within $\pm$ 3 lp/mm which was the best that could be judged by eye.

This is equivalent to 350 line pairs across the 880 mRad (50^{o}) of the horizontal field. The limiting resolution is therefore 0.4 lines

lines pairs/mRad. which, for the normal target (see Fig.32) occurs at about 0.6 secs. after the triggering flash. However, the variation between module resolution could be equivalent to $\pm$0.04 line pairs/mRad. which is $\pm$1.0 seconds of viewing time. This must be taken into account when considering the results, although the average recognition time for most objects is between three and six seconds which is over two seconds later than the visual contrast threshold time of the objects.

Essentially, this feature means that comparisons across systems employing different screens and modules must be done with care. Magnifiers which use the same screen and module allow a more direct comparison. For the second and subsequent experiments it was decided that the investigations should concentrate on the high-power magnifier and differences in trial duration and conditions should be looked at as well as optical differences introduced by add-on elements. The trial duration and conditions changes are described in the next chapter but the add-on elements are described in the next section.

SLAB Module II

When only add-on elements are changed between trials the module can be more permanent and complex. The mirror on the projector which folds the light through 90^{o} can now be located on the module and reduced in size so that only the axial light from the projector lens is reflected. With this mirror fixed relative to the vibrating screen the direct beam can be received on a second screen which is also fixed to the module. This receives light from the periphery of the projector lens. In fact, two horizontal parts of an annular aperture were used so that defocussing could be seen as a dividing of the image. The central portion was stopped down to f/6 with a 8mm stop and the brighter image from the annular apertures was used to trigger the photo-cells. This arrangement gave a better consistency of registration and focussing to the accuracies discussed in Chapter 6, Section 5.

5.7 Add-on Elements to modify visual aberration Values

Consideration of the visual aberrations in Chapters 2 and of the response of the visual apparatus considered in Chapters 3 & 4 suggests that parallax error may produce incorrect response or visual discomfort before any of the other aberrations. This aberration had in fact been relatively well corrected in the aspheric plastics magnifier at the expense of field curvature and astigmatism and in the high-powered magnifier at the expense of field curvature and binocular overlap.

To investigate this a series of 3 add-on prism arrangements were made to give a longitudinal shift to the convergence surface. At the same time a cylindrical add-on lens was manufactured to give a change in astigmatism. The physical shape of these items is given in Fig.36 and their optical effects in Fig.37. Although the use of base-in and base-out prisms in this way gives a lateral shift to each accommodation surface (up to 10mm) the most obvious change is the longitudinal shift in the convergence surface. In Fig.37 only this second effect has been shown. With the cylindrical lens the major effect in the horizontal plane containing the magnifier axis and the eyes is the shift of the sagittal image surface as shown in Fig.37.

The use of add-on elements does allow identical projection optics and diffusing screens to be used with each system. The remaining unwanted differences are therefore those due to the order of viewing by the subject and the visual tasks used. The experimental design as described in section 4 of this Chapter should remove

FIG. 36 ADD-ON ELEMENTs FOR EXPTS 3 & 4

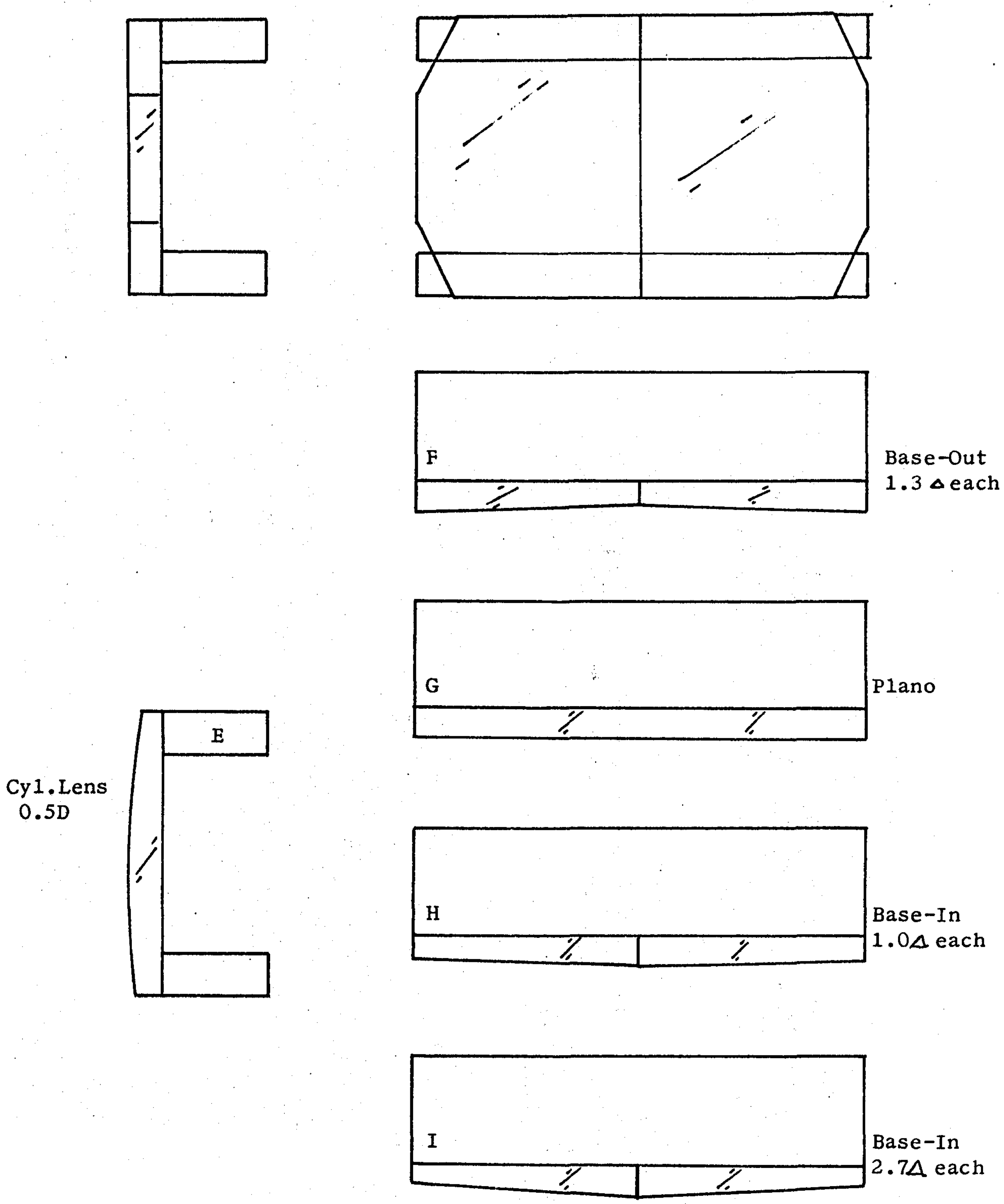
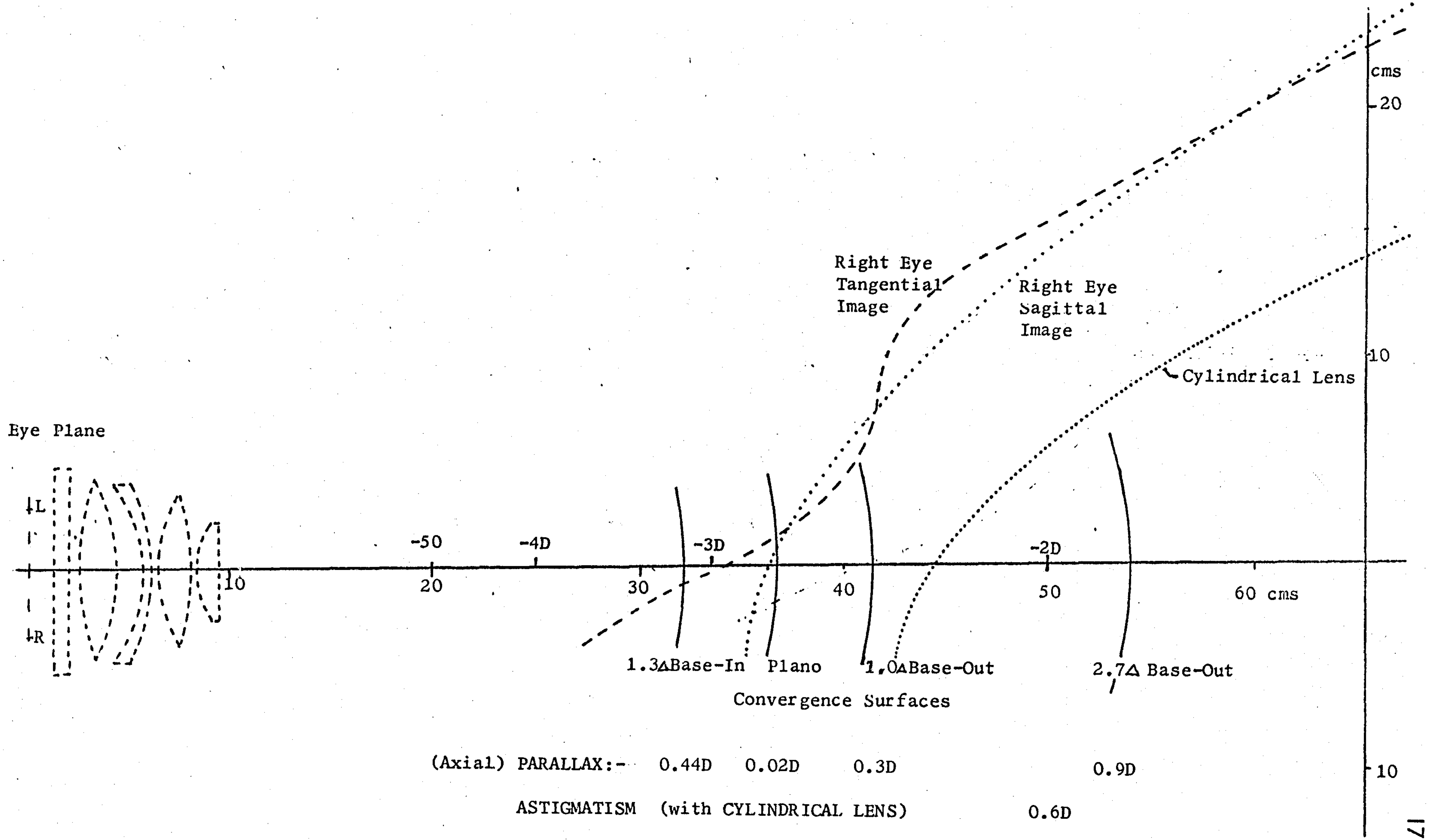


FIG.37 EFFECT OF ADD-ON ELEMENTS ON HIGH-POWERED MAGNIFIER (SLAB)



these leaving only differences due to the changes in visual aberrations. The way in which these interact with the existing visual aberrations and the interpupilliary distance of the observer is considered in Chapter 6.

CHAPTER 6

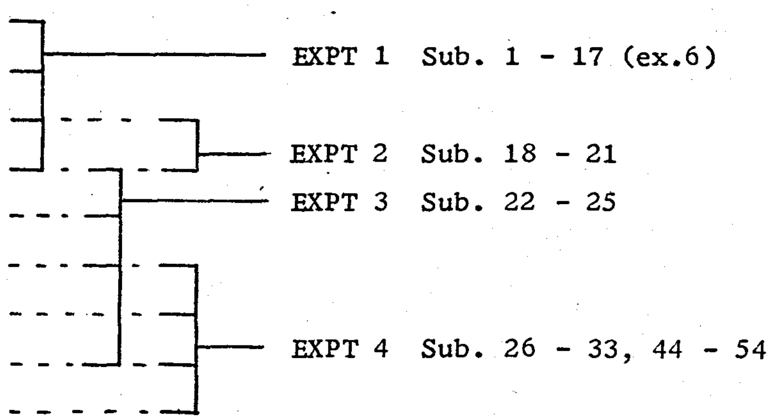
EXPERIMENTAL RESULTS

6.1 Introduction

During the course of the investigatory part of this study four experiments have been carried out. While some of these used too few subjects to yield conclusive results all four are reported as they provide useful pointers for future work. Experiment 1 compared three widely different biocular magnifiers and a high-power monocular magnifier. Experiment 2 investigated differences between interrupted and continuous viewing. Experiment 3 compared add-on elements on a high-power biocular magnifier as a preliminary to Experiment 4 which again used add-on elements but with more subjects who were selected and arranged as far as possible, according to inter-ocular distance and muscular balance.

The general pattern of experimental work may be shown diagramatically as follows:-

	Magnifier Designation
Plane Glass (STOG)	A
Plastics (COP)	B
Monocular	C
Biocular (SLAB)	D
Biocular + Cyl	E
Biocular + Base-out	F
Biocular + Plano	G
Biocular + Base-in (1)	H
Biocular + Base-in (2)	I



Although each experiment was directed towards a specific problem the analysis of viewing times has been common to all. The use of a natural task using real objects in a real environment as described in Chapter 5 was intended to form the basis of a comparison between magnifiers of the subject's performance on them. It was expected that some deterioration in performance might be found as fatigue effects set in. Contrary to this expectation only minor fatigue effects have been found. The centre of interest has therefore concentrated on the performance variations which have been found. Although the natural task has probably reduced subject variations by maintaining a more stable level of motivation than 80 minutes of a more repetitive task, the variability in contrast and location of each object does require careful analysis of the results if the maximum amount of information is to be extracted from them.

The experimental approach using filmed objects allowed the timing system to be triggered by a light flash, unseen by the subject, which generally occurred 10 seconds before the object went out of view, at the side of the scene. However, this does not allow for bends in the canal, partial obscuration by bushes and trees, differences in backgrounds etc. Each object must be treated individually. The experimental design allows that each object is viewed twice by each subject - directly and with the film laterally reversed. Each object is viewed via each magnifier an equal number of times. When sixteen subjects view four films of four sections having sixteen objects in each section each object viewing may be designated by five digits i,j,k,l,m where i is the subject number from one to sixteen,

j is the film number, from one to four
k is the section number, from one to four
l is the object number within a section from one to sixteen
m is the magnifier used, from one to four.

If a new section number k is defined as 4(j - 1) +k this gives a single k factor from one to sixteen. Each sighting provides a viewing time $t_{i,k,l,}$ which is part of a 16 x 16 x 16 array. k and l define a specific object so that $\sum_{i=1}^{16} t_{ikl}$ can be divided by the number of actual sightings (which may be less than 16) to give $\bar{t}_{kl}$ or $t_{.kl}$, the mean sighting time for a given object.

It is now possible to define a reduced sighting time as $(t_{ikl}-t_{.kl})$ which is no longer biased with respect to the moment of the triggering flash or the conspicuity of the target assuming no interaction between the magnifier and these.

As each of these reduced sighting times may be replaced in the original array the designation must allow an independent location for each such as $(t_{ikl}-t_{.kl})_{ikl}$ The mean of these values for each section is then $(t_{ikl}-t_{.kl})_{ik.}$ These means can be simplified to T_{ik} but the k value is no longer important as the similarity between the films and the reduction process makes the T values comparable across films and film sections.

The interest is now directed to the particular magnifier, trial and sub-trial on which each T value was obtained. In this context trial refers to the first, second, third or fourth 20 minute viewing period of each subject while sub-trial refers to the first, second third or fourth 5 minute viewing period within each trial.

The value of these might be definable mathematically from the greco-latin squares described in Chapter 5, but a reference file in the computer program is easier and in practice the 16 viewing times punched on each computer card were separately designated for subject, magnifier, trial, film, section, sub-trial; the last two being in the code number. Thus each T value may be averaged over each trial (u) or each magnifier (m) for each sub-trial(v). Over the sixteen sights of each sub-trial the mean of the T values may be designated T_{imv} or T_{iuv}. When results are taken over all subjects the values $T_{.mv}$ and $T_{.uv}$ can be obtained. As a figure of merit for a given magnifier or trial the values $T_{.m}$ or $T_{.u}$ may be calculated across the four sub-trials. In practice these values have been found easier to comprehend when given about an artifical mean of 5.00 secs. as this avoids negative values. The treatment of missing values is considered in the next section.

6.2 Experiment 1 (subjects 1 - 17, excluding 6)

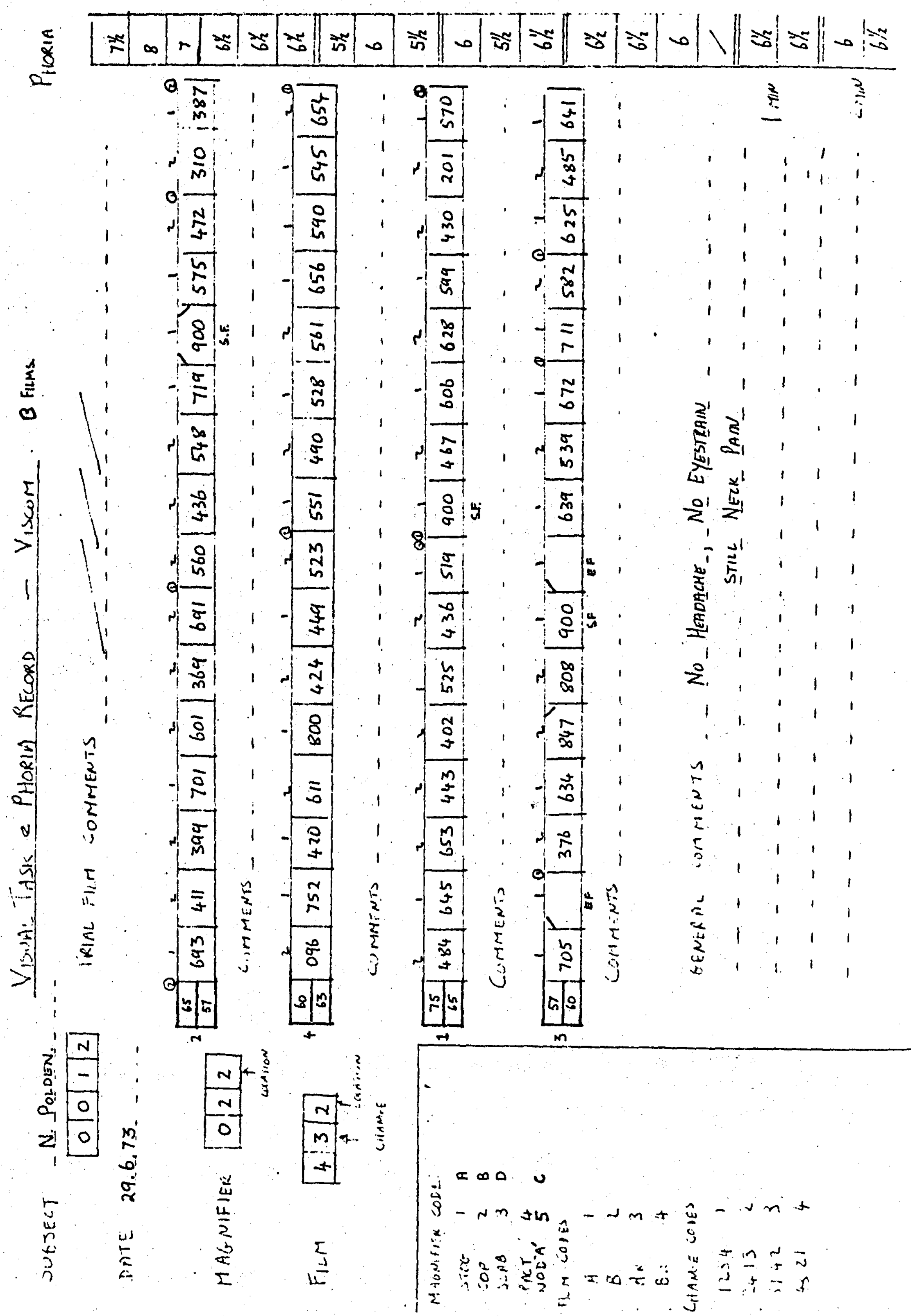
This first experiment was intended to examine a wide range in magnifier types and form an initial proving of the approach in general and the visual task material in particular. Three magnifier modules as described in Section 5.6 were required as the high-power monocular (C) and biocular (D) could use the same one. The four magnifiers investigated were therefore:

Straight-through glass (screen at 50 cms)	A
Plastic Aspheric Magnifier (COP)	B
Monocular Magnifier	C
Biocular Magnifier (SLAB)	D

These magnifiers were then used by 16 subjects drawn from PPE Ltd., The times of orientation recognition by these subjects were recorded manually from an electro-luminescent display onto charts of which Fig.38 is an example. This contains three subject failures (ie, object not seen) and two equipment failures (i.e, timing system not triggered) out of the 64 possible values. The values are given in 100ths of a second. During the analysis of the 64 sheets which comprise the results the question of how to treat these missing values had to be decided. Array 6 (Chapter 5, Page 148) was used.

In the calculation of the T values, each individual t value is used twice. In the first case the sightings of a given object are not over all conditions of magnifier, trial and sub-trial if less then 16 are obtained. As far as equipment failures go these should be random across trials and sub-trials but an object with a poor triggering flash will tend to produce equipment failures. Equally an object requiring considerable vigilance on the part of the

FIG 38 VISUAL TASK AND PHORIA RECORD - EXPTS 1,2 & 3



subject is not a good arbiter of visual performance via the magnifier at least not as a primary interaction. It was therefore decided that any object with less than 11 sightings should be abandoned in the calculation and all its times ignored. With objects where 4 or 5 of the sightings were lost, these should be random as regards equipment failures but obviously subject failures will tend to occur with the poorer magnifiers and less alert subjects. The absence of these values when calculating the mean value will tend to improve that value (make it a shorter time) which will make the remaining magnifiers appear less good. Thus, the action is towards a reduction of the differences found and therefore reduces rather than enhances the chances of significance. As significance of differences between magnifiers is the major criteria of the visual task performance values the effect of missing values was accepted as a necessary evil which was most unlikely to give spurious significance to any differences between magnifiers.

Within a sub-trial the T_{imv} and T_{iuv} were merely taken over the available results. Although the significance of a sub-trial having very few sightings is less than one having the total 16 no other values are available to calculate trends for each subject. When calculating the means over all subjects, $T_{\cdot mv}$ and $T_{\cdot uv}$, no justification can be advanced for deliberately weighting against such Timv or Tiuv values and as the variations between subjects and their trends are so large no 'missing value' techniques used in statistical analysis are applicable.

The values of T_{imv} and T_{iuv} are given in Figs 39 & 40 where the former are given for the four magnifiers used and the four five-

FIG 39. RESULTS BY MAGNIFIER OVER ALL OBJECTS - EXPT 1

MAGNIFIER	A m=1				B m=2				C m=4				D m=3			
OBJECT 1	3.07	3.32	2.83	3.11	5.43	6.72	5.56	5.56	5.96	6.20	5.42	5.44	6.40	6.19	5.66	[illegible]
	1.15	1.06	1.07	1.20	1.51	1.01	2.01	0.97	0.76	0.85	1.35	0.72	0.82	0.79	1.14	[illegible]
	-2.03	-1.77	-2.27	-1.99	0.33	1.61	0.45	0.45	0.86	1.10	0.31	0.33	1.29	1.08	0.55	-0.25
		-2.02	(1.11)			0.74	(1.48)			0.62	(1.00)			0.67	(1.07)	
2	4.46	3.81	4.84	4.67	5.53	5.35	5.17	5.13	6.35	6.34	6.18	6.65	5.14	4.99	5.16	5.45
	1.68	1.55	1.04	1.36	0.63	1.39	0.84	0.73	1.14	1.25	1.07	0.97	0.93	0.65	0.94	0.86
	-0.85	-1.51	-0.47	-0.65	0.23	0.03	-0.14	-0.19	1.03	1.01	0.86	1.30	-0.18	-0.33	-0.19	0.12
		-0.92	(1.47)			-0.02	(0.92)			1.05	(1.09)			-0.11	(0.65)	
3	5.39	5.25	4.09	3.82	5.90	6.38	5.09	5.32	5.38	4.74	4.57	4.61	4.67	4.96	4.61	[illegible]
	1.11	1.70	1.72	1.04	0.53	0.58	0.53	0.62	0.78	1.57	0.80	0.67	1.09	1.07	1.09	0.97
	0.37	0.22	-0.92	-1.20	0.88	1.35	0.06	0.30	0.35	-0.27	-0.45	-0.41	-0.34	-0.06	-0.41	[illegible]
		-0.34	(1.55)			0.66	(0.76)			-0.19	(1.00)			-0.20	(1.05)	
4	3.58	3.37	4.09	3.99	4.78	5.37	5.50	5.28	5.02	5.90	5.67	4.79	4.33	3.55	3.98	4.05
	0.90	1.02	1.06	1.00	0.70	1.30	1.16	0.96	0.94	1.12	1.06	1.14	0.63	0.76	0.70	0.95
	-0.99	-1.21	-0.48	-0.58	0.20	0.79	0.92	0.70	0.44	1.32	1.09	0.21	-0.24	-1.03	-0.60	-0.52
		-0.83	(1.03)			0.66	(1.06)			0.79	(1.13)			-0.57	(0.81)	
5	2.82	3.63	3.35	3.56	5.38	5.07	4.35	4.68	0.00	5.67	5.65	5.72	5.07	4.78	4.13	4.83
	0.70	0.95	1.11	1.21	0.81	0.60	0.47	0.76	0.00	0.82	0.81	0.57	0.86	0.75	0.72	1.16
	-1.71	-0.90	-1.18	-0.97	0.83	0.53	-0.18	0.13	-4.54	1.13	1.11	1.16	0.53	0.24	-0.40	0.29
		-1.21	(1.04)			0.32	(0.76)			1.21	(0.68)			0.15	(0.95)	
7	4.60	3.93	4.06	4.23	6.48	5.85	6.50	7.08	5.85	6.54	6.47	5.92	5.53	5.12	5.21	[illegible]
	1.20	0.62	1.15	1.03	1.68	1.21	1.03	1.40	0.61	0.69	0.70	0.46	0.95	0.71	0.51	0.54
	-0.86	-1.53	-1.40	-1.23	1.01	0.38	1.03	1.61	0.38	1.07	1.00	0.46	0.06	-0.34	-0.24	-0.40
		-1.24	(1.04)			1.00	(1.37)			0.71	(0.68)			-0.24	(0.69)	
8	2.67	3.29	3.07	2.38	6.03	5.68	6.36	5.48	3.84	4.01	4.43	3.74	3.72	3.99	4.08	[illegible]
	1.06	1.35	0.87	1.25	1.02	1.38	1.37	0.68	1.49	1.14	1.01	1.17	1.00	1.31	0.56	0.95
	-1.50	-0.88	-1.10	-1.79	1.85	1.50	2.18	1.30	-0.32	-0.15	0.25	-0.43	-0.45	-0.18	-0.09	0.02
		-1.31	(1.17)			1.71	(1.14)			-0.16	(1.20)			-0.17	(0.98)	
9	3.18	5.03	3.77	3.98	7.49	6.45	7.40	7.00	3.88	4.54	5.13	4.55	5.23	4.66	4.57	4.29
	1.93	1.05	1.85	1.65	0.73	0.92	0.87	1.95	1.25	0.89	1.34	0.89	1.50	0.99	0.54	1.47
	-1.73	0.11	-1.15	-0.93	2.57	1.53	2.48	2.08	-1.03	-0.37	0.21	-0.36	0.31	-0.25	-0.34	-0.62
		-1.01	(1.77)			2.12	(1.25)			-0.39	(1.16)			-0.25	(1.22)	
10	4.02	3.24	5.10	3.71	5.80	5.68	5.79	5.97	4.38	4.87	5.02	4.88	4.75	4.95	4.77	3.95
	1.06	1.33	1.16	1.66	1.39	0.78	0.79	1.29	1.33	1.19	0.88	1.13	0.80	0.91	0.65	0.77
	-0.77	-1.55	0.30	-1.08	1.00	0.88	0.99	1.17	-0.41	0.07	0.22	0.08	-0.04	0.15	-0.02	[illegible]
		-0.81	(1.45)			1.00	(1.05)			-0.02	(1.15)			-0.16	(0.65)	
11	6.26	4.39	5.72	5.52	6.90	6.83	6.05	6.90	7.40	7.17	7.59	7.82	5.16	5.87	5.70	[illegible]
	0.82	0.59	1.39	0.96	1.28	1.31	1.02	1.25	1.17	1.01	1.17	0.93	1.02	1.00	1.21	0.95
	0.08	-1.79	-0.45	-0.66	0.72	0.65	-0.12	0.72	1.21	0.98	1.40	1.64	-1.01	-0.30	-0.48	-0.67
		-0.76	(1.15)			0.57	(1.23)			1.34	(1.04)			-0.68	(1.05)	
12	4.16	3.31	2.99	2.86	4.36	5.46	5.58	5.48	5.37	5.71	5.68	4.78	3.62	3.47	3.65	3.93
	1.36	0.79	1.17	0.87	1.01	0.96	0.96	0.94	0.95	0.65	0.85	0.58	0.84	0.80	0.97	1.22
	-0.26	-1.11	-1.43	-1.56	-0.06	1.03	1.23	1.05	0.94	1.28	1.25	0.35	-0.80	-0.95	-0.77	[illegible]
		-1.09	(1.18)			0.78	(1.08)			0.97	(0.90)			-0.75	(0.92)	
13	3.82	3.38	3.22	3.08	5.01	4.57	4.71	4.73	6.72	4.77	4.37	4.58	4.27	4.58	5.12	5.67
	1.87	1.50	1.36	1.41	0.73	0.65	1.02	0.61	0.83	1.30	0.76	1.02	0.64	0.69	0.67	[illegible]
	-0.68	-1.12	-1.28	-1.42	0.50	0.06	0.20	0.22	2.21	0.26	-0.13	0.07	-0.23	0.07	0.61	[illegible]
		-1.12	(1.55)			0.25	(0.78)			0.57	(1.35)			0.40	(0.86)	
14	4.39	3.98	2.83	4.73	4.38	4.11	4.21	4.19	6.39	5.05	5.32	5.24	4.88	4.77	4.93	5.83
	1.36	1.86	1.77	0.90	0.77	0.75	0.63	1.11	1.02	0.79	0.71	0.88	1.12	1.36	1.66	[illegible]
	-0.31	-0.71	-1.86	0.03	-0.31	-0.58	-0.48	-0.50	1.69	0.35	0.62	0.54	0.18	0.07	0.23	[illegible]
		-0.63	(1.62)			-0.47	(0.82)			0.74	(0.96)			0.35	(1.53)	
15	4.20	4.38	4.46	4.18	5.01	5.41	6.01	5.38	5.29	5.63	4.49	5.24	4.70	4.69	4.93	[illegible]
	0.49	0.71	0.53	0.70	0.44	1.17	1.15	1.07	0.87	0.72	1.08	1.05	0.66	0.59	0.80	[illegible]
	-0.73	-0.55	-0.47	-0.76	0.06	0.46	1.07	0.44	0.35	0.69	-0.44	0.29	-0.24	-0.24	-0.01	[illegible]
		-0.63	(0.62)			0.53	(1.05)			0.25	(1.00)			-0.08	(0.69)	
16	4.61	4.17	3.14	4.46	5.38	5.86	6.35	5.88	6.49	6.31	6.47	5.58	5.42	4.82	4.21	[illegible]
	1.28	1.62	1.57	1.74	0.58	0.88	0.51	0.78	1.04	1.28	1.19	1.35	0.69	0.74	0.74	[illegible]
	-0.58	-1.03	-2.06	-0.74	0.18	0.65	1.14	0.67	1.29	1.11	1.26	0.37	0.27	-0.38	-0.99	[illegible]
		-1.14	(1.64)			0.66	(0.77)			1.00	(1.25)			-0.42	(0.79)	
17	5.46	5.18	5.32	5.80	6.06	5.66	5.87	6.16	6.68	6.14	6.94	6.80	7.28	6.85	6.71	6.41
	0.79	0.91	1.01	0.77	0.70	0.99	0.61	1.14	0.86	1.66	1.17	1.08	1.02	1.02	0.70	[illegible]
	-0.72	-1.00	-0.86	-0.38	-0.12	-0.52	-0.31	-0.02	0.49	-0.04	0.75	0.61	1.09	0.64	0.12	[illegible]
		-0.74	(0.88)			-0.25	(0.89)			0.47	(1.26)			0.62	(0.90)	
	4.17	3.98	3.93	4.00	5.62	5.65	5.66	5.64	5.67	5.60	5.59	5.40	5.02	4.89	4.84	[illegible]
	0.99	0.69	0.94	0.92	0.85	0.72	0.83	0.83	1.06	0.85	0.94	1.02	0.91	0.86	0.77	[illegible]
		4.02				5.64				5.56				4.91		

For key, see page 182

FIG 40 RESULTS BY TRIAL OVER ALL OBJECTS - EXPT 1

TRIAL	u=1				u=2				u=3				u=4			
JECT 1	5.43	6.72	5.56	5.56	5.96	6.20	5.42	5.44	3.07	3.32	2.83	3.11	6.40	6.19	5.66	4.84
	1.51	1.01	2.01	0.87	0.75	0.35	1.35	0.72	1.15	1.06	1.07	1.20	0.92	0.79	1.14	[illegible]
	0.33	1.61	0.45	0.45	0.86	1.10	0.31	0.33	-2.03	-1.77	-2.27	-1.99	1.29	1.08	0.55	[illegible]
		0.74	(1.48)			0.62	(1.00)			-2.02	(1.11)			0.67	(1.27)	
2	6.35	6.34	6.18	6.65	5.14	4.99	5.16	5.45	5.56	5.35	5.17	5.13	4.46	3.31	4.34	4.67
	1.14	1.25	1.07	0.97	0.93	0.68	0.94	0.86	0.63	1.39	0.84	0.73	1.68	1.55	1.04	1.36
	1.03	1.01	0.86	1.33	-0.18	-0.33	-0.15	0.12	0.23	0.03	-0.14	-0.19	-0.85	-1.51	-0.47	-0.65
		1.05	(1.09)			-0.11	(0.86)			-0.02	(0.92)			-0.92	(1.47)	
3	5.39	5.25	4.09	3.82	5.90	6.38	5.09	5.32	4.67	4.96	4.61	5.02	5.38	4.74	4.57	4.61
	1.11	1.70	1.72	1.04	0.53	0.58	0.53	0.62	1.09	1.07	1.09	0.97	0.78	1.57	0.80	0.67
	0.37	0.22	-0.92	-1.20	0.38	1.35	0.06	0.30	-0.34	-0.06	-0.41	-0.00	0.35	-0.27	-0.45	-0.41
		-0.34	(1.55)			0.66	(0.76)			-0.20	(1.05)			-0.19	(1.00)	
4	4.33	3.55	3.98	4.05	3.58	3.37	4.09	3.99	5.02	5.90	5.67	4.79	4.78	5.37	5.50	5.26
	0.63	0.76	0.70	0.99	0.90	1.02	1.06	1.08	0.94	1.12	1.06	1.14	0.70	1.30	1.16	0.90
	-0.24	-1.03	-0.60	-0.52	-0.99	-1.21	-0.48	-0.58	0.44	1.32	1.09	0.21	0.20	0.79	0.92	0.70
		-0.57	(0.81)			-0.83	(1.03)			0.79	(1.13)			0.66	(1.06)	
5	5.38	5.07	4.35	4.68	0.00	5.67	5.65	5.72	2.82	3.63	3.35	3.56	5.07	4.78	4.13	4.63
	0.81	0.60	0.47	0.78	0.00	0.82	0.81	0.57	0.70	0.95	1.11	1.21	0.86	0.75	0.72	1.18
	0.83	0.53	-0.18	0.13	-4.54	1.13	1.11	1.18	-1.71	-0.90	-1.18	-0.97	0.53	0.24	-0.40	0.29
		0.32	(0.76)			1.21	(0.68)			-1.21	(1.04)			0.18	(0.95)	
7	5.85	6.54	6.47	5.92	5.53	5.12	5.21	5.06	6.48	5.85	6.50	7.08	4.60	3.93	4.06	4.23
	0.61	0.69	0.70	0.46	0.95	0.71	0.51	0.54	1.68	1.21	1.03	1.40	1.20	0.62	1.15	1.03
	0.38	1.07	1.00	0.46	0.06	-0.34	-0.24	-0.40	1.01	0.38	1.03	1.61	-0.86	-1.53	-1.40	-1.23
		0.71	(0.68)			-0.24	(0.69)			1.00	(1.37)			-1.24	(1.04)	
8	2.67	3.29	3.07	2.38	6.03	5.68	5.36	5.40	3.72	3.95	4.08	4.20	3.84	4.01	4.43	3.74
	1.06	1.35	0.87	1.25	1.02	1.36	1.37	0.68	1.00	1.31	0.56	0.95	1.49	1.14	1.01	1.17
	-1.50	-0.88	-1.10	-1.79	1.85	1.50	2.18	1.30	-0.45	-0.16	-0.09	0.02	-0.32	-0.15	0.25	-0.43
		-1.31	(1.17)			1.71	(1.14)			-0.17	(0.98)			-0.16	(1.20)	
9	5.73	4.66	4.57	4.29	3.18	5.03	3.77	3.98	3.88	4.54	5.13	4.55	7.49	6.45	7.40	[illegible]
	1.50	0.99	0.94	1.47	1.93	1.05	1.85	1.65	1.25	0.89	1.34	0.89	0.73	0.92	0.87	[illegible]
	0.31	-0.25	-0.34	-0.62	-1.73	0.11	-1.15	-0.93	-1.03	-0.37	0.21	-0.36	2.57	1.53	[illegible]	[illegible]
		-0.25	(1.22)			-1.01	(1.77)			-0.39	(1.10)			2.12	(1.25)	
10	4.75	4.95	4.77	3.95	4.02	3.24	5.10	3.71	4.38	4.57	5.02	4.98	5.80	5.68	5.79	5.97
	0.80	0.91	0.65	0.77	1.06	1.33	1.16	1.66	1.33	1.18	0.88	1.13	1.39	0.78	0.79	1.29
	-0.04	0.15	-0.02	-0.84	-0.77	-1.55	0.30	-1.08	-0.41	0.07	0.22	0.08	1.00	0.89	0.99	1.17
		-0.16	(0.85)			-0.81	(1.45)			-0.02	(1.15)			1.00	(1.05)	
11	6.90	6.83	6.05	6.90	7.40	7.17	7.59	7.82	6.26	4.39	5.72	5.52	5.16	5.87	5.70	5.30
	1.28	1.31	1.02	1.25	1.17	1.01	1.17	0.93	0.82	0.59	1.39	0.96	1.02	1.00	1.21	0.93
	0.72	0.65	-0.12	0.72	1.21	0.98	1.40	1.64	0.08	-1.79	-0.45	-0.66	-1.01	-0.30	-0.48	-0.87
		0.57	(1.23)			1.34	(1.04)			-0.76	(1.15)			-0.68	(1.05)	
12	4.16	3.31	2.99	2.86	4.36	5.46	5.68	5.48	3.62	3.47	3.65	3.93	5.37	5.71	5.66	4.78
	1.36	0.79	1.17	0.87	1.01	0.96	0.96	0.94	0.84	0.80	0.97	1.22	0.95	0.66	0.85	0.88
	-0.26	-1.11	-1.43	-1.56	-0.06	1.03	1.25	1.05	-0.80	-0.95	-0.77	-0.49	0.94	1.28	1.25	0.85
		-1.09	(1.18)			0.78	(1.08)			-0.75	(0.96)			0.97	(0.90)	
13	5.72	4.77	4.37	4.58	4.27	4.58	5.12	5.87	5.01	4.57	4.71	4.73	3.32	3.38	3.22	3.08
	0.83	1.30	0.76	1.02	0.64	0.69	0.67	0.56	0.75	0.65	1.02	0.61	1.67	1.50	1.36	1.41
	2.21	0.26	-0.13	0.07	-0.23	0.07	0.61	1.36	0.50	0.06	0.20	0.22	-0.68	-1.12	-1.28	-1.42
		0.57	(1.35)			0.40	(0.66)			0.25	(0.78)			-1.17	(1.55)	
14	4.38	4.11	4.21	4.19	6.39	5.05	5.32	5.24	4.39	3.98	2.83	4.73	4.80	4.77	4.93	5.60
	0.77	0.75	0.63	1.11	1.02	0.78	0.71	0.88	1.35	1.65	1.77	0.50	1.12	1.38	1.60	1.65
	-0.31	-0.58	-0.48	-0.50	1.69	0.35	0.62	0.54	-0.31	-0.71	-1.86	0.03	0.18	0.07	0.23	0.93
		-0.47	(0.82)			0.74	(0.96)			-0.63	(1.62)			0.35	(1.53)	
15	4.20	4.38	4.46	4.18	5.01	5.41	6.01	5.38	4.70	4.69	4.93	5.08	5.29	5.63	4.49	5.24
	0.49	0.71	0.58	0.70	0.44	1.17	1.15	1.07	0.86	0.59	0.60	0.69	0.87	0.72	1.28	1.06
	-0.73	-0.55	-0.47	-0.76	0.06	0.46	1.07	0.44	-0.24	-0.24	-0.01	0.14	0.35	0.69	-0.44	0.29
		-0.63	(0.62)			0.53	(1.05)			-0.08	(0.69)			0.25	(1.00)	
16	5.48	4.82	4.21	4.59	4.61	4.17	3.14	4.46	6.49	6.31	6.47	5.58	5.78	5.86	6.35	[illegible]
	0.69	0.74	0.74	0.50	1.28	1.62	1.57	1.74	1.04	1.28	1.19	1.35	0.58	0.88	0.81	0.76
	0.27	-0.38	-0.99	-0.61	-0.58	-1.03	-2.06	-0.74	1.29	1.11	1.26	0.37	0.18	0.65	1.14	0.67
		-0.42	(0.79)			-1.14	(1.64)			1.00	(1.25)			0.66	(0.77)	
17	6.68	6.14	6.94	6.80	7.28	6.83	6.71	6.41	6.06	5.56	5.87	6.16	5.46	5.18	5.32	5.80
	0.86	1.65	1.17	1.08	1.02	1.02	0.76	0.56	0.70	0.99	0.61	1.14	0.79	0.91	1.01	0.77
	0.49	-0.04	0.75	0.61	1.09	0.64	0.52	0.22	-0.12	-0.52	-0.31	-0.02	-0.72	-1.00	-0.86	[illegible]
		0.47	(1.26)			0.62	(0.90)			-0.25	(0.89)			-0.74	(0.88)	
	5.24	5.05	4.77	4.71	5.25	5.27	5.34	5.30	4.76	4.72	4.78	4.88	5.20	5.09	5.13	5.06
	1.13	1.18	1.15	1.33	1.26	1.09	1.08	0.99	1.17	0.91	1.16	0.96	0.89	0.92	1.00	0.95
		4.94				5.29				4.78				5.12		

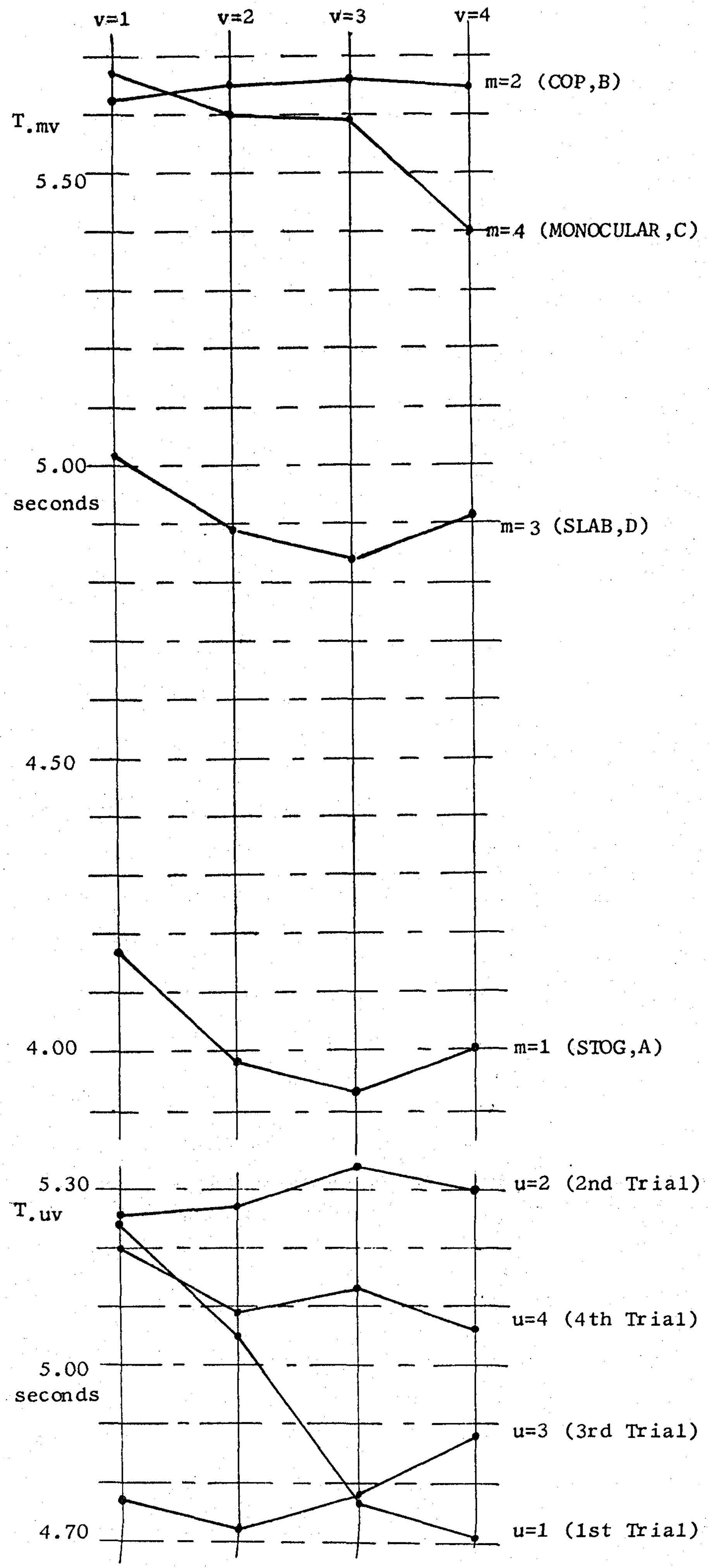
For key, see page 182

minute sub-trials on each (v = 1,4) followed by the standard deviation of the 16 or fewer results which provide the T value. The third line shows $\tau_{imv} = (T_{imv} - T_{i..})$. This is the difference for that particular sub-trial from the mean for that subject over all magnifiers. Finally, the mean of results over all four sub-trials is shown in the fourth line with respect to the subject mean, that is:- $T_{im.} - T_{i..}$ The standard deviation of this last value is shown in parenthesis alongside. As the fourth line value does not necessarily accrue from 64 sighting for each magnifier (due to missing values) the four values shown for each subject do not sum to exactly zero. The same format is used for the T_{iuv} values which (Fig.40) merely arranges the same figures for each subject in the order in which he viewed them.

Beneath these values for each subject the mean values over all subjects are given for each sub-trial and below these the standard deviation of the mean over all subjects. The mean of these values over the four sub-trials is then given. The last three lines of Figs.39 & 40 give $T_{.mv}$, $\left(\sum_{i=1}^{16} (T_{imv} - T_{.mv})^2 / 15 \right)^{\frac{1}{2}}$ and $T_{.m.}$ and $T_{.uv}$, $\left(\sum_{i=1}^{16} (T_{iuv} - T_{.uv})^2 / 15 \right)^{\frac{1}{2}}$ and $T_{.u.}$ respectively. All T values are given about an artificial mean of 5.00 secs.

The values of $T_{.mv}$ and $T_{.uv}$ are plotted in Fig.41. As the magnifiers had been specifically chosen to represent wide differences of type it is reassuring to see that the viewing times show differences between the magnifiers in the way to be expected from the quality of their imagery discussed in Chapter 2, although the monocular is, of course, excluded from that discussion. Concentrating on those magnifiers allowing two eye viewing it is seen that the differences

FIG.41 OVERALL RESULTS - EXPT 1



between magnifiers is considerably larger than the differences between trials. Although a sharp learning effect is observed in the first trial, these latter graphs lie between ± 0.32 secs.

When considering differences between these magnifiers it is important to remember that because of the large differences in format size it was not possible to ensure that the screens and projection lenses used did not contribute to the results obtained. However, this first investigation was intended to see if differences between widely different magnifiers could be detected and what differences between subject performance & trends could be found to indicate fatigue effects.

It is seen immediately that the effect with time for each magnifier is much smaller than the differences between them when averaged over all subjects. As a start and because of this small movement with time, a two-way analysis was carried out which assumed that performance was not influenced by time so that each five minute result for each subject (T_{imv}) could be considered as a repeat observation of the value $T_{im.}$.

This analysis gave the following results:-

Source	Sum of Squares	Degrees of Freedom	Mean of Squares	Mean Square Ratio	
Bet.Subjects	83.3091	15	5.5539	26.322	xxx
Bet.Magnifiers	108.2960	3	36.0986	26.139	xxx
Interaction	62.1438	45	1.3810	6.545	xxx
Residual	40.5294	192	0.2110		
TOTAL	294.2783	255			

The xxx sign indicates significance at the 0.1% level. Obviously, the difference between subjects is large and an experiment using magnifiers of a more similar type could run into this limiting precision.

The correct application of the F-test to the mean square ratio requires the magnifier mean square to be compared against the interaction mean square if the 16 subjects are to be regarded as a sample of the population.

A further analysis may be done when the different types of object are considered. The most obvious division of objects used, as described in Chapter 5, is into vertical and horizontal types. An extra file in the data reduction program stored this information about each object and separate computations were run. The T_{imv} values are given in Figs 42 and 43 while the graphs of Fig.44 show the $T_{.mv}$ values for each type of object. It is seen that only magnifier B shows any significant difference between the two object types.

On reference to Chapter 2 it is seen that this magnifier has about 1D of astigmatism over all the field. More significant is that this astigmatism is biased away from the convergence surface so that the accommodation of the eyes as determined by the convergence required for fusion will be more correct for the sagittal image surface than for the tangential over most of the field. The tangential plane of the analysis is defined as that plane containing the field point and the axis of the lens. With the objects mainly in the horizontal plane though the axis of the lens as are the eyes, this horizontal plane becomes the tangential plane in which vertical objects are seen. The sagittal plane is therefore the image plane of the horizontal objects and this is in accord with the result that the $T_{.mv}$ values for this magnifier show shorter viewing times for horizontal objects compared with vertical objects.

FIG 42 RESULTS BY MAGNIFIER FOR VERTICAL OBJECTS - EXPT 1

MAGNIFIER	A m=1	B m=2	C m=4	D m=3
OBJECT 1	2.59 2.91 2.24 2.95 1.07 1.15 0.90 1.60 -2.46 -2.14 -2.82 -2.10 -2.42 (1.18)	6.72 7.21 5.78 5.70 0.03 0.49 2.82 0.97 1.65 2.15 0.71 0.64 1.32 (1.52)	5.76 6.44 5.24 5.50 0.55 0.31 1.44 0.76 0.69 1.37 0.18 0.43 0.59 (1.01)	6.59 6.27 5.52 4.37 0.70 0.91 1.45 0.39 1.52 1.20 0.45 -0.60 0.61 (1.26)
2	3.67 3.64 4.92 5.09 1.26 2.05 1.02 1.75 -1.67 -1.69 -0.42 -0.24 -1.01 (1.57)	5.49 5.65 5.48 5.07 0.97 1.62 0.70 0.72 0.14 0.31 0.13 -0.20 0.03 (0.98)	6.31 7.06 6.49 6.86 1.32 1.85 1.46 1.08 0.97 1.72 1.15 1.51 1.36 (1.30)	5.24 4.49 5.31 5.05 1.10 0.23 1.09 0.67 -0.09 -0.34 -0.02 -0.28 -0.20 (0.92)
3	5.40 5.67 3.88 3.57 1.46 1.94 1.09 1.21 0.51 0.78 -1.00 -1.31 -0.29 (1.67)	5.57 6.32 5.22 5.55 0.50 0.70 0.62 0.54 0.68 1.43 0.33 0.66 0.76 (0.71)	5.43 3.85 4.30 4.33 0.97 0.78 0.61 0.76 0.54 -1.03 -0.58 -0.55 -0.38 (0.97)	4.93 5.19 4.24 4.56 1.56 1.33 1.52 0.94 0.04 0.29 -0.54 -0.32 -0.12 (1.29)
4	3.75 3.23 4.10 3.69 0.72 1.28 1.19 1.15 -0.71 -1.24 -0.37 -0.78 -0.76 (1.09)	4.62 5.17 5.81 5.64 0.76 1.54 0.97 1.02 0.14 0.70 1.33 1.17 0.95 (1.13)	4.84 6.06 5.16 4.70 1.09 1.11 1.32 1.22 0.37 1.58 0.69 0.23 0.78 (1.26)	4.05 2.91 3.57 3.60 0.61 0.64 0.60 0.61 -0.42 -1.56 -0.89 -0.87 -0.87 (0.73)
5	2.79 4.05 3.58 3.47 0.71 0.07 1.32 1.32 -1.83 -0.58 -1.04 -1.15 -1.19 (1.15)	5.32 5.12 4.39 4.61 0.38 0.60 0.43 0.40 0.58 0.48 -0.24 -0.01 0.29 (0.58)	5.51 5.50 5.59 5.69 0.66 0.23 1.25 0.44 0.87 0.87 0.95 1.05 0.95 (0.71)	5.17 4.52 4.16 5.04 0.63 0.50 0.36 0.75 0.54 -0.10 -0.47 0.41 0.08 (0.72)
7	5.28 3.86 4.47 4.09 1.62 0.55 0.73 0.89 -0.21 -1.62 -1.02 -1.40 -1.08 (1.08)	7.57 6.16 6.97 7.29 1.61 1.30 0.67 1.26 2.08 0.67 1.47 1.80 1.34 (1.28)	6.01 6.21 6.49 5.68 0.65 0.61 1.25 0.65 0.52 0.71 0.99 0.18 0.58 (0.68)	4.79 5.03 4.85 5.23 0.61 0.54 0.43 0.59 -0.70 -0.45 -0.64 -0.26 -0.48 (0.53)
8	2.36 2.98 2.92 1.99 1.24 1.54 1.15 1.30 -1.65 -1.03 -1.09 -2.02 -1.45 (1.32)	6.56 6.01 7.02 5.40 0.74 1.51 1.88 0.75 2.54 1.99 3.00 1.38 2.17 (1.19)	2.98 3.63 4.15 3.47 0.76 1.26 1.12 1.58 -1.03 -0.38 0.13 -0.54 -0.46 (1.23)	3.46 4.10 4.18 4.30 0.97 1.65 0.58 0.69 -0.55 0.08 0.16 0.28 0.00 (1.07)
9	2.79 5.60 3.91 4.12 1.56 0.53 1.81 2.12 -1.94 0.85 -0.85 -0.62 -0.86 (1.88)	7.56 6.77 7.32 6.04 0.91 0.87 1.12 2.36 2.81 2.02 2.57 1.29 2.17 (1.32)	3.41 4.60 5.33 4.59 1.35 1.03 2.15 1.34 -1.33 -0.14 0.58 -0.15 -0.37 (1.50)	4.47 4.54 4.41 3.94 1.19 1.19 1.11 1.66 -0.26 -0.20 -0.33 -0.30 -0.42 (1.27)
10	3.67 3.48 4.85 3.16 1.00 1.48 0.99 1.82 -1.35 -1.53 -0.17 -1.86 -1.29 (1.40)	6.54 5.36 5.99 5.95 1.34 0.75 0.92 0.94 1.51 0.34 0.96 0.92 0.94 (1.02)	4.42 6.22 5.52 5.50 1.85 0.77 0.62 1.08 -0.59 1.20 0.49 0.47 0.34 (1.27)	4.80 5.34 5.22 4.06 0.80 1.13 0.51 0.90 -0.22 0.32 0.19 -0.93 -0.09 (0.92)
11	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 -6.11 -6.11 -6.11 -6.11 -6.11 (0.00)	6.13 0.00 0.00 7.18 1.79 0.00 0.00 1.29 0.01 -6.11 -6.11 1.06 0.36 (1.59)	7.66 7.01 8.04 8.20 0.92 0.10 1.04 0.32 1.54 0.89 1.92 2.08 1.71 (0.80)	4.58 5.69 5.74 4.94 0.47 1.13 1.30 0.73 -1.53 -0.42 -0.37 -1.17 -0.90 (1.03)
12	3.98 3.20 3.07 2.39 1.30 1.03 1.29 0.86 -0.56 -1.35 -1.47 -2.15 -1.33 (1.24)	4.45 6.51 6.20 6.03 1.30 0.74 0.86 0.88 -0.09 1.96 1.65 1.47 1.21 (1.21)	5.74 5.17 5.69 4.33 0.76 0.18 0.98 0.82 1.19 0.62 1.13 -0.21 0.77 (0.96)	3.60 3.75 3.63 3.67 1.00 0.58 0.38 1.77 -0.94 -0.79 -0.91 -0.87 -0.88 (1.01)
13	4.23 3.74 2.97 2.87 1.89 1.41 0.70 1.97 -0.31 -0.80 -1.57 -1.67 -1.00 (1.67)	5.19 4.87 4.79 4.77 0.75 0.84 1.24 0.64 0.64 0.32 0.24 0.21 0.34 (0.93)	6.86 5.29 4.30 4.23 1.39 1.01 1.06 1.14 2.31 0.73 -0.24 -0.31 0.44 (1.48)	4.27 4.74 5.04 6.06 0.53 0.81 0.71 0.29 -0.25 0.16 0.49 1.51 0.34 (0.86)
14	4.27 3.78 2.87 4.54 0.59 1.75 0.98 0.82 -0.52 -1.01 -1.92 -0.25 -0.82 (1.27)	4.67 4.56 4.49 4.77 0.48 0.42 0.49 0.53 -0.13 -0.23 -0.31 -0.03 -0.19 (0.46)	5.75 4.65 5.24 5.21 1.09 0.91 0.74 1.15 1.94 -0.14 0.43 0.41 0.71 (1.24)	5.20 4.70 4.55 5.96 1.43 1.70 2.11 2.05 0.39 -0.10 -0.25 1.18 0.27 (1.85)
15	3.94 4.11 4.52 3.88 0.45 0.74 0.79 0.82 -1.05 -0.39 -0.47 -1.11 -0.92 (0.70)	5.18 6.31 6.35 5.56 0.43 1.17 1.23 0.28 0.18 1.31 1.34 0.55 0.87 (1.04)	4.93 5.88 4.96 5.41 0.50 0.71 1.18 1.45 -0.07 0.88 -0.04 0.41 0.26 (0.95)	4.57 4.87 5.11 5.16 0.94 0.58 0.75 0.61 -0.42 -0.12 0.11 0.16 -0.07 (0.73)
16	3.08 4.55 3.44 4.03 0.82 1.40 1.47 2.07 -0.19 -0.71 -1.22 -1.24 -1.03 (1.57)	5.55 6.15 6.59 5.74 0.55 0.79 0.52 0.57 0.28 0.87 1.31 0.46 0.69 (0.70)	6.41 5.94 6.81 5.41 1.36 1.69 1.06 1.86 1.13 0.67 1.54 0.14 0.96 (1.47)	5.51 4.62 4.14 4.66 0.73 0.79 1.01 0.52 0.23 -0.55 -1.13 -0.56 -0.50 (0.85)
17	5.76 5.42 4.83 5.85 0.87 0.96 1.26 0.71 -0.60 -0.95 -1.54 -0.52 -0.92 (1.01)	6.32 5.86 5.96 6.03 0.64 1.20 0.76 1.05 -0.04 -0.51 -0.40 -0.33 -0.30 (0.88)	7.29 6.54 7.53 6.69 0.49 2.39 0.89 1.36 0.92 0.16 1.15 0.32 0.72 (1.37)	7.51 7.27 6.73 6.50 1.25 0.76 0.18 0.66 1.14 0.89 0.36 0.13 0.69 (0.91)
	3.97 4.02 3.77 3.71 1.06 0.91 0.64 0.97 3.87	5.84 5.87 5.89 5.71 0.97 0.73 0.90 0.75 5.83	5.64 5.63 5.58 5.35 1.30 1.03 1.12 1.16 5.58	4.92 4.88 4.77 4.82 1.01 0.99 0.83 0.54 4.85

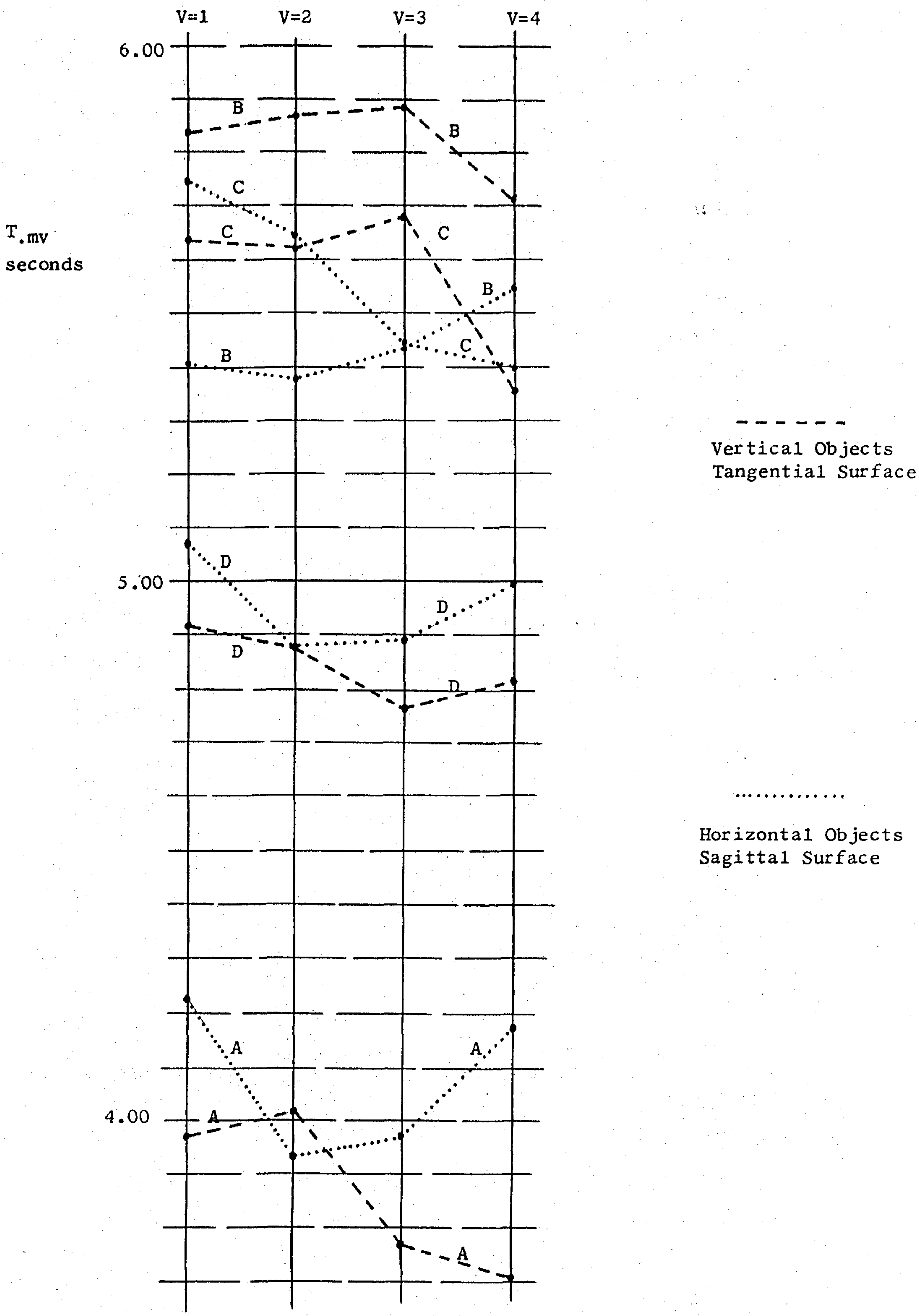
For key, see page 182

FIG 43 RESULTS BY MAGNIFIER FOR HORIZONTAL OBJECTS - EXPT 1

ECT	MAGNIFIER A m=1	B m=2	C m=4	D m=3
1	3.54 3.58 3.72 3.26	4.79 6.08 5.40 5.34	6.08 6.00 5.65 5.34	6.24 6.13 5.84 5.26
	1.08 0.98 0.61 0.68	1.42 1.17 1.31 0.70	0.86 1.12 1.30 0.71	0.94 0.73 0.62 0.69
	-1.60 -1.55 -1.42 -1.87	-0.34 0.93 0.25 0.19	0.93 0.86 0.51 0.20	1.09 0.98 0.70 0.11
	-1.62 (0.85)	0.20 (1.27)	0.66 (1.01)	0.73 (0.86)
2	5.26 3.92 4.65 4.24	5.60 5.09 4.94 5.24	6.37 5.86 5.98 6.19	5.02 5.17 4.97 5.84
	1.74 1.23 1.31 0.79	0.41 1.21 0.90 0.81	1.14 0.31 0.75 0.48	0.75 0.72 0.74 0.68
	-0.04 -1.38 -0.64 -1.08	0.29 -0.21 -0.36 -0.06	1.06 0.55 0.67 0.88	-0.28 -0.13 -0.35 0.53
	-0.83 (1.38)	-0.08 (0.86)	0.81 (0.81)	-0.03 (0.82)
3	5.39 4.74 4.27 4.31	6.11 6.42 4.94 5.09	5.33 5.38 4.92 4.68	4.54 4.66 4.85 5.75
	1.00 1.37 2.20 0.32	0.47 0.50 0.40 0.64	0.63 1.73 0.68 0.46	0.83 0.57 0.68 0.47
	0.24 -0.40 -0.87 -0.82	0.96 1.27 -0.20 -0.05	0.18 0.23 -0.22 -0.25	-0.59 -0.48 -0.29 0.61
	-0.28 (1.46)	0.56 (0.81)	-0.01 (0.96)	-0.28 (0.78)
4	3.43 3.48 4.08 4.25	4.84 5.54 5.26 4.73	5.11 5.66 6.12 4.96	4.62 4.00 4.49 4.51
	1.06 0.83 0.98 1.04	0.70 1.16 1.28 0.57	0.90 1.19 0.54 1.11	0.55 0.45 0.43 0.99
	-1.24 -1.20 -0.60 -0.43	0.16 0.85 0.57 0.05	0.42 0.97 1.43 0.28	-0.06 -0.67 -0.18 -0.17
	-0.90 (0.99)	0.41 (0.99)	0.81 (0.98)	-0.26 (0.66)
5	2.83 3.51 3.11 3.66	5.43 4.97 4.33 4.72	6.59 6.36 5.71 5.77	5.02 4.96 4.09 4.60
	0.75 1.06 0.89 1.17	1.13 0.65 0.51 0.98	0.16 0.00 0.28 0.78	1.00 0.89 0.98 1.56
	-1.62 -0.94 -1.33 -0.79	0.98 0.51 -0.12 0.26	2.13 1.91 1.25 1.31	0.56 0.50 -0.35 0.14
	-1.20 (0.97)	0.34 (0.90)	1.52 (0.60)	0.28 (1.13)
7	4.11 3.99 3.66 4.36	5.93 5.22 6.18 6.86	5.68 6.79 6.47 6.01	5.89 5.21 5.49 4.89
	0.48 0.74 1.41 1.22	1.55 0.75 1.16 1.61	0.57 0.72 0.65 0.43	0.89 0.88 0.39 0.47
	-1.32 -1.44 -1.78 -1.07	0.49 -0.22 0.73 1.41	0.23 1.34 1.02 0.56	0.45 -0.22 0.04 -0.55
	-1.40 (0.99)	0.68 (1.38)	0.78 (0.69)	-0.05 (0.76)
8	2.78 3.59 3.21 2.96	5.34 5.28 6.16 5.54	4.59 4.65 4.57 3.94	3.95 3.89 3.99 4.09
	1.05 1.16 0.51 1.00	0.96 1.24 1.24 0.67	1.60 0.51 0.99 0.77	1.04 1.04 0.56 1.08
	-1.53 -0.71 -1.09 -1.35	1.02 0.96 1.84 1.22	0.27 0.33 0.25 -0.36	-0.36 -0.42 -0.32 -0.22
	-1.17 (0.95)	1.33 (1.05)	0.09 (1.03)	-0.33 (0.90)
9	3.53 4.78 3.64 3.80	7.40 5.94 7.44 7.56	4.60 4.42 5.03 4.52	5.61 4.77 4.74 4.59
	2.25 1.15 2.01 0.89	0.56 0.82 0.80 1.61	0.68 0.56 0.84 0.36	1.55 0.85 0.46 1.25
	-1.54 -0.28 -1.43 -1.27	2.32 0.86 2.36 2.48	-0.47 -0.65 -0.04 -0.55	0.55 -0.30 -0.33 -0.38
	-1.16 (1.70)	2.07 (1.20)	-0.38 (0.66)	-0.11 (1.11)
10	4.43 3.04 5.26 4.08	5.30 5.87 5.47 6.00	4.35 4.19 4.23 4.08	4.70 4.60 4.32 3.67
	1.03 1.25 1.29 1.55	1.26 0.76 0.39 1.74	0.85 0.63 0.61 0.58	0.87 0.51 0.45 0.74
	-0.16 -1.55 0.66 -0.51	0.70 1.28 0.88 1.41	-0.24 -0.39 -0.36 -0.50	0.10 0.01 -0.27 -0.72
	-0.40 (1.48)	1.05 (1.07)	-0.37 (0.66)	-0.23 (0.70)
11	6.26 4.39 5.72 5.52	7.29 6.83 6.05 6.81	7.22 7.25 6.70 7.57	5.83 6.06 5.66 5.59
	0.82 0.59 1.39 0.96	0.83 1.31 1.02 1.35	1.36 1.29 1.11 1.14	1.10 0.91 1.22 1.00
	0.05 -1.82 -0.48 -0.69	1.07 0.62 -0.16 0.60	1.01 1.03 0.48 1.36	-0.37 -0.15 -0.55 -0.62
	-0.80 (1.15)	0.60 (1.16)	1.07 (1.17)	-0.43 (1.02)
12	4.34 3.36 2.92 3.15	4.30 4.93 4.95 4.77	5.08 5.93 5.66 5.16	3.65 3.22 3.67 4.10
	1.50 0.72 1.12 0.78	0.80 0.52 0.57 0.41	1.02 0.66 0.66 0.79	0.69 0.91 1.24 0.76
	0.01 -0.96 -1.40 -1.16	-0.02 0.61 0.62 0.44	0.75 1.60 1.33 0.84	-0.67 -1.10 -0.65 -0.21
	-0.90 (1.13)	0.39 (0.64)	1.14 (0.85)	-0.64 (0.94)
13	3.29 3.06 3.40 3.24	4.90 4.38 4.57 4.70	6.64 4.54 4.46 4.92	4.28 4.42 5.19 5.75
	1.84 1.60 1.73 0.87	0.74 0.47 0.57 0.62	0.39 1.41 0.07 0.84	0.80 0.55 0.67 0.65
	-1.17 -1.41 -1.06 -1.23	0.42 -0.09 0.09 0.22	2.17 0.07 -0.00 0.45	-0.18 -0.05 0.71 1.27
	-1.22 (1.44)	0.17 (0.62)	0.68 (1.27)	0.45 (0.88)
14	4.50 4.22 2.81 4.86	3.85 3.77 3.64 3.90	5.77 5.35 5.39 5.25	4.65 4.87 5.27 5.28
	1.91 2.11 2.15 0.99	0.98 0.78 0.64 1.24	0.56 0.55 0.72 0.74	0.85 0.81 1.18 1.66
	-0.10 -0.37 -1.78 0.25	-0.74 -0.82 -0.75 -0.70	1.17 0.75 0.79 0.65	0.05 0.27 0.67 0.68
	-0.45 (1.89)	-0.75 (0.92)	0.78 (0.66)	0.43 (1.16)
15	4.49 4.73 4.43 4.48	4.73 4.73 5.51 5.31	5.67 5.47 4.16 5.17	4.82 4.48 4.77 5.00
	0.36 0.51 0.47 0.41	0.30 0.58 0.88 1.27	1.07 0.73 0.96 0.95	0.81 0.57 0.42 0.79
	-0.39 -0.15 -0.45 -0.40	-0.15 -0.15 0.62 0.42	0.98 0.58 -0.72 0.28	-0.06 -0.40 -0.11 0.11
	-0.35 (0.43)	0.20 (0.93)	0.25 (1.04)	-0.10 (0.66)
16	4.33 3.67 2.90 4.89	5.14 5.61 6.17 5.96	6.63 6.60 6.03 5.68	5.45 5.09 4.25 4.49
	1.48 1.85 1.69 1.35	0.58 0.92 0.47 0.90	0.34 0.84 1.27 1.10	0.71 0.64 0.58 0.49
	-0.81 -1.47 -2.25 -0.24	0.00 0.46 1.03 0.81	1.48 1.46 0.89 0.53	0.30 -0.05 -0.59 -0.65
	-1.24 (1.71)	0.63 (0.82)	1.03 (1.04)	-0.35 (0.75)
17	5.20 4.92 5.76 5.76	5.60 5.49 5.78 6.23	6.07 5.90 6.19 6.85	7.04 6.32 6.70 6.34
	0.65 0.84 0.48 0.86	0.64 0.82 0.49 1.24	0.72 1.12 1.10 0.98	0.77 1.10 0.95 0.52
	-0.82 -1.10 -0.26 -0.25	-0.36 -0.53 -0.24 0.20	0.05 -0.12 0.16 0.82	1.01 0.30 0.67 0.31
	-0.59 (0.77)	-0.21 (0.89)	0.27 (1.05)	0.57 (0.86)
	4.23 3.94 3.97 4.18	5.41 5.38 5.44 5.55	5.75 5.65 5.45 5.40	5.08 4.87 4.89 5.00
	0.97 0.62 0.97 0.92	0.94 0.76 0.87 0.96	0.84 0.88 0.80 0.94	0.88 0.82 0.78 0.72
	4.08	5.45	5.56	4.96

For key, see page 182

FIG 44 VERTICAL AND HORIZONTAL RESULTS - EXPT 1



Comparison of vertical and horizontal viewing times as above is not totally valid as the particular contrasts, conspicuities, backgrounds etc. of the objects with vertical bars are not related to those with horizontal bars as these are in different locations and timed at different moments. The data reduction process means that the values for magnifier 2 are only comparison values with magnifiers A C & D in each category of object. Thus, the difference in the values for magnifier B may be due to opposite smaller changes in magnifiers A, C and D. Apart from the inherent unlikelihood of this it must be accepted that the plane glass of magnifier A cannot introduce any major effect while the projection lens used was the same for magnifiers B C and D (although at different conjugates for C and D). Differences in visual acuity in the vertical and horizontal planes should affect all magnifiers equally. For a statistical analysis of these results, the two-way analysis of variance were carried out on each. These gave the following values:

HORIZONTAL

Source	Sum of Squares	Degrees of Freedom	Mean of Squares	Mean Square Ratio	
Bet. subjects	76.3794	15	5.092	22.236	xxx
Bet. magnifiers	87.1919	3	29.064	21.956	xxx
Interaction	59.6194	45	1.325	5.786	xxx
Residual	43.9254	192	0.229		
TOTAL	267.1161	255			

VERTICAL

Source	Sum of Squares	Degrees of Freedom	Mean of Squares	Mean Square Ratio	
Bet. subjects	68.3322	14	4.881	13.672	xxx
Bet. magnifiers	128.1442	3	42.715	25.023	xxx
Interaction	71.6982	42	1.707	4.782	xxx
Residual	64.1960	180	0.357		
TOTAL	332.3706	239			

This analysis is reduced by one subject in the vertical as subject 11 experienced an equipment failure on the vertical channel while viewing magnifier A.

Although this type of analysis does show significant differences a further test is required to isolate these. As the vertical and horizontal values can be considered independent experiments it is permissable to apply a student's t test to results. Only the difference of 0.56 seconds for magnifier B (for vertical sightings compared to Magnifier A less horizontal sightings compared to magnifier A) was found to be significant and that at the 1% level.

In investigating the effects of time on subjects' performance with magnifiers a major difficulty lies in the variation within subjects. Whereas 8 of the 16 placed the magnifiers in the order: A first, D second, with B & C in third and fourth position, a further 5 subjects only exchanged D for B or C. However, the varation with time is much more random. Taking the figures for the biocular magnifiers (A, B and D),it is seen on inspection that the trends among subjects is:-

	Improvement	No Change	Deterioration
Magnifier A	6	6	4
Magnifier B	4	5	6
Magnifier D	7	3	6

Within these numbers, only two subjects showed the same variation for Magnifiers A and D, three for B and D and six for A and B. Thus, the variation with time that appears in the mean values over all subjects ($T_{.mv}$ and $T_{.uv}$) are not very meaningful. More specific analysis over smaller groups of subjects immediately suffers from the large variations between them and with this sort of task it appears necessary to take means over at least eight subjects.

Various divisions have been tested but no significant effects have been found. In this experiment the phoria of each subject was measured three times at the start of each trial. Between each sub-trial a further three measurements were taken and also at the end of the trial. While discussing the reactions of the subject to the magnifier two sets of two readings each were carried out at approximately one minute and two minutes after the end of the trial.

In total this gives nineteen phoria readings. The phoria shifts encountered were generally towards esophoria. As explained in Chapter 5, a single scale, 0 to 10 was used with 5 as the orthophoric condition, while values greater than 5 indicated exophoria. Thus, a shift towards esophoria is indicated by a reduction in the figure quoted which is also multiplied by a factor of 10 to provide a single indication of the $\frac{1}{2}$ & $\frac{1}{4}$ values recorded by subjects.

The shift obtained was considered the first point of interest, and it was apparent that the values obtained after each section could not be considered as three attempts at a constant value. The timescale of the shift and its return meant that changes were often occurring during the time of the measurement. It was also apparent that in the majority of cases most of the shift had occurred by the end of the first section. The charts show the results for the Magnifier A and Magnifier D, and the totals over 16 subjects for the Magnifiers B & C.

Trial

Subjects	Start	After 5 mins	After 10 mins	After 15 mins	After 20 mins	21 mins	21 mins
1	90 90 95	80 80 85	80 80 80	65 65 70	70 65 65	75 75	80 80
2	40 40 30	40 30 30	20 20 30	35 30 30	40 30 20	30 30	40 40
3	50 50 50	50 45 45	50 45 45	40 45 45	50 50 50	50 50	50 50
4	60 60 60	50 50 55	60 65 60	55 60 60	60 60 60	60 65	60 65
5	60 70 60	50 50 50	60 55 55	50 55 50	50 50 50	55 55	55 55
7	77 77 77	77 77 77	70 70 70	67 67 67	70 70 70	77 77	77 77
8	69 69 69	63 63 63	62 62 62	60 60 60	60 60 60	67 67	68 68
9	53 53 53	55 55 55	57 57 57	53 53 53	53 53 53	50 50	50 50
10	90 95 95	90 90 95	90 95 95	90 90 95	90 90 95	85 90	90 95
11	73 88 83	73 75 83	80 80 83	60 68 73	60 65 70	60 68	60 68
12	80 85 80	60 70 80	60 70 70	70 75 75	70 70 70	70 70	70 70
13	40 50 50	30 40 50	30 50 60	55 55 60	45 55 60	40 50	30 50
14	60 63 70	53 53 63	53 63 63	50 43 63	60 63 53	48 48	50 53
15	88 83 85	73 75 78	65 78 78	70 73 70	68 73 75	70 70	78 80
16	60 65 65	50 55 55	50 55 55	50 55 55	50 50 55	60 60	60 60
17	80 80 80	70 70 75	70 70 80	70 70 80	70 75 80	70 75	80 80
	67 70 69	60 61 65	60 63 62	59 60 63	60 61 62	60 62	62 65

MAGNIFIER B

67 68 67	65 67 68	66 65 65	65 65 65	66 66 67	65 68	66 67

MAGNIFIER C

68 68 69	70 72 72	70 68 70	67 69 69	68 66 68	65 67	66 67

MAGNIFIER D

Subject	Start	After 5 mins	After 10 mins	After 15 mins	After 20 mins	21 mins	22 mins
1	85 90 90	70 75 75	55 60 60	60 60 60	60 55 55	75 70	75 80
2	40 30 30	35 30 40	40 35 40	30 30 30	20 20 20	40 40	40 40
3	50 50 50	50 45 45	45 45 45	45 45 45	45 45 45	50 50	50 50
4	70 60 65	60 60 60	50 55 60	50 50 60	55 60 65	65 70	70 70
5	55 55 55	45 50 45	40 40 45	45 45 45	50 50 50	50 50	50 50
7	78 78 78	65 65 65	63 63 63	60 60 60	67 67 67	78 78	78 78
8	72 72 72	58 58 58	55 55 55	57 57 57	48 48 48	67 67	68 68
9	49 49 49	54 54 54	47 47 47	53 53 53	47 47 47	50 50	47 47
10	95 95 95	80 90 95	70 85 90	80 85 90	80 85 90	95 95	95 95
11	85 85 88	63 65 63	65 78 78	60 68 73	73 68 65	70 70	65 73
12	80 80 80	60 70 65	60 60 60	60 60 60	60 60 60	65 63	60 65
13	50 50 60	20 30 40	20 30 40	20 30 40	20 30 40	10 30	10 30
14	45 53 53	50 53 55	55 55 55	50 55 63	50 50 55	45 45	50 58
15	70 78 79	65 68 70	65 65 60	65 68 70	70 65 63	65 70	65 70
16	60 70 70	50 50 60	50 50 60	50 50 55	50 55 60	50 60	50 55
17	75 80 80	70 80 80	80 85 90	80 90 90	85 90 95	80 90	85 90
	66 67 67	56 60 60	54 57 60	54 57 59	52 56 57	60 62	60 64

It is seen that magnifiers A & D give similar effects with the greater being accorded to D, the high-power biocular (SLAB). The simple plastic lens (Magnifier B) has no appreciable effect while the monocular magnifier (C) has a slight inverse effect even though all systems were set for a viewing distance of 50 cms. When the particular shift with each subject is compared with his performance no correlation coefficients above 0.3 were found.

After each trial, subjects were asked to comment on their state of vision and general well-being. Of the sixteen subjects those who made specific comments were analysed of magnifier, location and films by recording the number of occurances of five symptoms.

	Magnifier				Location				Film			
	A	B	C	D	1	2	3	4	1	2	3	4
Headache following	2	-	4	3	1	3	1	4	2	4	3	-
Eyes strained following	2	6	7	7	10	5	6	1	4	7	4	7
Eyes strained in use	2	5	1	1	2	2	2	3	2	2	3	3
O.K. Relaxed	5	3	2	2	3	2	4	3	5	1	3	3
Bored	2	-	-	1	-	1	1	1	-	1	-	2

Broad conclusions only may be drawn from the underlined values. Magnifier one most often allowed relaxed viewing without subsequent tiredness of the eyes. Magnifier two gave most eyestrain during use. However, 'eye strain' as a comment was used mainly after the first trial.

In assessing the overall value of this first experiment it must be recognised that the differences between subjects are at least as large as those found between magnifiers. Added to this is the possibility that the magnifier differences may be due in part to the different screen materials used. On the other hand the astigmatic effect found with magnifier B may be related to a visual aberration with reasonable confidence. Subsequent experiments (2 to 4) have used the same projector lens and screen material at fixed conjugates and magnification and so this affect is reduced to the setting accuracies of these parameters.

6.3 Experiment 2 (Subjects 18 - 21)

Subsequent to the results of experiment 1, which were inconclusive as regards variations with time, a short experiment of four subjects was undertaken in which they worked with one magnifier for 80 minutes. The SLAB and monocular magnifiers (C & D) were chosen as most interest centred around the former and the latter had shown a considerable improvement trend. No phoria readings were taken during these trials.

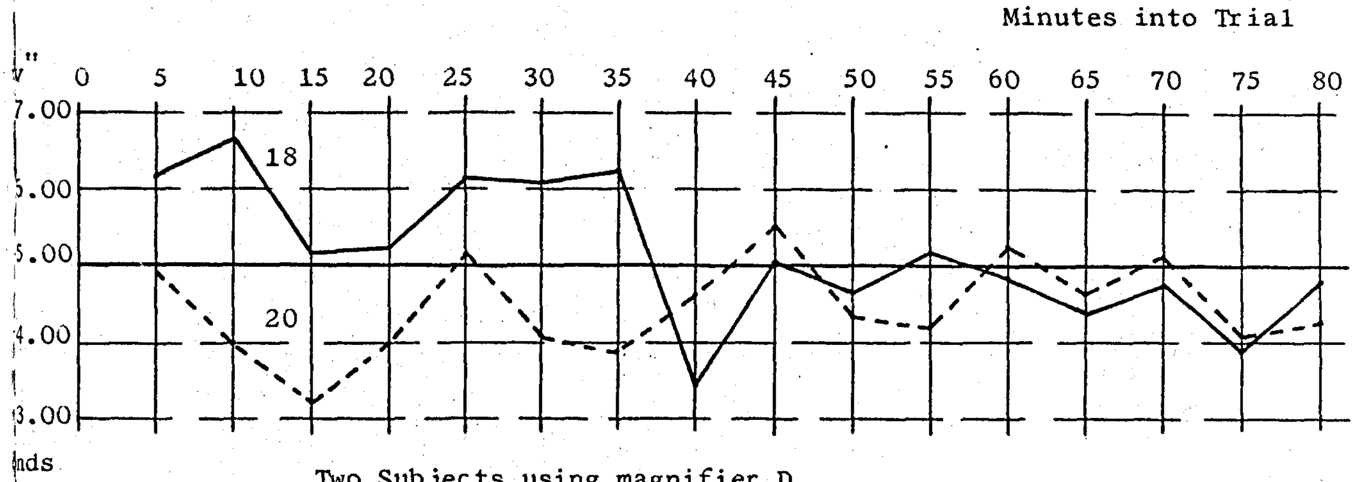
In order to test whether or not the eyes adapted with time to the magnifier, a simple interrupted task was devised. This merely required the subject to read from a book for one minute in every two, returning to the visual task for the other minute. This means that of the 16 targets in each five minutes, an average of eight will be seen.

With this reduced number of values and only four subjects, it is not feasible to calculate mean values for each target. Accordingly, the mean values obtained by the sixteen subjects in experiment 1 were used. These were subtracted from the actual viewing times of the subjects, and the means over five minutes plotted on the graphs shown in Fig.45.

With such a small number of subjects one must be cautious at jumping to conclusions. However, whilst it is by no means proven, the graphs do suggest a hypothesis that a visual adaptation may occur during continuous viewing, which is inhibited by interrupted viewing, and that during the time of adaptation the subject may perform worse than after adaptation or without adaptation.

Obviously, further work is required to verify this.

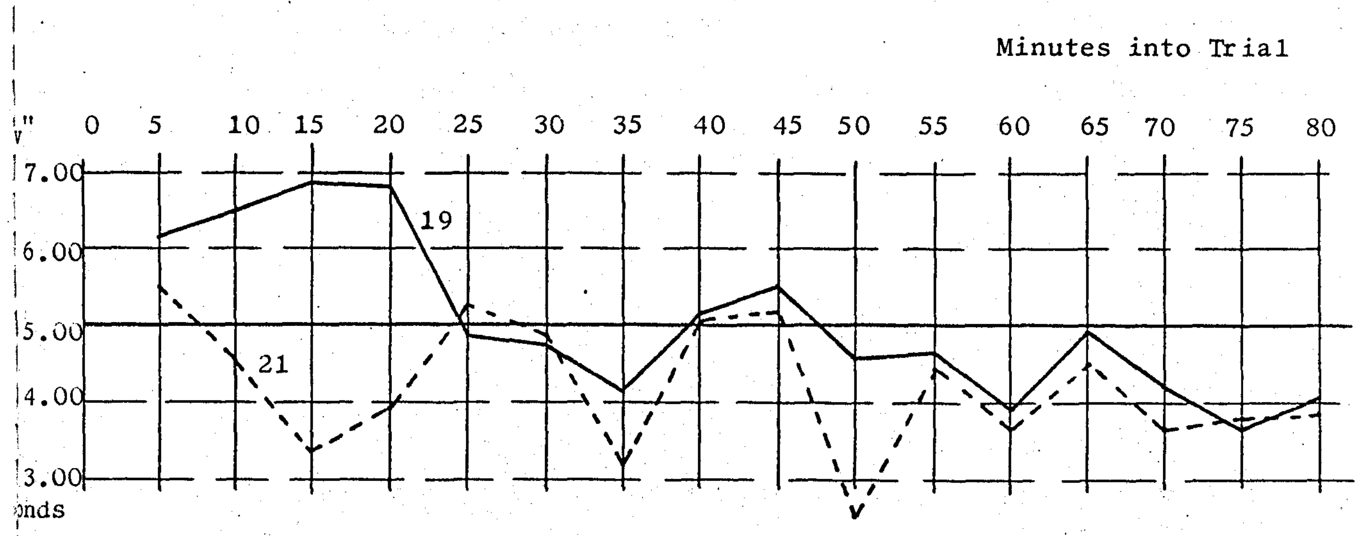
FIG 45 RESULTS - EXPT 2



Two Subjects using magnifier D

Solid Line - Continuous Viewing

Broken Line - Interrupted Viewing



Two subjects using Magnifier C

Solid Line - Continuous Viewing

Broken Line - Interrupted Viewing

6.4 Experiment 3 (Subjects 22-25)

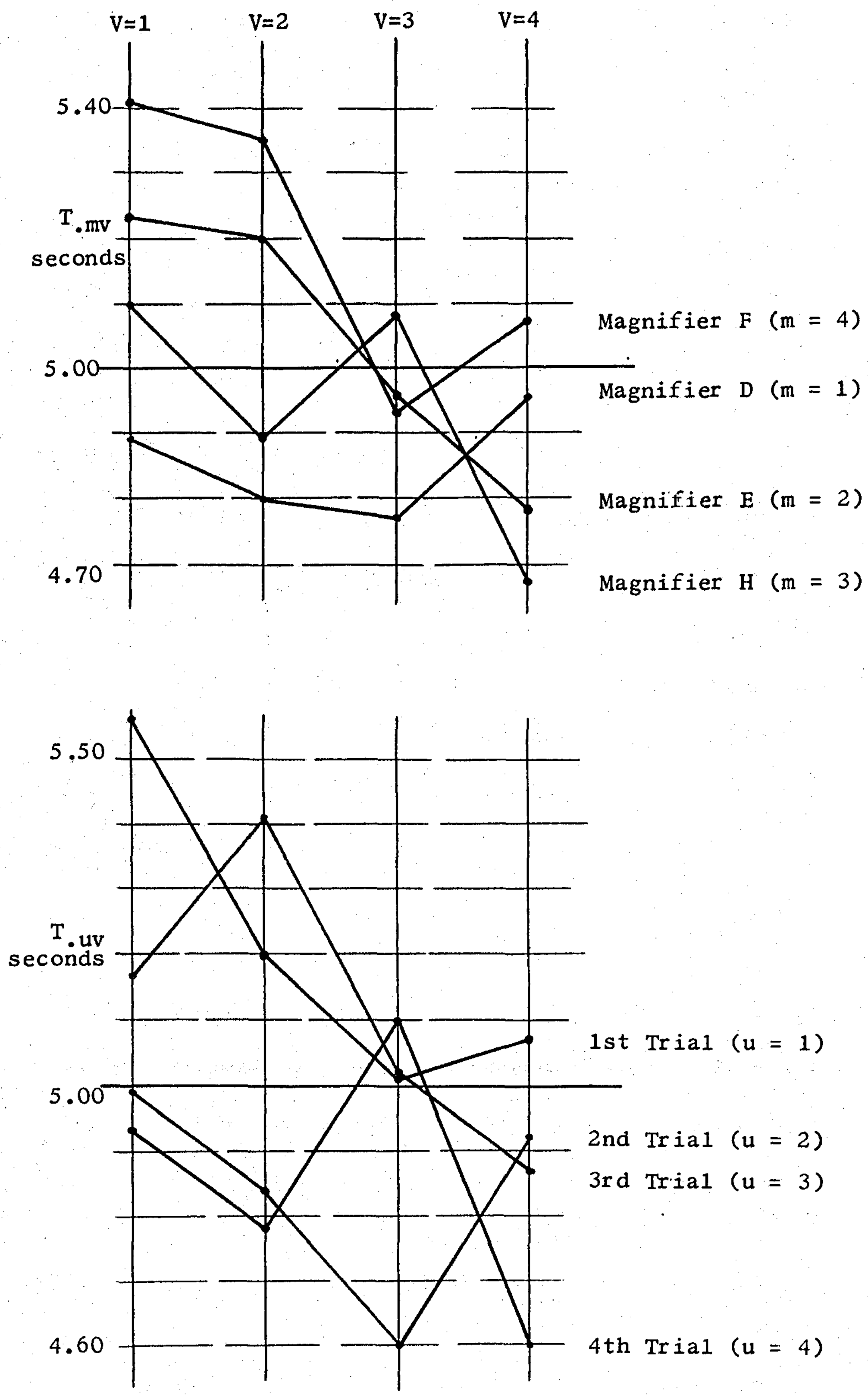
A further small experiment was run with four subjects to see if the system allowed the detection of performance variation with known incremental amounts of visual aberration. For this a SLAB magnifier was used as a basis and known amounts of accommodation/convergence discrepancy (Parallax) and astigmatism introduced using add-on prisms and a weak cylindrical lens.

The prisms were mounted base-in and base-out between the subject's eyes and the magnifiers and were of power 1 prism dioptre and 1.3 prism dioptres respectively. These relocated the convergence surface of the SLAB magnifier to the positions marked on Fig.37. The cylindrical lens was of the power $+\frac{1}{2}$D in the vertical, and so for the eyes located horizontally about the magnifier axis the sagittal accommodative surface is shifted to the new location shown in Fig. 37 These modifications were designated as follows:-

Biocular (SLAB)	Mag D
Biocular + C (+ $\frac{1}{2}$Dcyl. axis 90^{o})	Mag E
Biocular + P (1.0Δ prisms, base-in)	Mag H
Biocular + N (1.3Δ prisms, base-out)	Mag F

The subjects and magnifiers were arranged according to Array 10 Chapter 5, which is not a balanced array. The results are shown in the graphs of Fig.46. Apart from some indication that all the modified magnifiers performed less well than the unmodified example, and the reduction in the spread of results by the third five minute period, there is little to be extracted from the results. The larger swings in the figures for successive trials also makes the magnifier figures suspect when the unbalanced nature of the array is remembered. It is thus apparent that little will be learned from four subject trials, and that future trials must contain at least eight subjects.

FIG 46 OVERALL RESULTS - EXPT 3



6.5 Experiment 4 (Subjects 26-33) & 4C (Subjects 45-52)

Following the conclusions of experiment 3 an eight subject trial was undertaken using substantially the same magnifiers. This was increased to 16 subjects by a repeat experiment involving a further eight subjects.

On the grounds that results for one value of astigmatic error would not be very useful, the cylindrical lens modification was replaced by a stronger base-in prism assembly. This gave four values of the accommodation/convergence ratio over which to examine the results. So that the presence of extra glass in the magnifier would not constitute a difference, the standard magnifier was used with a plain piece of glass mounted in the same way as the prisms.

A further departure was that the fourth trial of the first eight subjects was extended for a further twenty minutes (comprising a fifth trial), in order to check what the longer term performance variations might be.

Up to subjects 25 the visual task films had contained a twenty second dark period between each five minute task (sub-trial) which was intended for the measurement of the subject's phoria. On the basis of the phoria shifts obtained with Experiment 1 this dark period was reduced to less than one second and the phoria tests restricted to the beginning and end of the twenty minute trials. New printings of the visual task films were used.

The data recording was augmented with a digital printer which was actuated by the display. Only one major equipment failure occurred (Subject 31, trial 4, magnifier F) but the results required some slight annotating to exclude the occassional spurious trigger or repeat value due to one time being printed before the other had finished displaying. A typical trial sheet is shown in Fig.47.

The magnifiers were designated as follows:-

SLAB + 1.3 Δ Prisms, Base-out	F
SLAB + Plano glass	G
SLAB + 1.0 Δ Prisms, Base-in	H
SLAB + 2.7 Δ Prisms, Base-in	I

The choice of 1.3ΔB.O. and 1.0ΔB.I. was intended to give a similar linear shift in the convergence surface although in opposite directions. The choice of 2.7Δ B.I. it must be frankly admitted was intended as the sledge-hammer approach as its size should give a significant decrement in performance even if the F and H results were indistinguishable from G.

Although, the obvious problems of experiment 1 had been over come by using the same projection lens and screen, it is important to ascertain what variation in setting and focus could occur between trials (and during trials).

The setting of the projector was checked with the registration film viewed through the magnifier. This gives, of course, a x5.5 magnification of the 40mm format. As the screen used was masked at 40mm diameter it was relatively easy to obtain a match of each side of the film and mask to $\pm$0.1mm on the screen. From this the magnification has a setting accuracy of $\pm$0.5%. The size of objects on the film is increasing due to

FIG 47 VISUAL PERFORMANCE, PHORIA & VISUAL COMFORT RECORD - EXPT 4

1

SUBJECT'S NAME __ Robert Evans ______
NO _26___ DATE _30 Oct 73_

MAGNIFIER SLAB + 0___ NO __10__

FILM NO __1__ CHANGE CODE __1___

LOCATION __1____

PHORIA BEFORE __5·0___ AFTER __4·0__

VISUAL COMFORT SCORE __3.___ P.D. 62

EYES HOT _No_ DRY _No_ WATERING _No__
OTHER ____________

HEADACHE ___No___________

BORED __Interesting

ATTENTION __Consistent - like driving.

OPINION OF MAGNIFIER __________

COMMENTS __Time Passed Quickly
__No muscular aches.__

	5 08
6 53	
4 57	
	7 46
4 76	
	9 00
6 13	
[illegible]	
	5 63
2 86	
2 89	
	4 29
5 25	
	4 80
	3 33
5 88	
	5 48
[illegible]	
2 40	
	5 09
2 96	
	5 82
	4 34
3 76	
	6 77
3 06	
	4 77
0 02	
3 22	
	4 48
4 36	
3 11	
8 84	
	1 53
3 10	
	[illegible]
	9 00
	5 72
	4 67
6 78	
	5 60
3 11	
	5 24
	5 12
4 70	
	7 82
9 00	
	9 00
3 93	
9 00	
	4 73
8 63	
5 60	
4 69	
	6 01
6 05	
	5 61
	5 17
	4 78
	6 11
3 08	
4 39	
	6 57
2 32	
	7 70
4 88	
	6 06

an effective boat speed of 7.5 metres per second. Most objects are recognised at a filmed distance of 40 metres. The error in magnification changes the effective filming distance by 0.2 metres which the boat takes 0.03 seconds to make up. Thus, $\pm$0.03 seconds is an outside estimate of the approximate error contribution between each trial of the repeatability of setting of the magnification.

Of greater concern is the focussing accuracy of the projection lens. The standard f/2, 50mm lens was masked with an 8mm diameter stop which illuminated the screen for the subject and an outer annulus which illuminated a second screen carrying the triggering photo-cells. The image on this second screen was used to observe the quality of focus and a dial gauge against the lens indicated a longitudinal precision of $\pm$0.05mm. Error in focussing this lens will introduce a variation in contrast of the observed image. The extent of this variation can be estimated if the projection lens is assumed to be diffraction limited at this aperture. At the reduced aperture of this lens and the finite conjugates this amount of defocussing corresponds to a difference between axial and marginal rays of approx. $\lambda/5$. The effect of defocussing on Optical Transfer Function of a diffraction limited lens has been investigated by Birch (1961) and Levi & Austing (1968). The former uses the defocussing coefficient W_{20} in units of $n = \lambda/\pi$ while the latter uses units of the Rayleigh criterion $\Delta = \lambda/4$. Thus, the adjustment error of $\pm$0.05mm is equivalent to $n = 0.66$ and $\Delta = 0.8$.

Both use reduced spatial frequencies in terms of the diffraction limit for incoherent illumination which is approx 250 cycles per millimetre in the film plane for this aperture and object conjugate of the projection lens. When related to the film plane the approaching object spatial frequencies of Fig.32 (Page 140) are multiplied by 100 to give cycles per mm. (using a 10m.m. e.f.l. camera lens). Thus, between 3 seconds and 6 seconds after trigger the filmed object has a spatial frequency of 33 to 16 cycles per m.m. Mean recognition time of these objects is just before 5 seconds. Taking 25 cycles per m.m. as a mean value it is clear from Birch's graphs that a modulation drop due to defocussing ~~of between~~ from 0.88 ~~and~~ to 0.84 can be expected. Interpolation of Levi and Austing tables gives 0.873 to 0.850. These figures apply to monochromatic light and a perfect lens. The presence of aberrations will reduce both these values but the ~~0.25%~~ 0.015 change indicated by this simple analysis probably constitutes the worst case.

Unfortunately, this change in contrast cannot be converted into a change in seeing time using theoretical principles and it is not possible to make contrast measurements at this frequency with the moving film imaged onto the screen. A rough assessment of the likely Modulation Transfer Function of the entire system may be made by estimated cut-off frequencies for the various components of the system and assuming linear change with frequency. These components, assessed at the film plane, are:-

Haze :- This affects the high spatial frequencies more than the lower as the objects are further away in the former case. Taken on overcast October days the films are assumed to have seen an 80% contrast object at 75 metres. This effect is generated by assuming a cut-off due to haze of 200 cycles per m.m.

Camera Lens :- F/10 diffraction limit gives 200 cycles per m.m.

Negative Film Stock (Plus x) :- Cut-off about 125 cycles per m.m.

Positive Film Stock (Plus x) :- Cut-off about 125 cycles per m.m

Projection Lens :- f/8 diffraction limit gives 250 cycles per mm

Screen :- Although this has a maximum resolution of about 60 cycles per m.m. when viewed directly, the large numerical aperture of the magnifier means that the screen is viewed at a considerable angle to the normal. A rough estimate of the cut-off is 20 cycles per m.m which gives 80 when related to the film plane. However, as a rear projection screen it also suffers from scattered light within the screen. A factor of 0.5 is included for this.

Taking all these into account means that for a spatial frequency x the final modulation y is given by:-

$$y = \left(1 - \frac{x}{200}\right)\left(1 - \frac{x}{200}\right)\left(1 - \frac{x}{125}\right)\left(1 - \frac{x}{125}\right)\left(1 - \frac{x}{250}\right)\left(1 - \frac{x}{80}\right) 0.5$$

For the spatial frequencies 26,25 and 24 cycles per mm. This gives the values:- 14.36%, 15.16%, and 16%. A change of ~~0.25%~~ 2.5% at 80% is equivalent to 0.5% at these values. As the film reduces the spatial frequency by 1 cycle per mm each 0.25 seconds it can be seen that the modulation loss due to defocussing is made up in about 0.15 seconds. This is about 5 times smaller than the effect due to variations between subjects.

Although the values of about 15% modulation make it look large when compared with visual threshold contrast values reported in the literature the visual resolution limit associated with 3 bar targets is often estimated to be 15% contrast (8% modulation).

The subjects do sometimes record very short response times of between one and two seconds so that a supra-threshold value must be occuring at the mean times. Obviously this analysis is very crude but the effect of the focus accuracy is unlikely to be larger than that found. Reasons for the delay in subject response will be examined after the detail results have been presented.

The results over all subjects and all objects are given in Fig.48 over magnifier (T_{imv}) and in Fig.49 over trial (T_{iuv}). The values of $T_{.mv}$ and $T_{.uv}$ are plotted on Fig.50 which includes the fifth sub-trial period over the first eight subjects only. Because each magnifier was used by only two subjects in this fifth period these performance values show large swings.

The differences between magnifiers as shown by these results over 16 subjects are seen to be very much smaller than those of experiment 1 It is reassuring to see that over the main 20 minute period the reduced viewing times for magnifier I which exhibited the largest parallax error do show greater values indicating poorer visual performance than the other three magnifiers. Similarly, the unmodified magnifier G gives the shortest viewing times in all except for the first sub-trial.

However, it is clear that the differences between these magnifiers are only marginally greater than those between successive trials as shown by the $T_{.uv}$ values. Some careful statistical analysis is required to assess what significant effects can be deduced from these results. As with the Expt.1 the variations with time are not particularly meaningful with the exception of the improvement in performance shown by magnifier G. Of the 16 subjects, 7 show a distinct improvement with time although 2 deteriorate and 7 show no distinct trend.

FIG 48 RESULTS BY MAGNIFIER OVER ALL OBJECTS - EXPT 4

CT

MAGNIFIER	F m=2	G m=1	H m=3	I m=4
26	5.36 4.43 4.55 5.16 0.56 0.53 1.01 0.72 0.48 -0.44 -0.32 0.28 -0.02 (0.82)	4.81 5.60 3.95 4.63 1.24 1.19 0.88 0.94 -0.06 0.72 -0.92 -0.24 -0.15 (1.19)	4.80 5.00 4.69 4.91 1.02 0.56 0.90 0.61 -0.07 0.12 -0.18 0.03 -0.02 (0.79)	5.34 5.00 4.64 5.22 0.69 0.90 0.72 0.60 0.46 0.12 -0.23 0.54 0.19 (0.76)
27	4.91 5.65 4.28 4.92 0.80 1.36 1.24 1.26 0.33 1.07 -0.29 0.34 0.36 (1.24)	4.98 4.77 4.63 4.98 0.58 0.60 0.70 0.85 0.40 0.19 0.04 0.40 0.25 (0.68)	4.10 3.95 3.95 4.01 0.96 1.29 0.93 0.80 -0.47 -0.62 -0.62 -0.56 -0.57 (0.99)	4.89 4.66 4.92 4.03 0.87 0.42 0.98 0.92 0.31 0.08 0.34 -0.54 0.05 (0.89)
28	5.78 5.77 6.42 6.00 0.67 0.41 0.74 0.63 -0.06 -0.07 0.57 0.16 0.12 (0.65)	5.96 5.18 4.42 4.52 1.28 0.84 1.20 1.15 0.11 -0.66 -1.42 -1.32 -0.85 (1.25)	5.94 7.18 6.02 6.08 0.73 1.00 1.01 1.39 0.09 1.34 0.17 0.23 0.44 (1.15)	5.68 6.36 6.05 6.72 0.87 1.38 1.35 1.28 -0.16 0.51 0.20 0.87 0.32 (1.25)
29	5.87 5.75 5.61 5.63 0.85 0.59 0.88 0.98 0.34 0.21 0.07 0.09 0.18 (0.82)	5.54 5.13 5.83 5.45 0.72 0.42 0.43 0.61 0.00 -0.40 0.29 -0.08 -0.05 (0.60)	5.42 5.58 5.33 5.56 0.75 0.72 0.86 1.11 -0.11 0.05 -0.20 0.03 -0.06 (0.85)	5.26 5.83 5.23 5.60 0.87 0.97 1.28 0.79 -0.26 0.29 -0.29 0.07 -0.06 (0.99)
30	4.46 4.23 4.31 4.02 0.52 1.24 0.58 1.31 -0.07 -0.30 -0.22 -0.52 -0.29 (1.01)	4.83 4.85 4.55 4.18 0.78 0.86 0.99 0.84 0.28 0.31 0.01 -0.35 0.06 (0.89)	4.33 4.06 4.37 4.41 0.76 0.74 0.77 1.18 -0.20 -0.48 -0.17 -0.12 -0.25 (0.87)	4.65 4.73 5.10 5.25 0.79 0.87 0.40 0.61 0.10 0.19 0.56 0.71 0.38 (0.72)
31	6.20 0.00 0.00 6.20 0.72 0.00 0.00 0.94 -0.19 -6.40 -6.40 -0.19 -0.21 (0.80)	6.35 6.42 6.35 5.80 1.23 0.77 1.03 0.79 -0.03 0.02 -0.05 -0.60 -0.17 (0.97)	6.49 5.97 6.82 6.15 1.28 0.82 1.22 1.58 0.08 -0.42 0.41 -0.24 -0.05 (1.25)	7.06 6.64 6.59 6.85 1.13 1.01 1.37 1.09 0.65 0.24 0.18 0.44 0.38 (1.06)
32	6.70 6.22 6.50 6.12 0.81 0.59 0.50 0.50 0.66 0.18 0.46 0.08 0.35 (0.64)	5.32 5.85 5.50 6.30 0.55 0.67 0.82 1.09 -0.71 -0.18 -0.52 0.26 -0.30 (0.86)	5.87 6.70 5.66 5.79 0.83 0.70 0.50 0.70 -0.15 0.66 -0.37 -0.24 -0.05 (0.79)	6.52 6.13 6.12 5.50 0.60 1.03 0.77 0.64 0.48 0.09 0.08 -0.53 0.00 (0.89)
33	4.88 4.73 4.29 3.93 1.24 0.58 1.43 0.78 0.26 0.11 -0.32 -0.68 -0.13 (1.11)	4.73 4.37 4.72 4.47 1.32 0.82 0.91 1.09 0.11 -0.24 0.10 -0.14 -0.04 (1.05)	4.38 4.24 5.05 4.99 1.27 1.15 0.61 1.14 -0.23 -0.37 0.43 0.37 0.06 (1.10)	4.84 5.04 4.59 4.44 1.40 0.99 0.91 0.81 0.22 0.42 -0.02 -0.17 0.10 (1.05)
45	4.45 4.72 4.31 4.50 1.14 1.31 0.48 0.44 0.20 0.47 0.06 0.25 0.25 (0.92)	4.50 3.85 3.68 4.67 1.12 0.58 0.86 0.76 0.25 -0.39 -0.56 0.42 -0.13 (0.90)	3.71 4.31 4.47 4.13 0.67 0.77 0.61 0.91 -0.53 0.06 0.22 -0.11 -0.09 (0.78)	4.16 4.27 4.02 4.31 0.91 0.75 0.83 0.61 -0.08 0.02 -0.22 0.06 -0.04 (0.77)
46	4.66 6.09 6.54 6.60 1.07 1.11 0.78 1.02 -1.17 0.24 0.69 0.75 0.15 (1.24)	5.43 5.74 5.51 5.61 1.20 1.16 0.93 1.42 -0.40 -0.10 -0.33 -0.23 -0.25 (1.16)	5.12 4.81 5.59 6.13 0.67 1.19 0.66 0.78 -0.72 -1.02 -0.25 0.28 -0.40 (0.93)	0.00 6.78 7.46 6.59 0.00 0.67 0.70 1.50 -5.84 0.93 1.61 0.74 0.94 (1.37)
47	3.51 2.68 3.56 3.16 1.16 0.64 0.56 0.93 -0.23 -1.05 -0.18 -0.57 -0.52 (0.91)	3.94 3.62 2.76 2.79 1.01 1.36 0.87 1.34 0.20 -0.12 -0.98 -0.94 -0.44 (1.25)	4.67 4.27 4.37 3.86 1.06 0.83 0.68 0.46 0.93 0.53 0.63 0.11 0.54 (0.81)	3.97 4.41 4.24 3.79 1.14 0.79 0.97 1.07 0.23 0.66 0.50 0.04 0.38 (1.00)
48	3.10 4.67 6.40 3.44 1.32 1.60 1.26 1.74 -1.40 0.17 1.89 -1.06 -0.26 (1.90)	4.91 4.36 4.17 4.30 0.88 0.61 1.01 1.11 0.40 -0.14 -0.32 -0.20 -0.08 (0.94)	4.34 4.65 4.67 4.88 1.34 0.86 0.84 1.20 -0.16 0.14 0.17 0.37 0.13 (1.05)	4.32 4.68 4.75 4.61 0.79 0.76 0.83 0.99 -0.17 0.17 0.24 0.30 0.16 (0.84)
49	5.75 4.40 4.58 4.88 0.84 0.54 0.60 0.62 1.02 -0.33 -0.15 0.14 0.17 (0.83)	4.57 4.03 4.62 4.80 1.62 1.42 1.12 0.78 -0.15 -0.69 -0.10 0.07 -0.19 (1.26)	5.23 4.57 4.69 4.20 1.25 0.53 0.58 0.76 0.49 -0.15 -0.04 -0.52 -0.05 (0.89)	4.58 4.89 5.19 4.72 0.82 0.58 0.68 0.97 -0.15 0.15 0.46 -0.00 0.07 (0.79)
50	3.34 4.08 4.39 3.94 1.25 1.28 0.87 1.35 -0.78 -0.03 0.27 -0.18 -0.20 (1.23)	4.00 3.95 3.68 3.87 0.92 0.59 0.56 0.49 -0.12 -0.17 -0.44 -0.25 -0.24 (0.66)	4.10 3.30 4.24 4.61 0.51 1.64 0.83 1.05 -0.02 -0.82 0.11 0.48 0.01 (1.01)	4.76 5.15 4.11 4.28 0.75 0.99 0.93 1.11 0.63 1.02 -0.01 0.15 0.50 (1.00)
51	5.04 5.06 5.18 5.13 0.83 1.12 1.15 0.76 0.26 0.28 0.40 0.35 0.32 (0.94)	4.71 4.65 4.27 4.34 0.36 0.57 0.73 0.85 -0.06 -0.12 -0.50 -0.43 -0.29 (0.67)	4.86 4.61 4.70 4.52 1.29 0.74 0.89 1.16 0.07 -0.16 -0.07 -0.25 -0.11 (0.99)	4.79 4.80 4.85 4.93 0.86 0.64 0.96 0.75 0.01 0.02 0.05 0.15 0.06 (0.79)
52	5.94 5.40 6.04 5.07 0.72 1.06 1.02 0.88 0.32 -0.21 0.42 -0.54 -0.01 (1.00)	5.29 5.91 5.83 5.62 1.09 0.79 0.98 0.95 -0.32 0.29 0.22 0.00 0.04 (0.97)	5.16 5.13 5.31 5.82 0.63 0.53 0.87 0.70 -0.45 -0.48 -0.30 0.20 -0.25 (0.73)	5.68 6.31 5.60 5.65 0.83 0.86 1.09 0.62 0.06 0.69 -0.01 0.23 0.23 (0.60)
	5.00 4.93 5.13 4.92 1.05 0.92 1.02 1.03 4.99	4.99 4.89 4.65 4.77 0.64 0.84 0.95 0.85 4.83	4.91 4.90 5.00 5.00 0.76 1.02 0.75 0.60 4.95	5.10 5.36 5.22 5.16 0.65 0.84 0.94 0.95 5.21

For key, see page 182

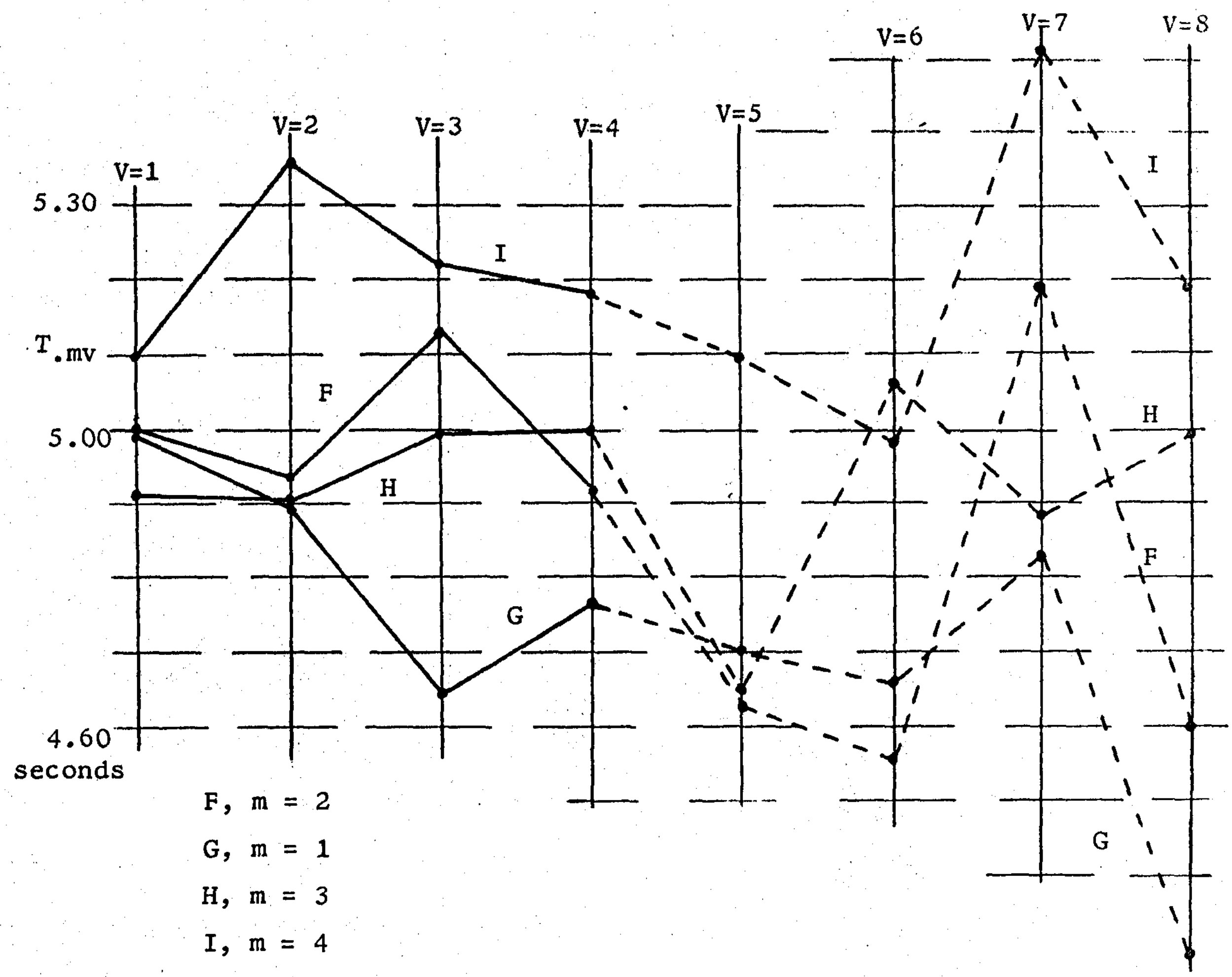
FIG 49 RESULTS BY TRIAL OVER ALL OBJECTS - EXPT 4

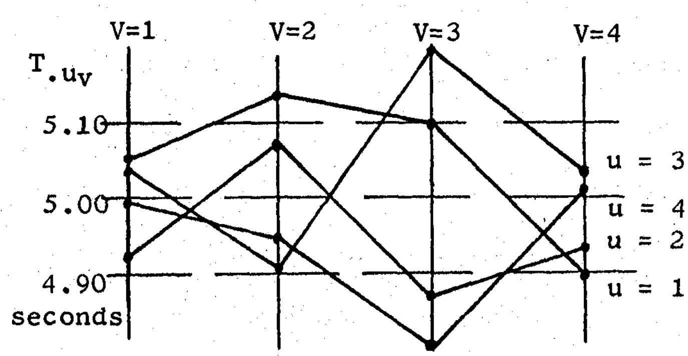
ECT

TRIAL	u=1				u=2				u=3				u=4			
26	4.81	5.60	3.95	4.63	5.36	4.43	4.55	5.16	4.80	5.00	4.69	4.91	5.34	5.00	4.64	5.22
	1.24	1.18	0.88	0.94	0.58	0.53	1.01	0.72	1.02	0.56	0.90	0.61	0.69	0.90	0.72	0.60
	-0.06	0.72	-0.92	-0.24	0.48	-0.44	-0.32	0.28	-0.07	0.12	-0.18	0.03	0.46	0.12	-0.23	0.04
		-0.15	(1.19)			-0.02	(0.82)			-0.02	(0.79)			0.19	(0.76)	
27	4.10	3.95	3.95	4.01	4.98	4.77	4.63	4.98	4.89	4.66	4.92	4.03	4.91	5.65	4.28	4.92
	0.96	1.29	0.93	0.80	0.58	0.60	0.70	0.85	0.87	0.42	0.98	0.92	0.80	1.36	1.24	1.26
	-0.47	-0.62	-0.62	-0.56	0.40	0.19	0.04	0.40	0.31	0.08	0.34	-0.54	0.33	1.07	-0.29	0.34
		-0.57	(0.99)			0.25	(0.68)			0.05	(0.89)			0.36	(1.24)	
28	5.68	6.36	6.05	6.72	5.94	7.18	6.02	6.08	5.78	5.77	6.42	6.00	5.96	5.18	4.42	4.52
	0.87	1.38	1.35	1.28	0.73	1.00	1.01	1.39	0.67	0.41	0.74	0.63	1.28	0.84	1.20	1.15
	-0.16	0.51	0.20	0.87	0.09	1.34	0.17	0.23	-0.06	-0.07	0.57	0.16	0.11	-0.66	-1.42	-1.32
		0.32	(1.25)			0.44	(1.15)			0.12	(0.65)			-0.85	(1.25)	
29	5.87	5.75	5.61	5.63	5.26	5.83	5.23	5.60	5.54	5.13	5.83	5.45	5.42	5.58	5.33	5.56
	0.85	0.59	0.88	0.98	0.87	0.97	1.28	0.79	0.72	0.42	0.43	0.61	0.75	0.72	0.86	1.11
	0.34	0.21	0.07	0.09	-0.26	0.29	-0.29	0.07	0.00	-0.40	0.29	-0.08	-0.11	0.05	-0.20	0.03
		0.18	(0.82)			-0.06	(0.99)			-0.05	(0.60)			-0.06	(0.85)	
30	4.83	4.85	4.55	4.18	4.46	4.23	4.31	4.02	4.33	4.06	4.37	4.41	4.65	4.73	5.10	5.25
	0.78	0.83	0.99	0.84	0.52	1.24	0.58	1.31	0.76	0.74	0.77	1.18	0.79	0.87	0.40	0.61
	0.28	0.31	0.01	-0.35	-0.07	-0.30	-0.22	-0.52	-0.20	-0.48	-0.17	-0.12	0.10	0.19	0.56	0.71
		0.06	(0.89)			-0.29	(1.01)			-0.25	(0.87)			0.38	(0.72)	
31	6.49	5.97	6.82	6.16	6.36	6.42	6.35	5.80	7.06	6.64	6.59	6.85	6.20	0.00	0.00	6.20
	1.28	0.82	1.22	1.58	1.23	0.77	1.03	0.79	1.13	1.01	1.07	1.09	0.72	0.00	0.00	0.94
	0.08	-0.42	0.41	-0.24	-0.03	0.02	-0.05	-0.60	0.65	0.24	0.18	0.44	-0.19	-6.40	-6.40	-0.19
		-0.05	(1.25)			-0.17	(0.97)			0.38	(1.06)			-0.21	(0.80)	
32	6.52	6.13	6.12	5.50	5.87	6.70	5.66	5.79	6.70	6.22	6.50	6.12	5.32	5.85	5.50	6.30
	0.60	1.03	0.77	0.84	0.83	0.70	0.50	0.70	0.81	0.59	0.50	0.50	0.55	0.67	0.82	1.09
	0.48	0.09	0.08	-0.53	-0.15	0.66	-0.37	-0.24	0.66	0.18	0.46	0.08	-0.71	-0.18	-0.52	0.26
		0.00	(0.89)			-0.05	(0.78)			0.35	(0.64)			-0.30	(0.86)	
33	4.88	4.73	4.29	3.93	4.84	5.04	4.59	4.44	4.73	4.37	4.72	4.47	4.38	4.24	5.05	4.99
	1.24	0.58	1.43	0.78	1.40	0.99	0.91	0.31	1.32	0.82	0.91	1.09	1.27	1.15	0.61	1.14
	0.26	0.11	-0.32	-0.68	0.22	0.42	-0.02	-0.17	0.11	-0.24	0.10	-0.14	-0.23	-0.37	0.43	0.37
		-0.13	(1.11)			0.10	(1.05)			-0.04	(1.05)			0.06	(1.10)	
45	4.50	3.85	3.68	4.67	4.45	4.72	4.31	4.50	3.71	4.31	4.47	4.13	4.16	4.27	4.02	4.31
	1.12	0.58	0.86	0.76	1.14	1.31	0.48	0.44	0.67	0.77	0.61	0.91	0.91	0.75	0.83	0.61
	0.25	-0.39	-0.56	0.42	0.20	0.47	0.06	0.25	-0.53	0.06	0.22	-0.11	-0.08	0.02	-0.22	0.06
		-0.13	(0.90)			0.25	(0.92)			-0.09	(0.78)			-0.04	(0.77)	
46	0.00	6.78	7.46	6.59	5.12	4.81	5.59	6.13	4.66	6.09	6.54	6.60	5.43	5.74	5.51	5.61
	0.00	0.67	0.70	1.50	0.67	1.19	0.66	0.78	1.07	1.11	0.78	1.02	1.20	1.16	0.93	1.42
	-5.84	0.93	1.61	0.74	-0.72	-1.02	-0.25	0.28	-1.17	0.24	0.69	0.75	-0.40	-0.10	-0.33	-0.23
		0.94	(1.37)			-0.40	(0.93)			0.15	(1.24)			-0.25	(1.16)	
47	4.67	4.27	4.37	3.86	3.94	3.62	2.76	2.79	3.97	4.41	4.24	3.79	3.51	2.68	3.56	3.15
	1.06	0.83	0.68	0.46	1.01	1.36	0.87	1.34	1.14	0.79	0.97	1.07	1.16	0.64	0.56	0.93
	0.93	0.53	0.63	0.11	0.20	-0.12	-0.98	-0.94	0.23	0.66	0.50	0.04	-0.23	-1.05	-0.18	-0.57
		0.54	(0.81)			-0.44	(1.25)			0.38	(1.00)			-0.52	(0.91)	
48	3.10	4.67	6.40	3.44	4.33	4.68	4.75	4.31	4.91	4.36	4.17	4.30	4.34	4.65	4.67	4.66
	1.32	1.60	1.26	1.74	0.79	0.76	0.83	0.99	0.88	0.61	1.01	1.11	1.34	0.88	0.64	[illegible]
	-1.40	0.17	1.89	-1.06	-0.17	0.17	0.24	0.30	0.40	-0.14	-0.32	-0.20	-0.16	0.14	0.17	0.37
		-0.26	(1.90)			0.16	(0.84)			-0.08	(0.94)			0.13	(1.05)	
49	5.75	4.40	4.58	4.88	4.58	4.89	5.19	4.72	4.57	4.03	4.62	4.80	5.23	4.57	4.68	4.20
	0.84	0.54	0.60	0.62	0.82	0.58	0.68	0.97	1.62	1.42	1.12	0.78	1.25	0.53	0.58	0.76
	1.02	-0.33	-0.15	0.14	-0.15	0.15	0.46	-0.00	-0.15	-0.69	-0.10	0.07	0.49	-0.15	-0.04	-0.52
		0.17	(0.83)			0.07	(0.79)			-0.19	(1.26)			-0.05	(0.89)	
50	4.00	3.95	3.68	3.87	3.34	4.08	4.39	3.94	4.10	3.30	4.24	4.61	4.76	5.15	4.11	4.28
	0.92	0.59	0.56	0.42	1.25	1.28	0.87	1.35	0.51	1.64	0.83	1.05	0.75	0.99	0.93	1.11
	-0.12	-0.17	-0.44	-0.25	-0.78	-0.03	0.27	-0.18	-0.02	-0.82	0.11	0.48	0.63	1.02	-0.01	0.15
		-0.24	(0.66)			-0.20	(1.23)			0.01	(1.01)			0.50	(1.00)	
51	4.86	4.61	4.70	4.52	4.71	4.65	4.27	4.34	4.79	4.80	4.83	4.93	5.04	5.06	5.18	5.13
	1.29	0.74	0.89	1.16	0.36	0.57	0.73	0.35	0.83	0.64	0.96	0.75	0.83	1.12	1.15	0.75
	0.07	-0.16	-0.07	-0.25	-0.06	-0.12	-0.50	-0.43	0.01	0.02	0.05	0.15	0.26	0.28	0.40	0.35
		-0.11	(0.99)			-0.29	(0.67)			0.06	(0.79)			0.32	(0.94)	
52	5.68	6.31	5.60	5.85	5.16	5.13	5.31	5.82	5.94	5.40	6.04	5.07	5.29	5.91	5.83	5.62
	0.83	0.66	1.09	0.62	0.63	0.53	0.87	0.70	0.72	1.06	1.02	0.88	1.09	0.79	0.98	0.95
	0.06	0.69	-0.01	0.23	-0.45	-0.48	-0.30	0.20	0.32	-0.21	0.42	-0.54	-0.32	0.29	0.22	0.00
		0.23	(0.88)			-0.25	(0.73)			-0.01	(1.00)			0.04	(0.97)	
	5.05	5.14	5.11	4.90	4.92	5.08	4.87	4.93	5.03	4.91	5.20	5.03	5.00	4.95	4.79	5.01
	0.95	0.97	1.19	1.04	0.76	0.97	0.65	0.92	0.94	0.91	0.95	0.92	0.68	0.53	0.64	0.60
		5.05				4.95				5.04				4.94		

For key, see page 182

FIG 50 OVERALL RESULTS - EXPT 4



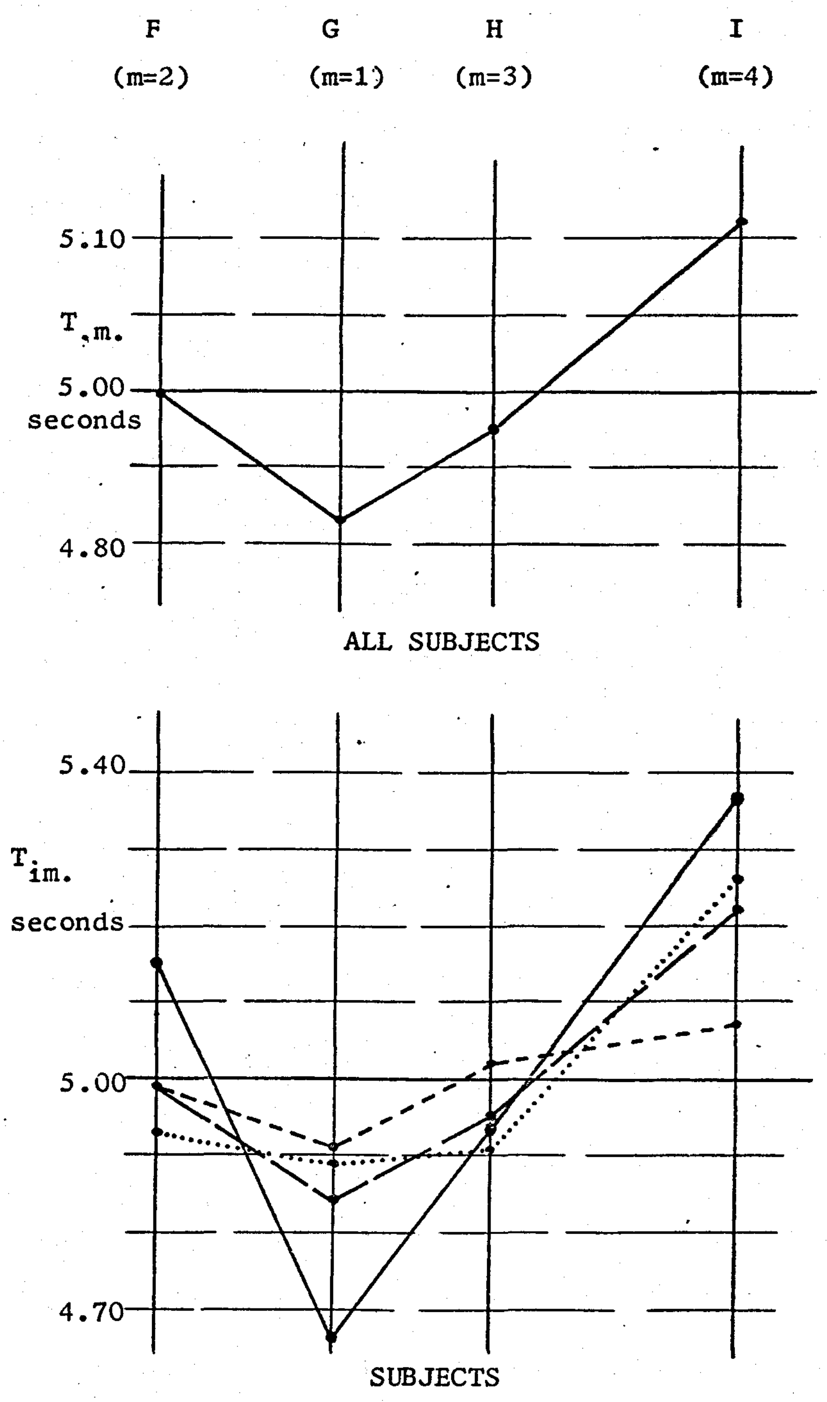


With the other magnifiers the distinct trends are fewer and more nearly balanced between improvement and deterioration.

The extra 20 minute period which was imposed on the first 8 subjects, shows in spite of the large swings due to having only two subjects each, that the general downward trend of the unmodified magnifier G is generally maintained. The general deterioration in performance during the penultimate sub-trial is more likely to be related to subject motivation with the last sub-trial showing an 'end effect' rather than any specifically physiological interaction between subjects and magnifiers.

A more specific analysis may be applied if the four sub-trial values obtained from each subject on each magnifier are regarded as repeat observations of the same true value and the mean for each magnifier compared. Over all subjects it is seen from Fig.51 that the visual performance decreases with increasing parallax error independently of the sign of that error. If, however, the subjects are grouped according to the order in which they used the magnifiers (Array 11 Chap.5) an interactive effect with the visual performance/parallax error relation is seen. Such are the variations between subjects that the size of this effect is not statistically significant. In the division of subjects into physiological groups it would be preferable to have in each group equal numbers from each order of viewing group. At the time when subjects 26 to 33 were used any interactions between physiological parameters had not been recognised and the location of particular subject types within the order of viewing groups was entirely by chance. Although the location of subjects 45 to52 was chosen with this in mind it was not possible to achieve a complete balance as is described in Chapter 5 (Pages 153 and 154).

FIG 51 MAGNIFIER/ORDER OF VIEWING INTERACTION - EXPT 4



....	G F H I	26 30 45 50	(1 2 3 4)
----	H G I F	27 31 47 51	(3 1 4 2)
— —	F I G H	29 33 48 49	(2 4 1 3)
——	I H F G	28 32 46 52	(4 3 2 1)

The subjects may be arranged in the square array at the top of Fig.52. If a vertical line is drawn to divide these into two groups it is seen from the array of inter-pupilliary distances exhibited by the subjects that the mean P.D. of the left-hand eight is 62.2mm while that of the right is 65.6mm. Of the eight with narrow P.D. two saw the magnifiers in each of the orders shown in Fig.51 and similarly for the wide P.D. group.

A horizontal line through the subjects divides them according to their disassociated phoria at 50cms. The upper eight are virtually orthophoric while the lower group exhibits a mean of 6Δ exophoria. However, in these groupings a balance in the order of viewing was not possible. Three subjects in the upper group all used the magnifiers in the same order, GFHI, while only one used FIGH. The opposite imbalance exists in the lower group.

Accepting this limitation, the results are analysed within the groupings, using the relative performance figures for each subject with respect to the mean performance for that subject across the four magnifiers. This allows a simpler appreciation of the results before a more thorough analysis. These relative results are shown in Fig.52 in units of 0.01 seconds. Under these figures are shown the arbitrary scale values for the phoria shift obtained from before and after measurements of disassociated phoria made as described in Chapter 5, Section 5. The third row of figures records the visual comfort score accorded to each magnifier by each subject after every trial as described in Chapter 5, Section5. These results are laid out in the same array as given at the top of Fig.52.

The mean values taken over these groups of subjects are shown in Fig.53 and Fig.54. The best performance of the orthophoric group

FIG 52 SUBJECT/MAGNIFIER INTERACTION - EXPT 4

Subject No.	P. D. in mms		Base Phoria Single Scale:-	Mean
46 45 30 31	60 61	65 64	53 38 53 39	55
26 48 47 28	62 62	65 66	58 65 63 69	
27 32 50 49	61 63	63 64	75 71 70 70	79
51 33 29 52	60 68	69 69	75 84 85 99	
Mean	62.2	65.6		

10 = 8Δ eso
30 = 4Δ eso
50 = Orthophoric
70 = 4Δ exo
90 = 8Δ exo

Mag.	F	G	H	I	F	G	H	I	F	G	H	I	F	G	H	I
Perf.	+15	-25	-40	+94	+25	-13	-09	-04	-29	+06	-25	+38	-21	-17	-05	+38
Shift	-20	-25	-30	-20	-05	00	00	-05	-10	-30	-10	00	-10	-15	00	00
V.C.S	3	3	3	3	3	3	2	2	2	2	3	3	2	2	3	2
Perf.	-02	-15	-02	+19	-26	-08	+13	+16	-52	-44	+54	+38	+12	-85	+44	+32
Shift	-15	-10	-15	-15	-20	-20	-30	-05	-10	-10	-05	00	-25	-30	-20	-20
V.C.S	2	3	2	3	2	2	2	2	3	3	3	2	2	2	2	3
Perf.	+36	+25	-57	+05	+35	-30	-05	+00	-20	-24	+01	+50	+17	-19	-05	+07
Shift	-15	-15	-10	-10	-10	-10	+10	+10	-20	-15	-10	-15	-10	-10	-05	-05
V.C.S	3	3	3	2	2	2	2	2	3	2	2	2	2	1	2	2
Perf	+32	-29	-11	+06	-13	-04	+06	+10	+18	-05	-06	-06	-01	+04	-25	+23
Shift	-05	00	-15	-10	00	-15	-05	-15	+10	-20	-20	-20	00	+05	+05	+05
V.C.S	3	2	3	3	3	2	2	2	4	2	3	2	2	2	2	2

Performance figures show deviation from each subjects' mean viewing time in units of 0.01 seconds. Thus, negative values relate to better than average performance.

(most negative value) occurs with magnifier G while for the exophoric group, the best performance is recorded on magnifier H. The greatest phoria shift also tends to occur with the magnifier showing better performance, although the correlation by rank is only 0.47.

A similar shift in the best magnifier is shown by the groups having different inter-pupilliary distances. The wide P.D. group favours G and possibly F while narrow P.D. subjects prefer G and H. Again, the maximum Phoria shift is associated with the magnifier giving the best performance with a correlation by rank of 0.9.

In both cases the visual comfort score shows little change with magnifier and less correlation with the actual performance recorded. However, the relatively high correlation with P.D. while possibly fortuitous does merit comment. This division of subjects is the more clear cut of the two as the disassociated phoria values of the two groups are less than 1Δ different. With the division into groups having different mean phoria values the mean P.D. of these groups show a difference of 1.6mm which is almost half the difference obtained with the deliberate division into P.D. groups. As the P.D. effect on relative performance and the phoria effect appear to go in opposite directions the manifestation of the phoria effect is partially masked by that of the P.D. effect.

Although the variations between subjects is too large to provide statistical significance to each small difference in response to the magnifiers, it seems very likely that phoria shift under these conditions is related to visual performance which has a 'best' value and shows the same shape of curve and not to the prismatic (parallax) error which is linear across the four magnifiers. Thus, it cannot be postulated that the shift in the rest positions of the eyes is

FIG 53 SUBJECT/MAGNIFIER INTERACTION - EXPT 4

SUBJECTS:-

	46 45 30 31 26 48 47 28				27 32 50 49 51 33 29 52			
	Mean P.D. = 63.2mm				Mean P.D. = 64.6mm			
	Mean Phoria = 55 (1△exo)				Mean Phoria = 79 (6△ exo)			
Mag	F	G	H	I	F	G	H	I
Perf	-10	-25	+04	+34	+13	-10	-13	+12
Shift	-14	-18	-14	-08	-06	-10	-06	-08
V.C.S.	2.4	2.5	2.5	2.5	2.8	2.0	2.4	2.1

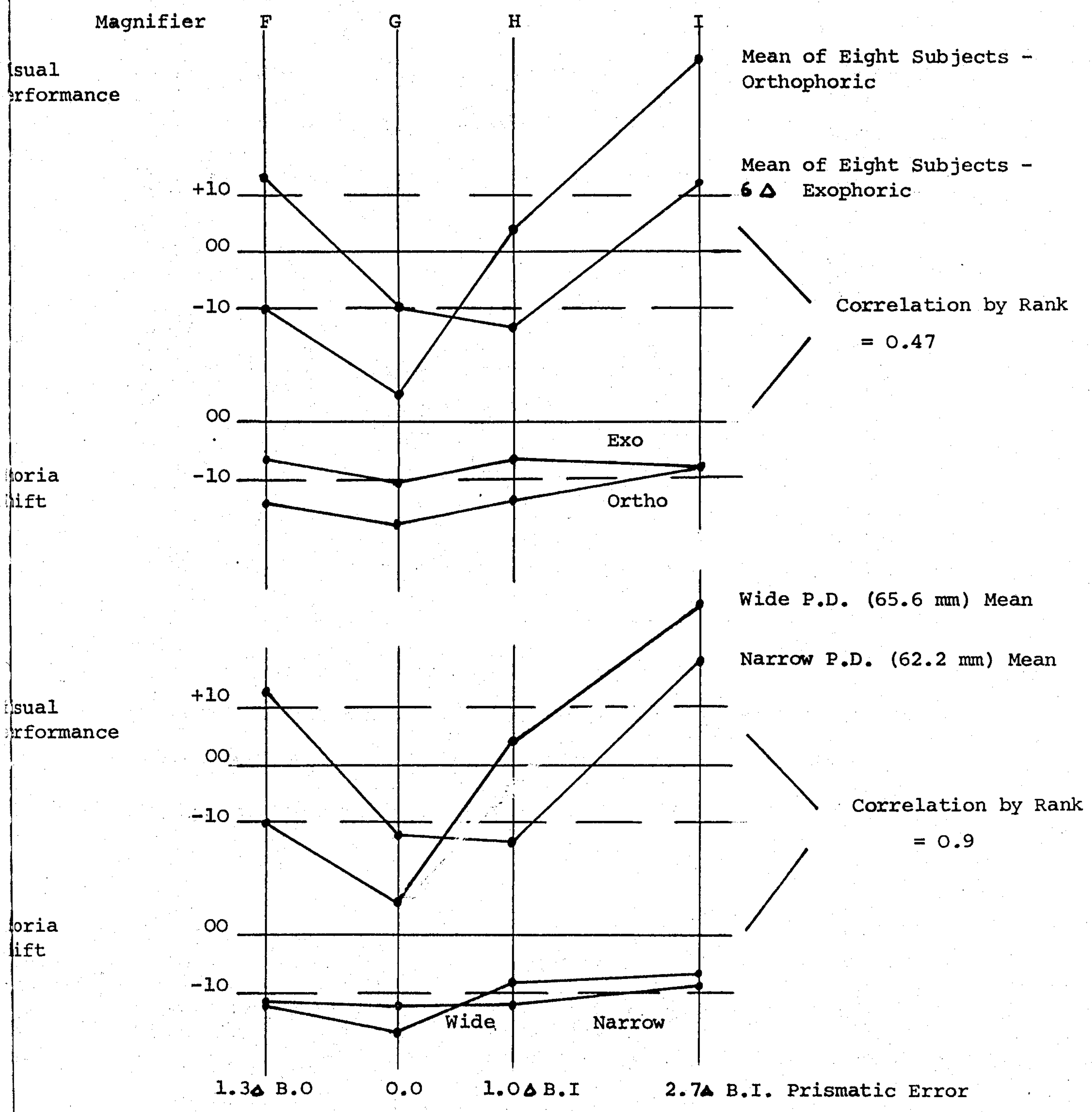
Correlation between Perf. and Shift by Rank = 0.47

SUBJECTS:-

	46 45 26 48 27 32 51 33				30 31 47 28 50 49 29 52			
	Mean P.D. = 62.2mm				Mean P.D. = 65.6mm			
	Mean Phoria = 65 (3△ exo)				Mean Phoria = 68 (3.5△ exo)			
Mag	F	G	H	I	F	G	H	I
Perf	+13	-12	-13	+18	-10	-23	+04	+28
Shift	-11	-12	-12	-09	-12	-16	-08	-07
V.C.S.	2.6	2.5	2.4	2.4	2.5	2.0	2.5	2.3

Correlation between Perf. and Shift by Rank = 0.9

FIG 54 SUBJECT/MAGNIFIER INTERACTION - EXPT 4



Visual Performance is given in 1/100 seconds change from mean.

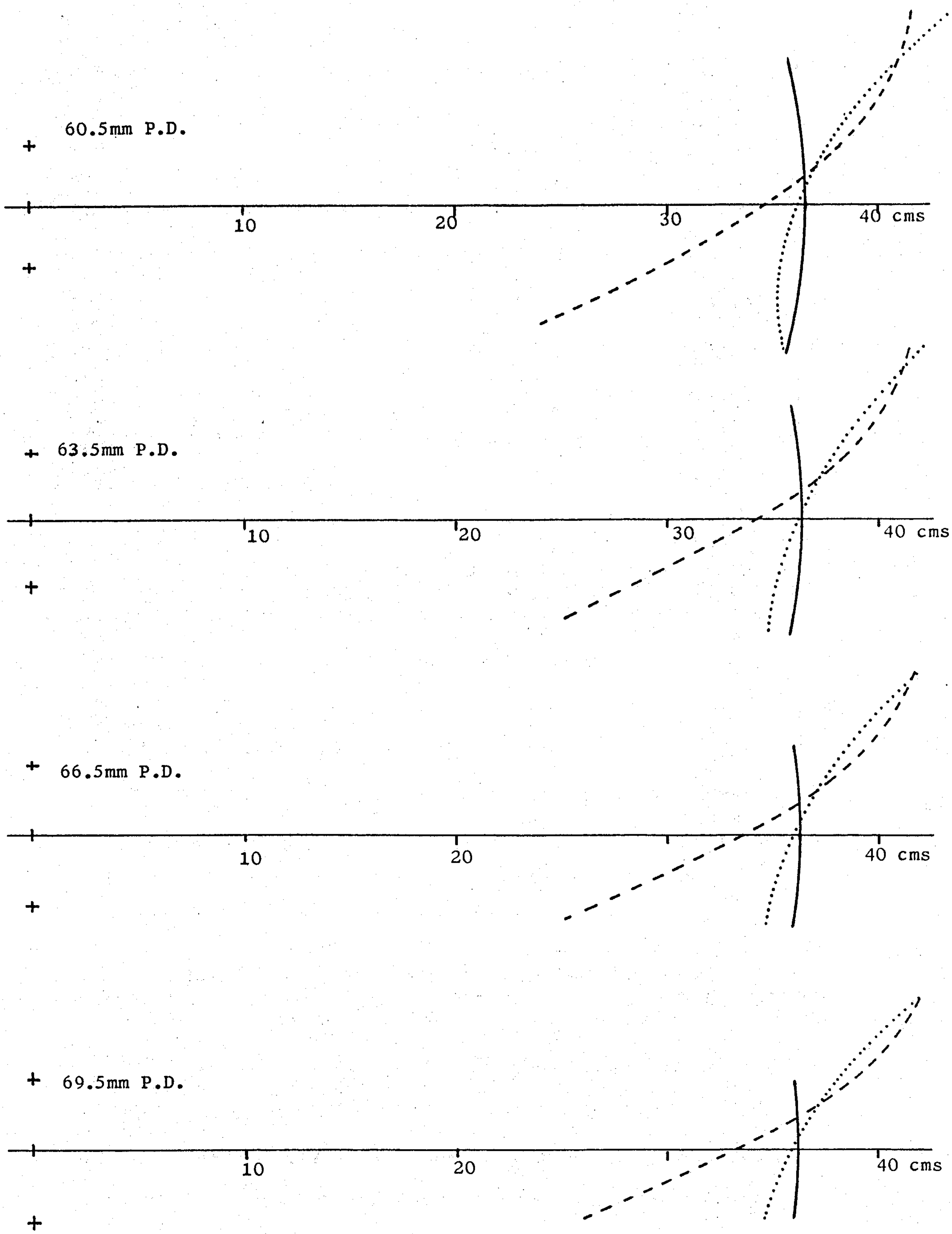
Phoria Shift is in arbitary units where - 10 indicates 2Δ shift towards esophoria.

an 'impedance matching' action similar to that found by Carter (1963) and described in Chapter 4 (Page 98).

The possibility that phoria shift constitutes a physiological correlate of visual performance cannot be ruled out by these results. There is however less evidence that phoria shift relates to absolute performance values across subjects. These values are the relative results for each subject with respect to the mean for that subject across the four magnifiers as this allows a simpler appraisal. When the actual $T_{.m.}$ values are used (see later) over the specific groups of subjects (These values are again relative but now to the mean over all subjects and magnifiers) the correlations are reduced to 0.38 and 0.84 respectively. When the mean for each subject over all magnifiers is compared with his mean phoria shift the correlation is 0.05! Clearly, parallax error and phoria condition are likely to be related in some way and the effective change of best magnifier with phoria condition is evidence of this. It remains an open question whether the phoria shifts found would still relate to relative performance if some other visual aberration were used.

However, the effect found with the different P.D.s of subjects demands an explanation in itself. The prisms placed between the subject and magnifier do not have an optical action that is related to P.D. The visual aberrations shown graphically in Figs.11 and 37 were examined more intensively using the computer program devised by the writer. When different eye positions related to larger and smaller inter-pupilliary distances were entered into the calculation it was found that the extent of the binocular overlap was changed. Fig.55 shows how observers with wide P.D. experience a binocular overlap which is

FIG 55 - EFFECT OF SUBJECT P.D.



vertical scale = horizontal scale

approximately one half of that seen by those of narrow P.D.

In the context of the division of subjects into groups having mean P.D.s. of 62.2 and 65.6 respectively the binocular overlap varies from a width of 4 inches down to 3 inches, at the viewing distance of 14.5 inches. Thus, a second visual aberration is being varied across the subjects. When the decision to use real magnifiers was taken the likelihood of interactions between other aberrations and subjects was accepted. Obviously an experiment in which this aberration is varied for each subject is needed. However, an attempt to analyse these interactive effects will be made in the next chapter.

Not only are the subjects different and the magnifiers different, the objects used on the task films are also different. Reference has already been made to the vertical and horizontal nature of these objects and their interaction with the astigmatism of one magnifier in Expt.1 A further distinction may be made according to the location of each object at its mean recognition time. Because of the twists and turns of the canal and the precise placement of the objects the loci they take in the field of view is varied as shown in Fig.33 (page 141) .

However, the data reduction process described earlier ascribes a mean sighting time, $t_{.k1}$, to each object. With these values obtained from the computer the visual task film was viewed against a pattern of squares over the field of view. After each triggering flash the projector was stopped at the moment of the mean sighting time calculated for that object. The location of each object was then noted. Subsequently, the objects were categorised as monocular or binocular according to their location at mean sighting being outside or inside the binocular overlap for an observer having a P.D. of 64mm.

This means that for each magnifier results from each set of objects may be obtained over all subjects as given in Figs 56 to 59. When these figures are presented in graphical form as shown in Fig.60 it can be seen that the greatest effect of the add-on prisms occurs with the vertical and binocular objects. It is to be expected that errors in parallax caused by the add-on prisms will effect those objects in the binocular overlap region more than those outside it. Equally, if the eyes adopt some non-normal fixation disparities as a result of the parallax error one would expect those objects with detail in the horizontal plane (that is, vertical bars) to suffer most.

Each of the figures yielding the points on the lower four graphs of Fig.60 are the means of 512 sightings less missing values (32 objects x 16 subjects). Any reduction in this figure will tend to reduce the chance of statistical significance but such an analysis must be done if the interactions between the visual aberrations of the magnifiers and subjects with visual performance are to be investigated. To this end a two-way analysis of variance was carried out for each class of object and each class of subject over the four magnifiers. In order to ascertain which differences between magnifiers were significant Tukey's test was applied to the results. In general, magnifier I3 is commonly worse than some or all of the others to an extent giving statistical significance at the 1% or 5% level. Differences between the other magnifiers are less distinct.

In this test the residual mean squares are used rather than the interactions which are rather high due probably to the subjects in each group having a wide spread about the mean value of P.D. or phoria. The significance indicated is therefore only applicable to the 16 subjects used. The full data is given in tables as Figs.61 and 64. In no case is there a conflicting difference with the hypothesis that

FIG 56 RESULTS BY MAGNIFIER FOR 'MONOCULAR' OBJECTS - EXPT 4

MAGNIFIER	F m=2				G m=1				H m=3				I m=4			
ECT 26	5.44	4.54	4.58	5.20	5.02	5.58	4.11	4.31	5.09	5.03	4.86	4.99	4.96	4.88	4.63	5.16
	0.56	0.61	1.20	0.40	0.95	0.29	0.50	0.86	0.78	0.78	0.59	0.56	0.61	0.76	0.65	0.65
	0.55	-0.33	-0.29	0.32	0.14	0.70	-0.76	-0.56	0.21	0.15	-0.01	0.11	0.08	0.00	-0.19	0.28
		-0.00	(0.89)			-0.19	(0.90)			0.11	(0.65)			0.05	(0.71)	
27	4.60	6.06	4.38	4.84	5.13	4.74	4.69	5.06	4.35	3.82	3.35	4.22	5.12	4.51	4.55	4.18
	0.65	0.81	1.50	1.15	0.57	0.91	0.72	0.74	0.43	0.81	1.06	1.03	0.77	0.35	0.69	1.27
	0.22	1.45	-0.19	0.26	0.54	0.16	0.11	0.48	-0.22	-0.75	-1.23	-0.36	0.54	-0.06	-0.03	-0.39
		0.32	(1.21)			0.33	(0.72)			-0.61	(0.99)			0.03	(0.85)	
28	5.38	5.71	5.99	6.22	6.53	5.23	4.98	4.62	5.76	7.12	5.83	6.09	5.78	6.78	5.52	7.11
	0.61	0.46	0.85	0.77	1.01	0.72	0.74	0.97	0.52	0.84	1.11	1.61	0.81	1.60	1.61	0.94
	-0.46	-0.13	0.14	0.36	0.68	-0.61	-0.86	-1.22	-0.09	1.27	-0.02	0.23	-0.06	0.92	-0.32	1.26
		-0.07	(0.70)			-0.65	(1.01)			0.27	(1.20)			0.44	(1.38)	
29	5.68	5.57	5.57	6.03	5.45	5.22	5.65	5.82	5.25	5.40	5.33	6.18	5.03	6.06	5.17	5.83
	1.06	0.67	0.68	0.76	0.73	0.40	0.55	0.48	0.84	0.54	1.10	0.58	1.03	0.85	1.45	0.89
	0.13	0.02	0.02	0.48	-0.09	-0.32	0.10	0.27	-0.30	-0.14	-0.22	0.63	-0.51	0.51	-0.37	0.28
		0.14	(0.77)			-0.04	(0.58)			-0.02	(0.86)			-0.06	(1.13)	
30	4.22	4.73	4.46	3.89	4.74	4.88	4.77	4.13	4.51	3.89	4.14	3.93	4.75	4.77	5.16	5.29
	0.72	1.53	0.30	1.65	0.62	1.00	0.74	0.96	0.62	0.78	0.60	1.24	1.12	0.90	0.26	0.36
	-0.33	0.17	-0.09	-0.66	0.18	0.32	0.21	-0.42	-0.04	-0.66	-0.41	-0.62	0.19	0.21	0.60	0.73
		-0.26	(1.28)			0.07	(0.34)			-0.41	(0.81)			0.44	(0.74)	
31	6.49	6.09	7.26	5.78	6.21	6.25	6.53	5.63	6.31	6.06	6.78	5.66	6.88	6.70	6.37	7.09
	0.86	0.40	0.00	0.76	1.42	0.82	1.16	1.01	1.14	0.96	1.24	2.03	1.09	1.03	1.00	0.57
	0.15	-0.24	0.91	-0.55	-0.02	-0.08	0.19	-0.71	-0.02	-0.27	0.43	-0.67	0.54	0.35	0.02	0.75
		-0.14	(0.83)			-0.15	(1.09)			-0.15	(1.36)			0.41	(0.95)	
32	6.76	6.22	6.58	5.83	5.80	6.04	5.65	6.38	6.10	6.46	5.71	5.92	6.72	5.71	6.28	5.30
	0.63	0.56	0.59	0.38	0.56	0.56	0.73	1.06	0.87	0.69	0.57	0.72	0.63	0.88	0.85	0.74
	0.68	0.15	0.51	-0.23	-0.26	-0.02	-0.42	0.31	0.03	0.39	-0.35	-0.14	0.65	-0.35	0.21	-0.76
		0.26	(0.63)			-0.13	(0.77)			-0.03	(0.73)			-0.09	(0.92)	
33	5.22	4.40	4.53	3.54	5.07	4.35	4.60	4.35	3.98	4.41	5.15	5.34	4.72	4.74	4.55	4.14
	0.94	0.60	1.13	1.02	1.57	0.66	1.24	0.74	1.09	0.70	0.56	0.97	1.05	1.03	0.79	0.90
	0.59	-0.21	-0.08	-1.07	0.45	-0.26	-0.01	-0.26	-0.63	-0.21	0.53	0.72	0.10	0.11	-0.06	-0.47
		-0.12	(1.05)			0.00	(1.13)			0.20	(0.94)			-0.09	(0.93)	
45	4.66	4.64	4.22	4.38	5.05	3.82	3.67	5.09	3.86	4.15	4.20	4.14	4.49	4.21	3.75	4.65
	0.90	1.06	0.45	0.29	1.21	0.48	0.44	0.98	0.53	0.97	0.70	0.85	0.95	0.52	0.93	0.36
	0.40	0.37	-0.04	0.11	0.78	-0.44	-0.58	0.83	-0.40	-0.11	-0.06	-0.12	0.22	-0.05	-0.50	0.36
		0.17	(0.69)			-0.03	(0.93)			-0.18	(0.74)			0.03	(0.77)	
46	5.17	6.34	6.41	6.57	5.17	5.48	5.17	5.42	5.29	5.24	5.51	6.05	0.00	7.50	8.00	7.00
	1.00	0.46	0.86	1.18	1.49	1.10	0.63	1.51	0.82	0.86	0.70	0.77	0.00	0.28	0.97	1.15
	-0.70	0.45	0.52	0.69	-0.70	-0.40	-0.71	-0.45	-0.59	-0.63	-0.36	0.16	-5.88	1.61	2.12	1.12
		0.27	(1.02)			-0.55	(1.18)			-0.32	(0.79)			1.45	(1.05)	
47	3.52	2.73	3.63	2.95	4.51	3.61	3.16	2.39	4.92	4.12	4.31	3.61	4.03	4.22	4.61	4.44
	1.18	0.76	0.45	0.92	0.60	0.99	0.82	1.37	1.30	0.70	0.84	0.25	1.15	0.62	0.74	0.99
	-0.25	-1.04	-0.13	-0.82	0.73	-0.15	-0.61	-1.38	1.14	0.34	0.53	-0.16	0.25	0.44	0.83	0.65
		-0.57	(0.92)			-0.44	(1.24)			0.48	(0.95)			0.52	(0.88)	
48	3.26	5.40	6.84	3.16	4.62	4.26	4.67	4.38	4.51	4.54	4.48	5.34	5.03	4.40	4.48	4.47
	1.72	1.95	1.88	1.38	0.75	0.72	0.79	1.21	1.33	0.92	0.94	1.35	0.68	0.62	0.81	1.01
	-1.28	0.85	2.29	-1.39	0.07	-0.28	0.12	-0.16	-0.03	-0.00	-0.07	0.79	0.47	-0.15	-0.07	-0.08
		-0.06	(2.13)			-0.06	(0.87)			0.15	(1.11)			-0.02	(0.79)	
49	5.96	4.50	4.46	4.55	5.59	4.49	5.40	4.74	5.22	4.72	4.70	3.89	4.51	5.04	5.00	4.92
	0.52	0.40	0.72	0.59	0.62	1.00	1.04	0.95	1.59	0.33	0.69	0.43	0.56	0.60	0.55	1.00
	1.09	-0.35	-0.39	-0.30	0.72	-0.36	0.53	-0.11	0.35	-0.13	-0.15	-0.96	-0.35	0.18	0.13	0.05
		0.04	(0.85)			0.24	(0.95)			-0.26	(0.93)			0.00	(0.69)	
50	3.61	3.53	3.89	3.78	3.95	3.89	3.75	4.06	3.96	0.00	3.94	4.44	4.68	5.25	4.72	3.61
	1.12	1.61	0.95	1.51	1.03	0.51	0.39	0.77	0.50	0.00	0.67	0.70	0.99	0.99	0.57	1.32
	-0.44	-0.52	-0.16	-0.27	-0.10	-0.16	-0.31	0.00	-0.10	-4.06	-0.12	0.38	0.62	1.19	0.65	-0.44
		-0.35	(1.25)			-0.16	(0.67)			0.04	(0.61)			0.53	(1.14)	
51	4.99	5.06	5.02	4.77	4.73	4.76	3.96	4.02	5.58	4.77	4.81	4.00	4.67	4.81	4.77	4.45
	0.71	0.90	1.41	0.69	0.33	0.77	0.52	0.78	1.28	0.98	1.12	0.93	0.94	0.43	0.95	0.85
	0.30	0.37	0.33	0.07	0.04	0.06	-0.72	-0.67	0.88	0.07	0.11	-0.69	-0.01	0.12	0.07	-0.27
		0.26	(0.95)			-0.35	(0.72)			0.06	(1.13)			-0.00	(0.77)	
52	5.85	5.52	5.94	4.83	5.17	5.68	5.85	5.60	5.55	5.05	5.18	5.64	5.63	5.84	6.26	5.74
	0.67	1.14	1.21	0.81	1.38	0.62	0.98	1.23	0.59	0.49	0.98	0.78	0.58	0.76	1.20	0.66
	0.28	-0.05	0.37	-0.73	-0.39	0.11	0.28	0.05	-0.01	-0.51	-0.38	0.07	0.06	0.27	0.69	0.17
		-0.03	(1.03)			0.00	(1.06)			-0.21	(0.76)			0.28	(0.80)	
	5.06	5.07	5.24	4.77	5.18	4.89	4.79	4.75	5.01	4.92	4.89	4.97	5.13	5.34	5.24	5.21
	1.02	1.00	1.13	1.11	0.65	0.79	0.90	0.94	0.76	0.95	0.84	0.91	0.80	0.99	1.03	1.09
		5.03				4.90				4.96				5.23		

For key, see page 182

FIG 57 RESULTS BY MAGNIFIER FOR 'BINOCULAR' OBJECTS - EXPT 4

MAGNIFIER	F m=2	G m=1	H m=3	I m=4
ECT				
26	5.32 4.34 4.51 5.12 0.62 0.47 0.81 1.01 0.44 -0.53 -0.36 0.24 -0.03 (0.82)	4.60 5.61 3.85 4.91 1.51 1.38 1.05 0.97 -0.27 0.73 -1.02 0.03 -0.13 (1.36)	4.55 4.98 4.57 4.86 1.19 0.38 1.11 0.67 -0.32 0.10 -0.30 -0.01 -0.13 (0.87)	5.63 5.10 4.59 5.28 0.63 1.05 0.62 0.56 0.75 0.22 -0.28 0.40 0.32 (0.80)
27	4.99 5.42 4.10 5.01 0.93 1.60 0.73 1.46 0.41 0.84 -0.47 0.42 0.39 (1.28)	4.86 4.80 4.57 4.85 0.59 0.27 0.74 1.13 0.28 0.21 -0.00 0.27 0.18 (0.63)	3.81 4.06 4.47 3.88 1.32 1.61 0.33 0.64 -0.76 -0.51 -0.10 -0.70 -0.53 (1.09)	4.68 4.78 5.22 3.93 0.96 0.46 1.11 0.67 0.10 0.19 0.64 -0.64 0.07 (0.94)
28	6.18 5.81 6.78 5.87 0.48 0.39 0.42 0.55 0.34 -0.02 0.94 0.03 0.29 (0.58)	5.71 5.13 3.77 4.43 1.36 0.96 1.34 1.36 -0.12 -0.70 -2.06 -1.40 -1.00 (1.40)	6.07 7.22 6.28 6.08 0.87 1.14 0.88 1.22 0.23 1.38 0.44 0.24 0.59 (1.10)	5.58 5.99 6.40 6.25 0.95 1.13 1.10 1.57 -0.25 0.15 0.56 0.41 0.21 (1.14)
29	6.01 5.87 5.64 5.41 0.70 0.54 1.07 1.05 0.49 0.34 0.12 -0.11 0.20 (0.86)	5.63 5.05 5.98 5.25 0.76 0.45 0.26 0.59 0.11 -0.47 0.46 -0.27 -0.07 (0.63)	5.55 5.74 5.34 4.94 0.69 0.05 0.48 1.21 0.03 0.22 -0.18 -0.57 -0.10 (0.85)	5.44 5.68 5.32 5.34 0.74 1.07 1.15 0.63 -0.07 0.16 -0.19 -0.17 -0.05 (0.87)
30	4.61 3.90 4.23 4.17 0.30 0.96 0.72 0.91 0.08 -0.62 -0.29 -0.35 -0.30 (0.78)	4.93 4.82 4.37 4.22 0.97 0.79 1.19 0.79 0.40 0.29 -0.15 -0.30 0.04 (0.95)	4.15 4.18 4.53 4.71 0.90 0.73 0.88 1.11 -0.37 -0.34 0.00 0.18 -0.12 (0.90)	4.56 4.70 5.03 5.21 0.46 0.89 0.54 0.80 0.03 0.17 0.50 0.68 0.33 (0.72)
31	5.96 5.17 6.01 6.63 0.52 0.00 0.85 0.95 -0.49 -1.29 -0.44 0.17 -0.27 (0.80)	6.40 6.58 6.10 5.95 1.20 0.74 0.87 0.58 -0.05 0.12 -0.35 -0.50 -0.19 (0.86)	6.66 5.91 6.84 6.58 1.47 0.77 1.31 1.06 0.20 -0.54 0.38 0.12 0.02 (1.17)	7.23 6.57 6.75 6.67 1.23 1.10 1.15 1.36 0.77 0.11 0.29 0.21 0.36 (1.18)
32	5.65 6.22 6.45 6.41 0.98 0.67 0.48 0.44 0.64 0.21 0.44 0.40 0.44 (0.65)	5.06 5.74 5.32 6.24 0.34 0.73 0.95 1.19 -0.95 -0.26 -0.68 0.22 -0.44 (0.90)	5.64 6.99 5.60 5.64 0.78 0.64 0.43 0.71 -0.36 0.98 -0.40 -0.36 -0.07 (0.84)	6.32 6.46 6.00 5.66 0.56 1.06 0.72 0.92 0.31 0.45 -0.00 -0.34 0.08 (0.88)
33	4.59 4.99 4.11 4.18 1.43 0.44 1.67 0.51 -0.02 0.37 -0.50 -0.43 -0.14 (1.17)	4.38 4.38 4.81 4.57 1.01 0.96 0.66 1.36 -0.23 -0.23 0.19 -0.04 -0.08 (0.99)	4.63 4.09 4.91 4.64 1.38 1.48 0.69 1.25 0.01 -0.52 [illegible] 0.02 -0.05 (1.22)	4.94 5.30 4.64 4.74 1.67 0.94 1.09 0.62 0.32 0.68 0.02 0.12 0.29 (1.14)
45	4.33 4.79 4.43 4.63 1.29 1.55 0.54 0.56 0.10 0.56 0.20 0.40 0.31 (1.09)	4.26 3.87 3.68 4.40 1.08 0.68 1.12 0.48 0.03 -0.35 -0.54 0.17 -0.19 (0.89)	3.54 4.44 4.70 4.11 0.80 0.57 0.44 1.01 -0.68 0.21 0.47 -0.11 -0.00 (0.82)	3.90 4.31 4.33 4.01 0.83 0.91 0.67 0.64 -0.32 0.08 0.10 -0.21 -0.11 (0.77)
46	4.23 5.90 6.64 6.62 0.99 1.43 0.75 0.94 -1.58 0.08 0.22 0.80 0.06 (1.40)	5.62 5.94 5.97 5.86 1.04 1.23 0.93 1.38 -0.19 0.12 0.15 0.04 0.03 (1.10)	4.97 4.57 5.70 6.22 0.52 1.34 0.63 0.86 -0.84 -1.24 -0.11 0.40 -0.49 (1.05)	5.55 6.43 7.29 6.01 2.66 0.47 0.40 1.86 -0.26 0.61 1.37 0.19 0.60 (1.46)
47	3.50 2.65 3.48 3.37 1.23 0.59 0.68 0.94 -0.20 -1.05 -0.22 -0.33 -0.48 (0.92)	3.57 3.62 2.28 3.26 1.07 1.62 0.72 1.24 -0.13 -0.08 -1.42 -0.44 -0.44 (1.29)	4.37 4.40 4.43 4.04 0.68 0.96 0.59 0.50 0.36 0.69 0.72 0.33 0.60 (0.69)	3.92 4.56 3.96 3.38 1.21 0.90 1.07 0.95 0.21 0.85 0.25 -0.32 0.26 (1.08)
48	3.03 4.07 6.07 3.68 1.36 1.04 0.67 2.07 -1.43 -0.39 1.60 -0.78 -0.40 (1.74)	5.19 4.42 3.80 4.23 0.96 0.57 1.04 1.09 0.72 -0.06 -0.66 -0.23 -0.10 (1.01)	4.16 4.73 4.87 4.50 1.47 0.89 0.78 1.01 -0.30 0.26 0.40 0.03 0.11 (1.01)	4.07 4.87 5.06 5.11 0.68 0.81 0.78 0.93 -0.39 0.40 0.59 0.64 0.30 (0.88)
49	5.52 4.31 4.68 5.16 1.10 0.66 0.49 0.52 0.90 -0.30 0.06 0.55 0.28 (0.82)	3.42 3.70 3.96 4.85 1.67 1.65 0.71 0.67 -1.19 -0.90 -0.65 0.24 -0.56 (1.30)	5.23 4.44 4.56 4.56 1.08 0.66 0.45 0.93 0.62 -0.16 0.05 -0.05 0.13 (0.85)	4.63 4.73 5.44 4.56 0.98 0.56 0.82 0.98 0.01 0.12 0.83 -0.05 0.14 (0.87)
50	3.17 4.43 4.68 4.17 1.37 1.00 0.75 1.25 -0.99 0.25 0.50 -0.00 -0.08 (1.21)	4.04 4.00 3.61 3.78 0.89 0.67 0.72 0.34 -0.12 -0.17 -0.56 -0.38 -0.30 (0.65)	4.24 3.30 4.48 4.77 0.52 1.64 0.94 1.39 0.06 -0.87 0.30 0.39 -0.01 (1.23)	4.82 5.07 3.30 4.63 0.53 1.06 0.96 0.49 0.65 0.89 -0.36 0.66 0.48 (0.90)
51	5.08 5.06 5.37 5.45 0.94 1.27 0.83 0.70 0.23 0.21 0.52 0.60 0.38 (0.93)	4.70 4.57 4.48 4.66 0.40 0.40 0.80 0.84 -0.15 -0.27 -0.36 -0.18 -0.25 (0.62)	4.26 4.50 4.59 5.03 1.04 0.53 0.66 1.21 -0.59 -0.35 -0.26 0.18 -0.26 (0.85)	4.88 4.80 4.88 5.19 0.90 0.80 1.05 0.59 0.03 -0.04 0.03 0.34 0.10 (0.80)
52	6.04 5.31 6.12 5.27 0.83 1.06 0.91 0.94 0.38 -0.34 0.45 -0.38 -0.00 (0.99)	5.42 6.14 5.82 5.63 0.71 0.92 1.06 0.82 -0.23 0.48 0.16 -0.02 0.09 (0.88)	4.87 5.19 5.50 6.02 0.50 0.58 0.72 0.58 -0.79 -0.46 -0.15 0.36 -0.29 (0.71)	5.73 6.70 5.04 5.94 1.06 0.78 0.63 0.61 0.06 1.04 -0.61 0.28 0.19 (0.95)
	4.95 4.89 5.21 5.07 1.10 0.91 1.05 1.00 5.03	4.86 4.90 4.52 4.82 0.80 0.90 1.08 0.80 4.78	4.79 4.92 5.09 5.04 0.85 1.06 0.72 0.82 4.96	5.12 5.38 5.23 5.13 0.89 0.80 0.95 0.88 5.21

For key, see page 182

FIG 58 RESULTS BY MAGNIFIER FOR VERTICAL OBJECTS - EXPT 4

MAGNIFIER	F m=2	G m=1	H m=3	I m=4
OBJECT 26	4.98 4.34 4.48 4.80 0.48 0.55 0.79 0.65 0.23 -0.39 -0.25 0.06 -0.11 (0.65)	4.32 4.83 3.54 4.25 1.47 1.02 1.03 0.52 -0.41 0.09 -1.20 -0.48 -0.54 (1.10)	4.95 5.09 4.43 5.06 1.26 0.27 1.04 0.62 0.20 0.34 -0.30 0.32 0.11 (0.90)	5.97 5.14 4.81 5.11 0.48 1.04 0.81 0.55 1.23 0.39 0.07 0.36 0.40 (0.92)
27	4.84 5.21 3.43 4.79 0.52 1.70 0.74 1.54 0.31 0.68 -1.09 0.26 0.13 (1.37)	4.83 4.73 4.63 4.69 0.38 0.67 0.71 0.98 0.31 0.20 0.11 0.17 0.19 (0.68)	4.13 3.81 3.66 4.10 0.73 0.91 1.01 0.93 -0.38 -0.71 -0.54 -0.42 -0.54 (0.87)	5.40 4.79 4.92 4.04 0.87 0.26 1.09 1.18 0.87 0.27 0.39 -0.47 0.27 (1.03)
28	6.00 5.71 6.34 5.89 0.56 0.23 0.72 0.54 0.39 0.10 0.73 0.28 0.39 (0.57)	4.71 4.75 3.31 3.85 0.48 0.77 0.90 0.54 -0.90 -0.85 -2.29 -1.75 -1.45 (0.86)	6.24 7.40 5.82 6.27 0.86 1.42 1.31 1.58 0.63 1.79 0.21 0.65 0.81 (1.41)	5.33 6.31 5.55 7.72 0.89 1.22 1.27 0.86 -0.27 0.70 -0.06 2.11 0.37 (1.33)
29	6.12 5.83 5.61 5.97 0.58 0.57 0.64 0.58 0.54 0.26 0.03 0.40 0.29 (0.59)	5.54 5.10 5.79 5.31 0.66 0.59 0.37 0.65 -0.03 -0.46 0.21 -0.25 -0.11 (0.60)	5.32 5.89 5.31 5.41 0.76 0.68 0.85 1.26 -0.24 0.31 -0.05 -0.16 -0.02 (0.97)	5.38 5.48 5.25 5.62 0.94 0.90 1.65 0.82 -0.19 -0.08 -0.52 0.04 -0.16 (1.05)
30	4.66 3.97 4.30 4.40 0.31 1.39 0.85 1.25 0.10 -0.57 -0.25 -0.14 -0.24 (1.10)	4.93 4.68 4.37 4.36 0.97 0.85 1.02 0.56 0.38 0.13 -0.17 -0.18 0.03 (0.87)	3.98 4.18 4.59 4.04 0.49 0.77 0.87 1.26 -0.56 -0.36 0.04 -0.51 -0.36 (0.83)	5.00 4.69 5.16 5.18 0.57 0.67 0.48 0.74 0.45 0.13 0.61 0.62 0.44 (0.64)
31	5.85 6.09 6.61 6.01 0.59 0.40 0.00 1.04 -0.50 -0.26 0.25 -0.34 -0.35 (0.81)	5.74 6.30 6.52 5.86 1.45 0.75 0.81 0.60 -0.61 -0.05 0.16 -0.50 -0.26 (0.98)	5.94 6.34 6.80 6.39 1.03 0.62 1.44 2.12 -0.42 -0.02 0.44 0.03 0.01 (1.38)	7.30 6.37 7.07 6.58 1.13 1.06 1.09 1.73 0.93 0.00 0.70 0.22 0.53 (1.22)
32	6.75 6.10 6.24 6.24 0.80 0.72 0.39 0.48 0.74 0.09 0.23 0.23 0.34 (0.63)	5.26 5.80 5.56 6.04 0.12 0.71 0.66 1.22 -0.74 -0.21 -0.45 0.02 -0.28 (0.85)	5.90 6.73 5.64 5.71 1.25 0.67 0.32 0.75 -0.11 0.72 -0.36 -0.30 -0.00 (0.87)	6.29 5.96 6.21 5.47 0.61 1.43 0.89 0.73 0.27 -0.04 0.20 -0.54 -0.05 (0.98)
33	4.24 5.00 3.91 3.60 0.98 0.44 1.84 0.92 -0.35 0.40 -0.68 -0.99 -0.38 (1.28)	4.64 4.32 4.78 4.59 0.70 0.96 0.94 0.44 0.04 -0.27 0.18 -0.00 0.00 (0.75)	4.89 4.03 5.20 4.98 1.01 1.35 0.64 1.39 0.29 -0.56 0.59 0.33 0.14 (1.22)	5.04 5.05 4.55 4.56 0.84 1.08 0.91 0.57 0.43 0.44 -0.04 -0.03 0.18 (0.95)
45	4.34 5.02 4.42 4.70 0.64 1.54 0.48 0.35 0.07 0.75 0.15 0.44 0.40 (0.93)	4.73 3.90 3.19 4.79 1.06 0.73 0.69 0.40 0.46 -0.35 -1.07 0.32 -0.22 (1.00)	3.52 4.24 4.23 4.40 0.60 0.54 0.64 0.94 -0.73 -0.01 -0.02 0.13 -0.17 (0.76)	3.74 4.58 4.31 4.21 1.01 0.73 0.68 0.72 -0.52 0.31 0.04 -0.05 -0.03 (0.80)
46	5.32 5.64 6.71 6.15 0.72 1.53 0.69 0.85 -0.87 -0.56 0.50 -0.05 -0.22 (1.09)	6.53 6.12 6.37 6.44 1.11 0.94 0.61 0.94 0.32 -0.07 0.17 0.24 0.13 (0.87)	5.33 4.44 5.74 6.21 0.57 1.31 0.53 0.88 -0.87 -1.75 -0.46 0.01 -0.53 (0.99)	7.09 6.36 7.48 7.20 0.43 0.85 0.55 1.21 0.88 0.66 1.27 0.99 1.00 (0.78)
47	3.51 2.42 3.44 3.26 1.62 0.39 0.64 1.10 -0.20 -1.29 -0.27 -0.45 -0.59 (1.07)	3.54 3.96 2.33 2.73 1.05 1.60 0.68 1.42 -0.17 0.24 -1.39 -0.98 -0.57 (1.39)	4.87 4.12 4.57 3.72 1.24 1.05 0.73 0.29 1.15 0.40 0.85 0.00 0.66 (0.97)	3.98 4.43 4.09 4.41 1.11 1.01 1.11 1.21 0.26 0.71 0.37 0.69 0.48 (1.06)
48	3.03 4.61 6.40 3.48 1.36 1.29 1.26 1.84 -1.60 -0.01 1.76 -1.14 -0.23 (1.96)	4.81 3.97 3.94 3.89 0.66 0.60 1.03 1.00 0.18 -0.66 -0.69 -0.73 -0.50 (0.91)	5.01 4.88 4.49 4.73 0.90 0.83 0.83 1.33 0.38 0.24 -0.13 0.09 0.17 (0.98)	4.71 5.01 5.47 5.30 0.75 0.74 0.59 0.56 0.08 0.37 0.93 0.57 0.51 (0.67)
49	5.72 4.44 4.63 4.83 0.95 0.71 0.59 0.63 1.01 -0.26 -0.08 0.11 0.22 (0.86)	4.45 4.13 4.41 4.80 1.63 0.81 1.06 0.54 -0.25 -0.58 -0.30 0.03 -0.22 (1.08)	5.69 4.48 4.65 4.30 1.53 0.61 0.66 0.85 0.98 -0.23 -0.05 -0.41 -0.00 (1.02)	4.59 4.59 5.71 4.51 0.55 0.53 0.76 1.08 -0.12 -0.12 1.00 -0.20 -0.01 (0.85)
50	2.90 4.60 4.22 3.95 1.00 1.01 1.16 1.39 -1.23 0.46 0.08 -0.18 -0.19 (1.26)	3.74 3.90 3.79 3.80 0.87 0.81 0.52 0.56 -0.39 -0.23 -0.34 -0.33 -0.32 (0.66)	4.25 3.29 4.28 4.99 0.45 1.83 0.88 0.76 0.11 -0.84 0.14 0.85 0.15 (1.09)	4.25 5.33 4.12 4.20 0.69 1.33 0.72 1.26 0.11 1.19 -0.01 0.12 0.40 (1.17)
51	5.16 4.73 5.30 5.32 0.65 0.95 0.82 0.79 0.26 -0.16 0.40 0.42 0.26 (0.79)	4.81 4.85 5.11 4.65 0.40 0.54 0.49 1.01 -0.08 -0.04 0.21 -0.24 -0.05 (0.63)	4.66 4.82 4.95 3.61 1.25 0.60 0.69 0.91 -0.23 -0.07 0.05 -1.28 -0.28 (0.96)	4.54 4.77 4.95 5.47 0.88 0.80 0.93 0.50 -0.35 -0.12 0.06 0.57 0.03 (0.83)
52	6.09 5.39 6.37 4.43 0.81 0.88 1.05 0.65 0.39 -0.30 0.67 -1.26 -0.07 (1.13)	5.23 6.00 5.98 5.48 1.33 0.39 1.12 0.94 -0.46 0.31 0.28 -0.20 -0.01 (1.07)	5.14 5.09 5.58 6.00 0.65 0.60 0.71 0.42 -0.54 -0.60 -0.11 0.31 -0.20 (0.68)	6.00 6.45 5.73 5.93 0.68 0.72 1.29 0.70 0.31 0.75 0.04 0.23 0.29 (0.90)
	4.97 4.95 5.15 4.86 1.14 0.93 1.17 0.98 4.98	4.86 4.83 4.60 4.72 0.72 0.82 1.22 0.95 4.76	4.99 4.93 5.02 5.00 0.75 1.13 0.77 0.92 4.95	5.29 5.36 5.32 5.35 1.03 0.78 0.97 1.06 5.33

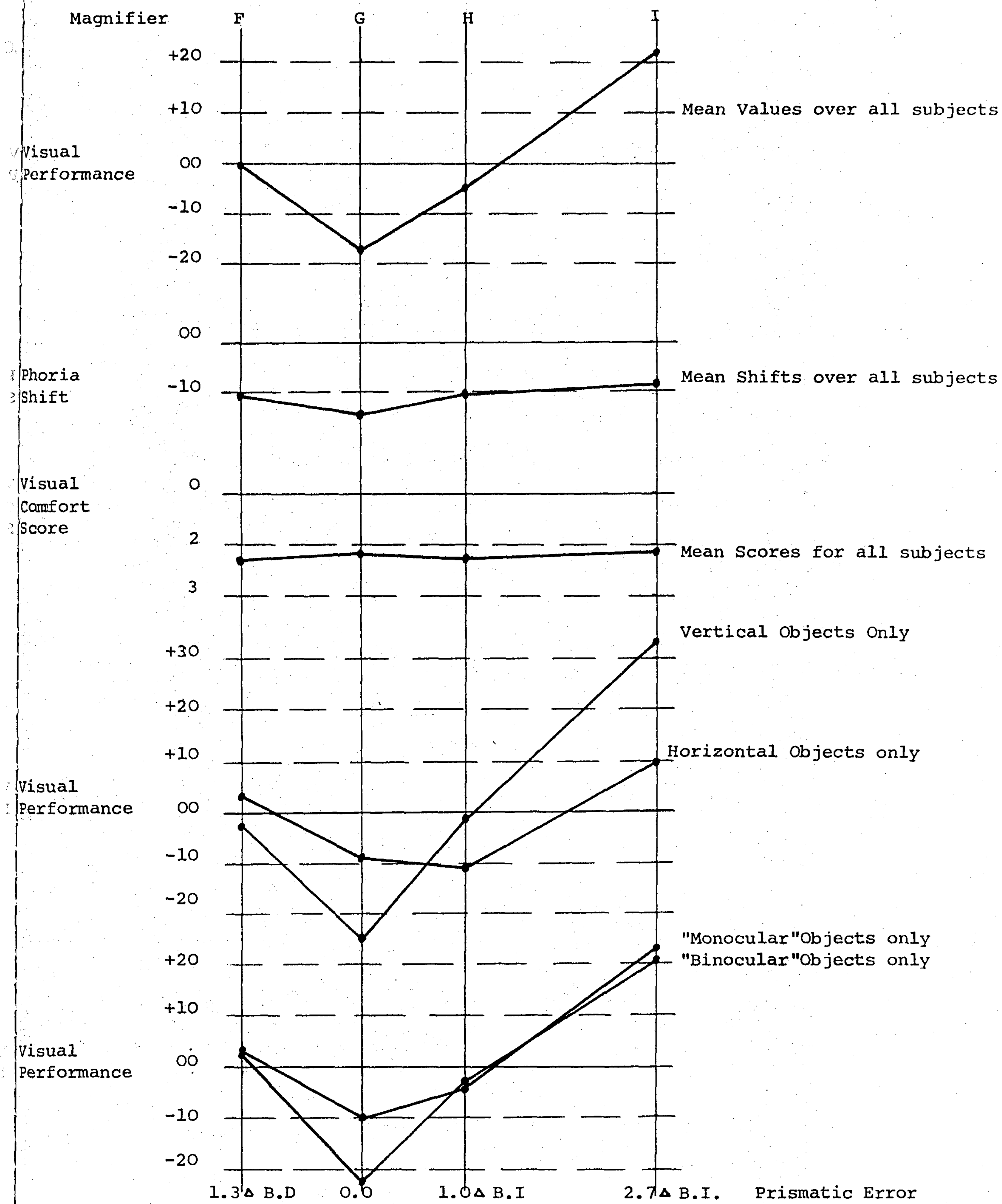
For key, see page 182

FIG 59 RESULTS BY MAGNIFIER FOR HORIZONTAL OBJECTS - EXPT 4

SUBJECT	MAGNIFIER F m=2	G m=1	H m=3	I m=4
26	5.59 4.53 4.60 5.71 0.53 0.52 1.20 0.43 0.50 -0.47 -0.40 0.69 0.06 (0.92)	5.30 6.15 4.35 5.06 0.77 1.01 0.48 1.16 0.28 1.14 -0.65 0.05 0.21 (1.06)	4.67 4.94 [illegible] 4.78 0.60 0.73 0.59 0.61 -0.33 -0.27 [illegible] -0.23 -0.15 (0.67)	[illegible] [illegible] [illegible] [illegible] 0.49 0.56 0.57 0.69 -0.05 [illegible] -0.01 [illegible] -0.10 (0.66)
27	4.96 6.03 4.77 5.17 0.99 1.00 1.23 0.56 0.33 1.[illegible] 0.13 0.53 0.57 (1.06)	5.07 4.82 4.62 5.33 0.68 0.56 0.75 0.57 0.44 0.18 -0.01 0.70 0.31 (0.66)	4.07 4.07 [illegible] 3.94 1.17 1.57 0.27 0.73 -0.56 -0.56 -0.55 -0.69 -0.59 (1.12)	4.44 4.56 4.93 4.92 0.63 0.51 0.89 0.71 -0.18 -0.06 0.30 [illegible] -0.15 (0.73)
28	5.56 5.81 6.54 6.14 0.73 0.52 0.85 0.76 -0.51 -0.26 0.46 0.06 -0.13 (0.74)	6.74 5.73 5.16 5.86 0.54 0.59 0.68 0.82 0.66 -0.35 -0.91 -0.21 -0.22 (0.95)	5.77 7.00 6.17 5.80 0.64 0.47 0.78 1.12 -0.30 0.91 0.09 -0.27 0.09 (0.87)	6.08 6.40 6.81 6.14 0.69 1.59 1.16 1.14 0.00 0.32 0.73 [illegible] 0.26 (1.17)
29	5.69 5.67 5.61 5.29 1.01 0.64 1.15 1.21 0.19 0.17 0.11 -0.20 0.07 (0.97)	5.53 5.14 5.89 5.63 0.82 0.31 0.56 0.54 0.03 -0.35 0.39 0.13 -0.00 (0.62)	5.47 5.24 5.19 5.77 0.78 0.63 0.89 0.96 -0.02 -0.25 -0.30 0.27 -0.10 (0.81)	5.19 6.13 [illegible] [illegible] 0.87 0.59 1.04 [illegible] -0.30 0.63 -0.11 [illegible] 0.03 (0.96)
30	4.29 4.62 4.32 3.15 0.62 0.97 0.47 1.14 -0.23 0.09 -0.20 -1.37 -0.34 (0.91)	4.71 4.96 4.82 4.02 0.53 0.90 0.98 1.04 0.17 0.43 0.29 -0.51 0.09 (0.95)	4.59 3.94 4.20 4.64 0.65 0.75 0.72 1.15 0.06 -0.59 -0.32 0.11 -0.16 (0.90)	4.43 4.79 5.05 [illegible] 0.85 1.13 0.35 [illegible] -0.09 0.25 0.51 [illegible] 0.32 (0.60)
31	6.44 5.17 6.33 6.55 0.74 0.00 1.30 0.68 0.00 -1.27 -0.10 0.10 -0.05 (0.77)	6.80 6.56 6.25 5.71 0.92 0.82 1.17 1.08 0.36 0.12 -0.18 -0.72 -0.08 (1.04)	7.03 5.77 6.84 5.96 1.34 0.88 1.00 1.08 0.59 -0.66 0.39 -0.48 -0.11 (1.16)	6.82 6.84 5.95 [illegible] 1.17 1.01 0.67 [illegible] 0.37 0.40 -0.48 [illegible] 0.24 (0.91)
32	6.64 6.32 6.84 5.96 0.89 0.48 0.45 0.53 0.57 0.25 0.78 -0.09 0.38 (0.67)	5.35 5.95 5.45 6.89 0.69 0.66 0.96 0.31 -0.70 -0.11 -0.59 0.83 -0.33 (0.89)	5.86 6.65 5.67 5.91 0.39 0.81 0.64 0.68 -0.20 0.59 -0.39 -0.15 -0.09 (0.68)	6.69 6.27 6.01 5.55 0.58 0.63 0.63 0.96 0.52 0.20 -0.05 -0.52 0.05 (0.81)
33	5.45 4.52 4.78 4.14 1.21 0.61 0.36 0.66 0.81 -0.11 0.14 -0.49 0.07 (0.88)	4.81 4.40 4.64 4.33 1.80 0.78 0.96 1.58 0.17 -0.23 0.00 -0.30 -0.09 (1.29)	3.94 4.55 4.93 5.00 1.38 0.79 0.60 0.65 -0.69 -0.08 0.29 0.26 -0.01 (0.95)	4.73 5.02 4.65 4.24 1.68 0.93 0.57 1.15 0.09 0.38 -0.00 -0.39 0.02 (1.24)
45	4.51 4.34 4.23 4.19 1.38 0.92 0.50 0.40 0.28 0.11 0.00 -0.03 0.10 (0.89)	3.96 3.80 4.30 4.59 1.28 0.48 0.65 0.94 -0.26 -0.42 0.07 0.36 -0.04 (0.80)	3.93 4.35 4.73 3.85 0.72 0.92 0.48 0.35 -0.29 0.12 0.50 -0.37 -0.01 (0.82)	4.41 3.92 3.77 4.51 0.79 0.65 0.93 0.41 0.18 -0.30 -0.45 0.28 -0.05 (0.75)
46	4.10 6.44 6.37 7.04 1.03 0.49 0.87 1.04 -1.41 0.92 0.85 1.52 0.50 (1.37)	4.89 5.24 5.03 4.50 0.86 1.30 0.71 1.20 -0.62 -0.27 -0.48 -1.01 -0.57 (0.99)	5.01 5.03 5.48 5.93 0.72 1.17 0.75 0.54 -0.50 -0.48 -0.03 0.41 -0.23 (0.86)	2.50 6.70 7.44 5.73 0.00 0.63 0.37 1.75 -3.02 1.18 1.92 0.21 0.71 (1.77)
47	3.50 3.03 3.67 2.99 0.78 0.77 0.49 0.57 -0.26 -0.72 -0.09 -0.77 -0.44 (0.70)	4.14 3.23 3.12 2.90 0.97 1.00 0.89 1.33 0.38 -0.53 -0.63 -0.86 -0.31 (1.11)	4.34 4.39 4.12 3.95 0.70 0.64 0.57 0.55 0.57 0.63 0.35 0.19 0.42 (0.60)	3.96 4.39 4.44 3.39 1.26 0.62 0.80 0.32 0.20 0.63 0.66 -0.36 0.28 (0.75)
48	3.26 4.72 0.00 3.37 1.72 1.94 0.00 1.76 -1.08 0.37 -4.35 -0.97 -0.41 (1.83)	5.00 4.60 4.60 4.66 1.11 0.50 0.94 1.13 0.65 0.25 0.25 0.31 0.35 (0.90)	3.88 4.24 4.75 5.29 1.46 0.89 0.90 0.77 -0.46 -0.10 0.40 0.93 0.11 (1.11)	4.01 4.19 4.27 3.63 0.73 0.50 0.58 0.96 -0.33 -0.15 -0.07 -0.52 -0.24 (0.66)
49	5.79 4.37 4.52 4.92 0.76 0.45 0.64 0.65 1.04 -0.37 -0.22 0.17 0.11 (0.81)	4.71 3.99 4.97 4.81 1.74 1.70 1.26 1.00 -0.03 -0.76 0.22 0.06 -0.16 (1.44)	4.92 4.68 4.71 4.06 1.01 0.45 0.55 0.55 0.16 -0.06 -0.03 -0.68 -0.10 (0.74)	4.57 5.19 4.93 5.20 0.99 0.48 0.52 0.42 -0.17 0.43 0.15 [illegible] 0.17 (0.72)
50	3.72 3.49 4.60 3.90 1.38 1.39 0.34 1.56 -0.38 -0.62 0.49 -0.20 -0.21 (1.23)	4.23 3.99 3.53 3.94 0.96 0.39 0.63 0.45 0.12 -0.11 -0.58 -0.16 -0.15 (0.66)	3.89 3.34 3.92 3.08 0.56 0.00 0.00 0.28 -0.21 -0.77 -0.19 -1.02 -0.43 (0.56)	4.98 4.94 4.09 4.32 0.69 0.34 1.27 0.75 0.87 0.83 -0.01 [illegible] 0.61 (0.79)
51	4.97 5.39 5.09 4.84 0.94 1.26 1.43 0.66 0.30 0.71 0.42 0.17 0.39 (1.07)	4.54 4.29 3.65 4.03 0.21 0.49 0.37 0.56 -0.12 -0.37 -0.51 -0.63 -0.50 (0.48)	5.02 4.45 4.45 4.97 1.42 0.64 0.89 1.06 0.35 -0.21 -0.21 0.30 0.03 (1.03)	5.09 4.34 4.58 [illegible] 0.87 0.50 1.08 [illegible] 0.41 0.17 0.00 -0.14 0.05 (0.76)
52	5.76 5.41 5.54 5.63 0.64 1.24 0.82 0.64 0.22 -0.12 0.00 0.09 0.03 (0.87)	5.34 5.88 5.59 5.74 0.92 0.92 0.72 1.01 -0.19 0.33 0.05 0.19 0.11 (0.89)	5.17 5.18 5.13 5.53 0.65 0.45 0.96 0.97 -0.36 -0.35 -0.40 -0.00 -0.30 (0.77)	5.36 6.22 5.39 5.75 0.88 0.97 0.76 0.41 -0.17 0.68 -0.14 0.21 0.17 (0.85)
	5.02 4.99 5.19 4.94 1.02 0.95 0.96 1.22 5.03	5.07 4.92 4.76 4.88 0.80 0.95 0.83 0.96 4.91	4.85 4.86 4.76 4.90 0.88 0.96 0.79 0.90 4.89	4.69 5.32 5.14 [illegible] 1.06 0.94 0.99 [illegible] 5.10

For key, see page 182

FIG 60 COMPARISON OF MAGNIFIERS IN EXPT 4.



Visual Performance is given in 1/100 seconds change from mean

Phoria Shift is in arbitary units where -10 indicates 2△ shift towards esophoria orthophoric and wide P.D. subjects tend to perform better on magnifiers having a parallax error opposite in sign to those on which exophoric and narrow P.D. subjects perform better.

Fig.65 shows in tabular form the near values and significant differences found. The values of Fig.65 are calculated as means of the four mean values (T_{ikv}) obtained for each subject. The number of actual sightings should be 8 for each type of object and 16 for all objects. Due to equipment failures affecting the horizontal objects more than vertical some slight imbalance enters these results so that the mean of the vertical and horizontal values does not always equal the mean for all objects. Fig.66 shows graphs of these values which are discussed further in Chapter 7. Statistical Significance is indicated in Figs 61 to 65 :-

* Significant Difference at 5% level.

** Significant Difference at 1% level.

*** Significant Difference at 0.1% level.

FIG 61 STATISTICAL ANALYSIS FOR 'NARROW P.D.' SUBJECTS

Subject Nos. 26,27,32,33,45,46,48,51

Mean P.D. 62.2mm Mean Phoria 3△ Exophoric

	Source	S.S.	D.F	M.S.	M.S.R	
	Between Subjects	51.1517	7	7.3073	35.3	***
ALL	Bet. Magnifiers	2.8648	3	0.9549	4.62	**
OBJECTS	Interaction	7.4226	21	0.3535	1.71	*
	Residual	19.8535	96	0.2068		
	TOTAL	81.2926	127			
	Between Subjects	55.8452	7	7.9778	27.9	***
'MONOC'	Bet. Magnifiers	2.4778	3	0.8259	2.89	*
OBJECTS	Interaction	13.9299	21	0.6633	2.32	**
	Residual	27.4287	96	0.2857		
	TOTAL	99.6816	127			
	Between Subjects	46.8256	7	6.6893	25.7	***
'BINOC'	Bet. Magnifiers	3.0354	3	1.0118	3.88	*
OBJECTS	Interaction	5.1058	21	0.2431	0.93	N.S.
	Residual	25.0186	96	0.26606		
	TOTAL	79.9855	127			
	Between Subjects	58.6017	7	8.3716	32.6	***
VERT	Bet. Magnifiers	4.4910	3	1.497	5.82	**
OBJECTS	Interaction	11.2391	21	0.5352	2.08	**
	Residual	24.6828	96	0.2571		
	TOTAL	99.0145	127			
	Between Subjects	45.7315	7	6.533	17.8	***
HORIZ	Bet. Magnifiers	1.6695	3	0.5565	1.51	N.S.
OBJECTS	Interaction	9.0294	21	0.43	1.17	N.S.
	Residual	35.3052	96	0.3677		
	TOTAL	91.7355	127			

FIG 62 STATISTICAL ANALYSIS FOR 'WIDE P.D.' SUBJECTS

Subject Nos. 28,29,30,31,47,49,50,52

Mean P.D. 65.6mm Mean Phoria 3.7△ Exophoria

	Source	S.S	D.F	M.S.	M.S.R	
	Between Subjects	51.1517	7	7.3073	35.3	***
ALL	Bet. Magnifiers	2.8648	3	0.9549	4.62	**
OBJECTS	Interaction	7.4226	21	0.3535	1.71	*
	Residual	19.8535	96	0.2068		
	TOTAL	81.2926	127			
	Between Subjects	94.9289	7	13.5612	60.4	***
'MONOC'	Bet. Magnifiers	4.3474	3	1.4491	6.45	***
OBJECTS	Interaction	7.0155	21	0.3341	1.49	N.S.
	Residual	21.5731	96	0.2247		
	TOTAL	127.8649	127			
	Between Subjects	101.1432	7	14.4490	70.8	***
'BINOC'	Bet. Magnifiers	4.5729	3	1.5243	7.47	***
OBJECTS	Interaction	8.6383	21	0.4113	2.02	*
	Residual	19.5909	96	0.2040		
	TOTAL	133.9452	127			
	Between Subjects	93.5194	7	13.3599	53.4	***
VERT	Bet. Magnifiers	8.6718	3	2.8906	11.6	***
OBJECTS	Interaction	15.377	21	0.7323	2.93	***
	Residual	24.0248	96	0.2502		
	TOTAL	141.5936	127			
	Between Subjects	105.6424	7	15.0917	80.5	***
HORIZ	Bet. Magnifiers	3.4159	3	1.1386	6.07	***
OBJECTS	Interaction	4.9589	21	0.2361	1.26	N.S.
	Residual	18.0018	96	0.1875		
	TOTAL	132.0190	127			

FIG 63 STATISTICAL ANALYSIS FOR 'ORTHOPHORIC' SUBJECTS

Subject Nos. 26,28,30,31,45,47,46,48

Mean P.D. 63.1mm Mean Phoria 1△ Exophoric

	Source	S.S	D.F	M.S.	M.S.R	
	Between Subjects	101.0372	7	14.4338	63.6	***
ALL	Bet. Magnifiers	6.0950	3	2.0316	8.96	***
OBJECTS	Interaction	10.1247	21	0.4821	2.13	**
	Residual	21.7790	96	0.2268		
	TOTAL	139.0359	127			
	Between Subjects	100.4087	7	14.3441	45.3	***
'MONOC'	Bet. Magnifiers	7.1884	3	2.3961	7.56	***
OBJECTS	Interaction	13.8189	21	0.6580	2.08	**
	Residual	30.4143	96	0.3168		
	TOTAL	151.8303	127			
	Between Subjects	102.3960	7	14.6280	51.9	***
'BINOC'	Bet. Magnifiers	4.1107	3	1.3702	4.86	**
OBJECTS	Interaction	8.5117	21	0.4053	1.44	N.S.
	Residual	27.0630	96	0.2819		
	TOTAL	142.0814	127			
	Between Subjects	103.5291	7	14.7898	50.2	***
VERT	Bet. Magnifiers	13.3652	3	4.4550	15.1	***
OBJECTS	Interaction	19.1644	21	0.9126	3.10	***
	Residual	28.2929	96	0.2947		
	TOTAL	164.3517	127			
	Between Subjects	101.7667	7	14.5381	35.7	***
HORIZ	Bet. Magnifiers	1.1919	3	0.3973	0.97	N.S.
OBJECTS	Interaction	9.0350	21	0.4302	1.06	N.S.
	Residual	39.0567	96	0.4068		
	TOTAL	151.0502	127			

FIG 64 STATISTICAL ANALYSIS FOR 'EXOPHORIC' SUBJECTS

Subject Nos. 27,29,32,33,49,50,51,52

Mean P.D. 64.6mm/Mean Phoria 6Δ Exophoria

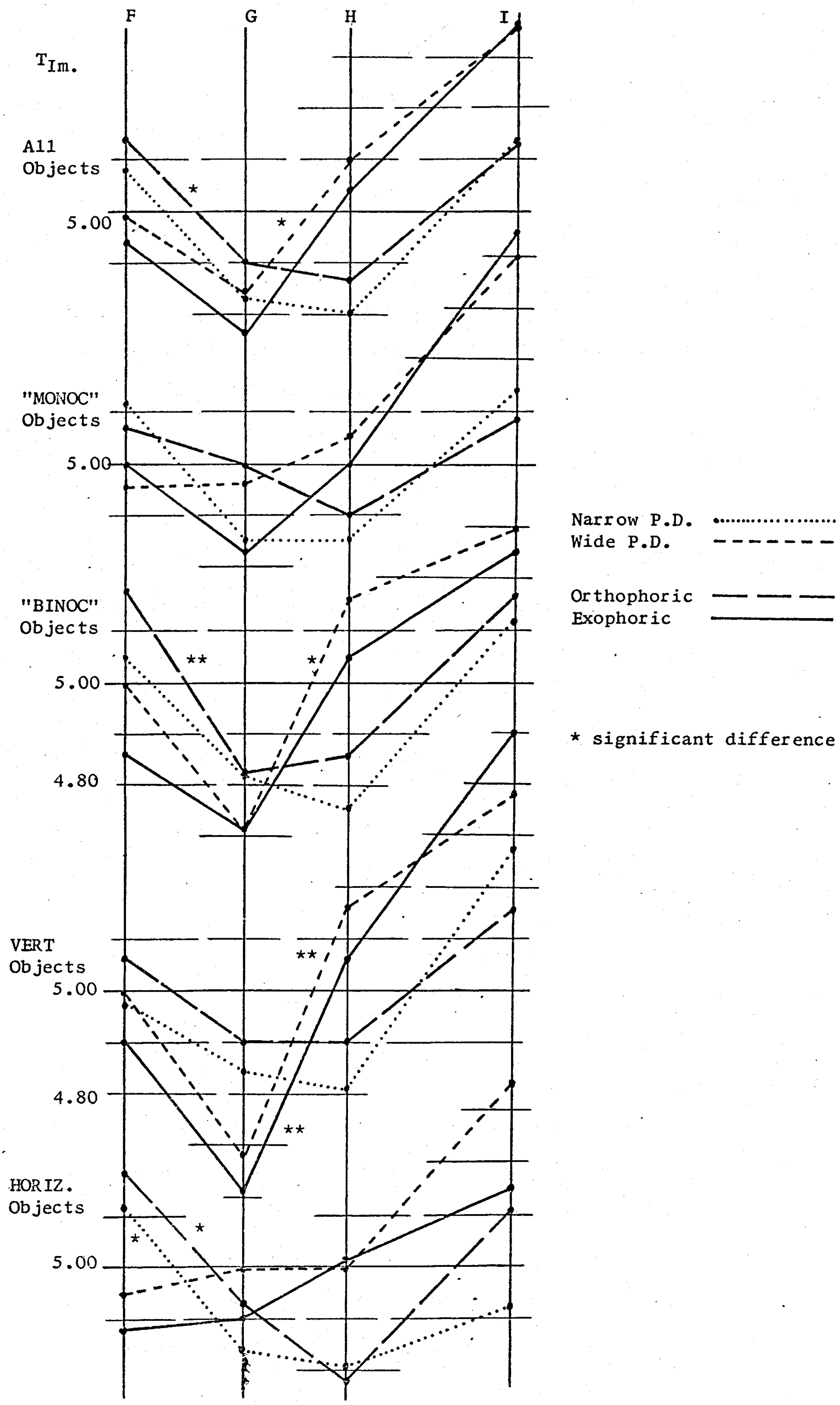
	Source	S.S	D.F	M.S	M.S.R	
	Between Subjects	48.0703	7	6.8671	56.9	***
ALL	Bet. Magnifiers	2.0064	3	0.6688	5.55	**
OBJECTS	Interaction	4.2122	21	0.2006	1.66	NS
	Residual	11.5759	96	0.1205		
	TOTAL	65.8648	127			
	Between Subjects	50.7467	7	7.2495	37.4	***
'MONOC'	Bet. Magnifiers	0.7316	3	0.2437	1.26	N.S.
OBJECTS	Interaction	6.0320	21	0.2872	1.48	N.S.
	Residual	18.5876	96	0.1936		
	TOTAL	76.0974	127			
	Between Subjects	46.5942	7	6.6563	36.4	***
'BINOC'	Bet. Magnifiers	3.5979	3	1.1993	6.56	***
OBJECTS	Interaction	5.1321	21	0.2444	1.34	N.S.
	Residual	17.5465	96	0.1827		
	TOTAL	72.8706	127			
	Between Subjects	48.9130	7	6.9875	32.9	***
VERT	Bet.Magnifiers	1.5350	3	0.5116	2.41	N.S.
OBJECTS	Interaction	5.7151	21	0.2721	1.28	N.S.
	Residual	20.4146	96	0.2126		
	TOTAL	76.5776	127			
	Between Subjects	51.5808	7	7.3686	49.7	***
HORIZ	Bet. Magnifiers	3.2419	3	1.0806	7.28	***
OBJECTS	Interaction	5.6049	21	0.2669	1.80	*
	Residual	14.2503	96	0.1484		
	TOTAL	74.6780	127			

FIG 65 MEAN VISUAL PERFORMANCE VALUES OVER SUBJECT GROUPINGS

	MAGNIFIERS				SUBJECT GROUP	Sig. DIFFERENCE		
	F	G	H	I		F to G	G to H	I
	5.08	4.82	4.80	5.14	'NARROW' P.D.			*
ALL	4.98	4.83	5.10	5.35	'WIDE' P.D.		*	**
OBJECTS	4.93	4.76	5.04	5.36	ORTHOPHORIC			*
	5.13	4.90	4.86	5.13	EXOPHORIC	*		*
	5.12	4.85	4.85	5.14	'NARROW' P.D.			
'MONOC'	4.95	4.96	5.05	5.40	'WIDE' P.D.			*
OBJECTS	5.00	4.82	5.01	5.45	ORTHOPHORIC			**
	5.07	4.99	4.90	5.08	EXOPHORIC			
	5.06	4.82	4.76	5.1_	'NARROW' P.D.			*
'BINOC'	5.00	4.75	5.16	5.30	'WIDE' P.D.		*	**
OBJECTS	4.87	4.73	5.06	5.26	ORTHOPHORIC			**
	5.18	4.82	4.86	5.17	EXOPHORIC	**		**
	4.98	4.84	4.81	5.28	'NARROW' P.D.			**
VERT	4.99	4.67	5.16	5.38	'WIDE' P.D.		**	**
OBJECTS	4.90	4.61	5.06	5.51	ORTHOPHORIC		**	**
	5.06	4.90	4.90	5.16	EXOPHORIC			
	5.12	4.83	4.80	4.92	'NARROW' P.D.	*		
HORIZ	4.94	4.99	4.99	5.35	'WIDE' P.D.			**
OBJECTS	4.87	4.90	5.01	5.15	ORTHOPHORIC			
	5.18	4.92	4.78	5.11	EXOPHORIC	*		**

(For Magnifier I, significance of difference is noted when this is with one or more of the other magnifiers.)

FIG 66 OBJECT/SUBJECT GROUP INTERACTION - EXPT 4



CHAPTER 7

CONCLUSIONS AND FUTURE WORK

1. Introduction

The initial decision to use real magnifiers means that the results must be evaluated with care if unanticipated interactions are to be seen. Obviously, the major uncertainty in the results of the experimental study lies in the response of the subjects which relates to their visual acuity, decision strategy, motivation, etc. None of the three measurements used is involuntary. The visual comfort score assessment was regarded as a difficult question by most subjects. The measurement of disassociated phoria while entirely subjective was uncertain with some subjects who had difficulty maintaining a stable value. The measurement of visual performance yeilded absolute values which depended considerably on the subject's risk commitment. Some subjects waited until they were absolutely certain before moving the joystick. Others were prepared to commit themselves at an earlier stage. However, the number of false reactions was very small. One or two subjects commented that on some objects they could recognise the orientation at an early stage but the object then deteriorated in resolution before growing to the size which gave them confidence.

This situation means that the number of sightings and subjects has to increase if small involuntary effects are to be detected. The experience of this work suggests ways in which these unstable effects may be reduced and these are considered in section 4 of this chapter. With the results obtained it is evident that the visual performance of a particular subject on a given magnifier depends on at least the four visual aberrations suggested, on at least two physiological parameters of the subjects visual apparatus and furthermore on the interaction between these. The physical interaction between binocular overlap and interpupilliar distance can be demonstrated by ray tracing. The interaction between disassociated phoria and parallax error is less obvious but is certainly suggested by the results. Other interactions particularly with astigmatism and curvature of field may well occur. The relative importance of these depends on the design of the magnifier. However, the designer of magnifiers would like some general guidelines on how to obtain minimum deleterious interactions or possibly mutually cancelling interactions in the true traditions of optical design.

At this point a working hypothesis is required which is generally in accord with these results and does not conflict with the known phenomena of physiological optics. In the first instance, effects with duration of viewing must be excluded and description sought of the average situation with each magnifier. Although the results of experiments 1 2 and 3 must not be put into conflict, the main source of data is obviously experiment 4. In particular use will be made of those presented in Fig.65, page 231 , where two magnifier parameters and two subject parameters are involved.

The figures for visual performance tabulated there are mean values taken over trials lasting 20 minutes. Although much work has been done on response times and threshold values of the components of the triad response the results of Fig.65 must be related initially to average visual response phenomena. It may be that such a simplification departs too far from the real case and dynamic effects play a significant part. However, significant static effects were noted in Chapter 3 in the section - Ocular Adjustments with Visual Aberrations, and these will be utilised as far as possible.

7.2 Working Hypothesis

The results given in Fig.65 show a maximum difference in visual performance on the magnifiers of about 0.5 to 0.6 seconds, which is roughly equivalent to a contrast loss of between 10 and 15 percent if the analysis of Chapter 6 Section 5 is accepted. Chapter 3 Section 3 reviews what effects the three components of the triad response have on contrast threshold. The effect of pupil size is such that a change of 2mm in diameter could, according to Campbell & Gubish (1966) (Fig.13, Page 62) give this change in contrast at 0.35 to 0.25 cycles per mm on the film (7 to 4 cycles per degree). However, it is difficult to see how a change in pupil size of this magnitude could be induced solely by different strengths of add-on prisms.

Campbell & Green (1965) obtained the results given in Fig.14, Page 63 which show the effects of incorrect accommodation. A 10% loss in Contrast Sensitivity at 9 cycles per degree might be expected for a 0.5 Dioptres error in accommodation. Unfortunately, this relates only to a pupil size of 2mm while sizes of 4 to 5 mms were found in practice in agreement with the results of Denny & Anthony (1974) (Fig.15, Page 69). With the larger size of pupil the 10% loss would be likely with about 0.2 dioptres error.

The effect of incorrect pointing of the eyes is reviewed on Page 64. Although pointing error does cause a loss in visual acuity, the amount, required in both eyes, would almost certainly cause considerable eye-strain and the absence of this in the subjects replies suggests that the most likely source of difference between the magnifiers of experiment 4 lies in the accommodative response.

The factors governing accommodative response are reviewed in Section 4 of Chapter 3. The major stimulus to accommodation is generally regarded as being the convergence with the blur of the retinal image as the major secondary stimulus. The results of Fincham & Walton (1957) given in Fig.16 Page 72 indicate that under normal conditions the accommodation shows a lag effect at convergences greater than 2 dioptres. Reference to Fig.37, Page 170 shows that most of the imagery with the magnifiers of experiment 4 lies between 2 and 3 dioptres. Thus, we must expect an accommodative error to exist when subjects are using these magnifiers which will be altered for different convergence surfaces although other stimuli will also affect it.

If these other stimuli are correctly assessed it should be possible to construct a further curve on the visual aberration plot, Fig.37 which indicates the Mean Accommodative Response of subjects. Furthermore, it should be possible by assessing the difference between this curve and the accommodation surfaces to estimate the Mean Accommodative Error. Such an error should then relate directly to the reductions in Visual performance.

Apart from accommodative lag under normal conditions Fincham & Walton (1957) also found that without the convergence stimulus the accommodation lagged even more. The convergence will therefore decrease the lag when the subjects are fixating in the binocular overlap. In the monocular regions close to the overlap the convergence action will still have some effect as found by Hennessy and Leibowitz (1971) Page 77.

When parallax occurs the accommodation will be pulled from the convergence value toward the accommodation value as found by Fincham & Walton (1957) and shown in Fig.17 Page 73.

The greatest problem with the concept of a Mean Accommodative Response arises from the work of Heath (1956) (Fig.18, Page 76) as the low contrast and spatial frequency of the scene viewed via the magnifiers probably reduces the amount of change shown by the accommodation as different parts of the scene are viewed. Thus, subjects who scan the scene vigorously may achieve a different visual performance than those who scan more slowly. However, this effect should not show a large difference with different add-on prisms. Until some monitor of subjects' eye movements is added to the system and some greater understanding as to how this affects the accommodative response it is not possible to include it in the analysis. The Mean Accommodative Response approach assumes that the same Mean Accommodative Error produces the same drop in visual performance, but obviously, a large range of the error could still give a small mean error if it spread equally in front of and behind the accommodation surface of the magnifier.

Accepting these limitations, it is possible to infer these general guidelines for the Mean Accommodative Response.

1. It attempts to follow the accommodation surfaces of the magnifiers but is generally further away.
2. It is influenced markedly by the convergence surfaces over the region of the binocular overlap and to a decreasing extent outside this region.
3. When parallax is evident within the region of binocular overlap a compromise value of accommodation is adopted.

Two further guidelines can be inferred which relate to the physiological parameters of the subjects.

4. The greater extent of the binocular overlap for subjects with narrow P.D. means that the convergence surface effect is felt over a larger area.

5. Subjects who are exophoric when disassociated will tend to adopt a higher value of accommodation under conditions of parallax error.

This last point is somewhat tentative. Further work along the lines of Fincham & Walton's (1957) study is required on a large number of subjects so that any interaction can be estimated.

Taking these guidelines and the results for the subjects divided according to P.D. and viewing objects in the 'monocular' and 'binocular' regions of the magnifiers it is possible to modify Fig.37 so that the convergence surface above the axis extend over the binocular overlap region related to narrow P.D. while the lower part shows the shorter convergence surfaces associated with wider P.D. This is shown in Fig.67.

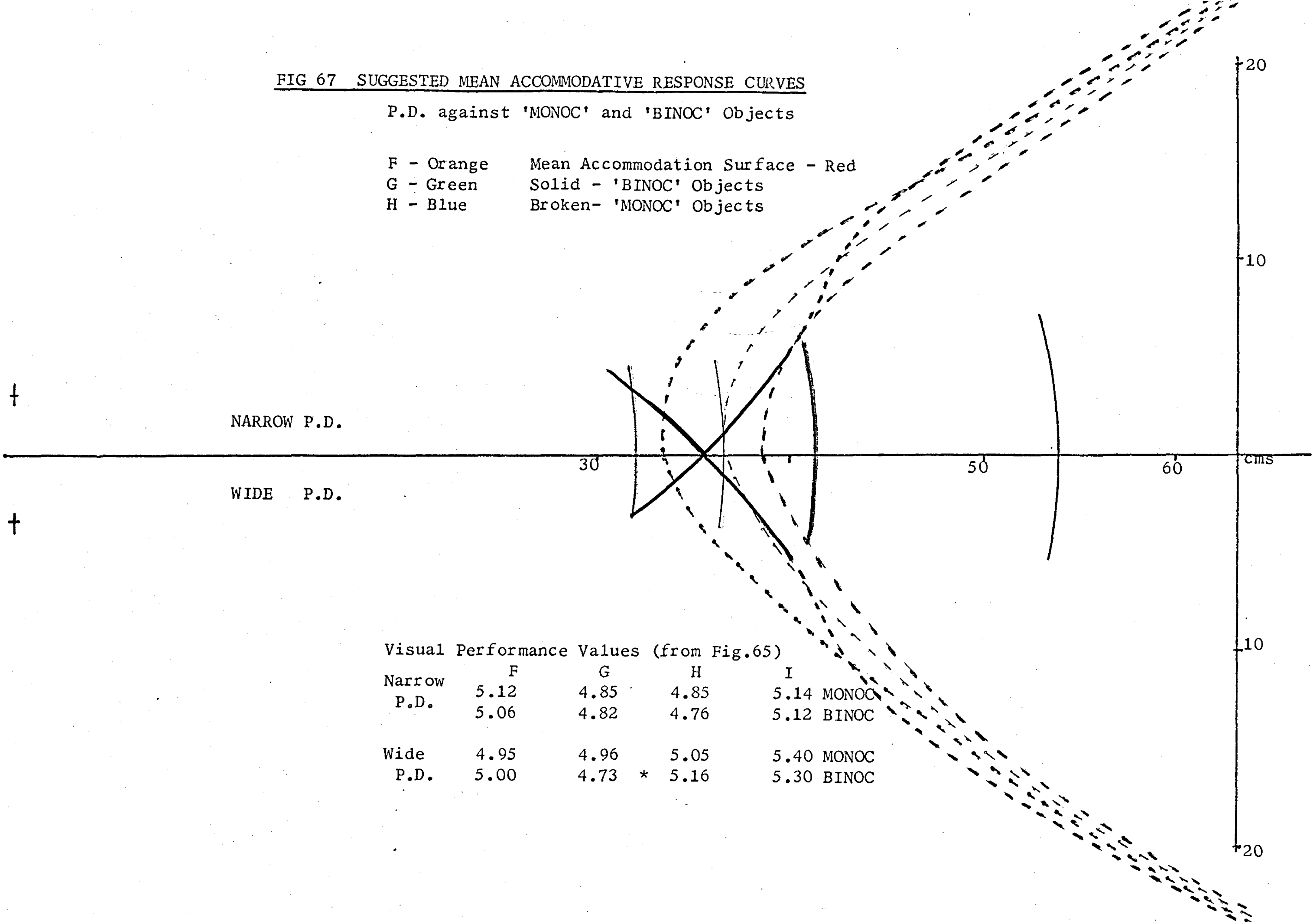
The mean accommodation surface is drawn in red beween the vertical and horizontal accommodation surfaces being a full line for the 'binocular' objects and broken for the 'monocular' region. Obviously, this is a somewhat arbitrary division and should change with P.D. However, the analysis method requiresindividual objects to be seen by all subjects so the division into Binocular and Monocular is taken for a P.D. of 64mm irrespective of the actual limit for each subject.

In Fig.67, the situation with magnifier I is excluded partly for clarity and partly because this magnifier is generally the worst of the four with little change with object or subjects. The effects with magnifier F are shown with orange lines, those for G with green and those for H with blue. The broken lines in each colour showing the postulated Mean Accommodative Response.

The binocular region results show that best performance occurs with magnifier H for narrow P.D. subjects and magnifier G for wide P.D. subjects.

FIG 67 SUGGESTED MEAN ACCOMMODATIVE RESPONSE CURVES

P.D. against 'MONOC' and 'BINOC' Objects



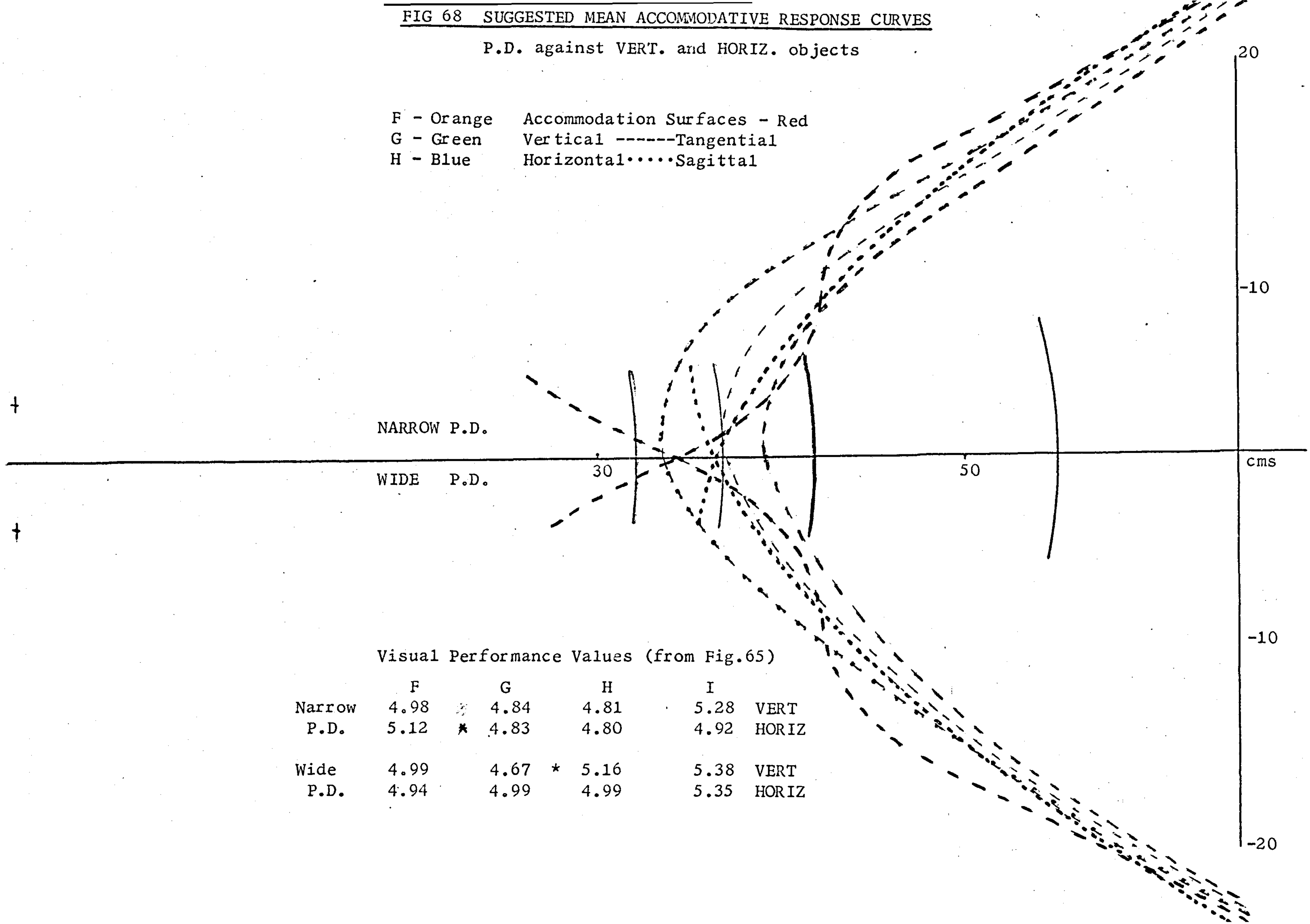
Visual Performance Values (from Fig.65)

	F	G	H	I	
Narrow P.D.	5.12	4.85	4.85	5.14	MONOC
	5.06	4.82	4.76	5.12	BINOC
Wide P.D.	4.95	4.96	5.05	5.40	MONOC
	5.00	4.73	* 5.16	5.30	BINOC

FIG 68 SUGGESTED MEAN ACCOMMODATIVE RESPONSE CURVES

P.D. against VERT. and HORIZ. objects

F - Orange Accommodation Surfaces - Red
G - Green Vertical ------Tangential
H - Blue Horizontal·····Sagittal



Visual Performance Values (from Fig.65)

		F	G	H	I	
Narrow		4.98	4.84	4.81	5.28	VERT
P.D.		5.12	* 4.83	4.80	4.92	HORIZ
Wide		4.99	4.67	* 5.16	5.38	VERT
P.D.		4.94	4.99	4.99	5.35	HORIZ

The F magnifier is nearly significantly worse than G & H for monocular objects, narrow P.D. subjects while the H magnifier is significantly worse for binocular objects, wide P.D. subjects. These are generally shown up by the mismatches in these areas from the red.Accommodation Surface of the magnifier.

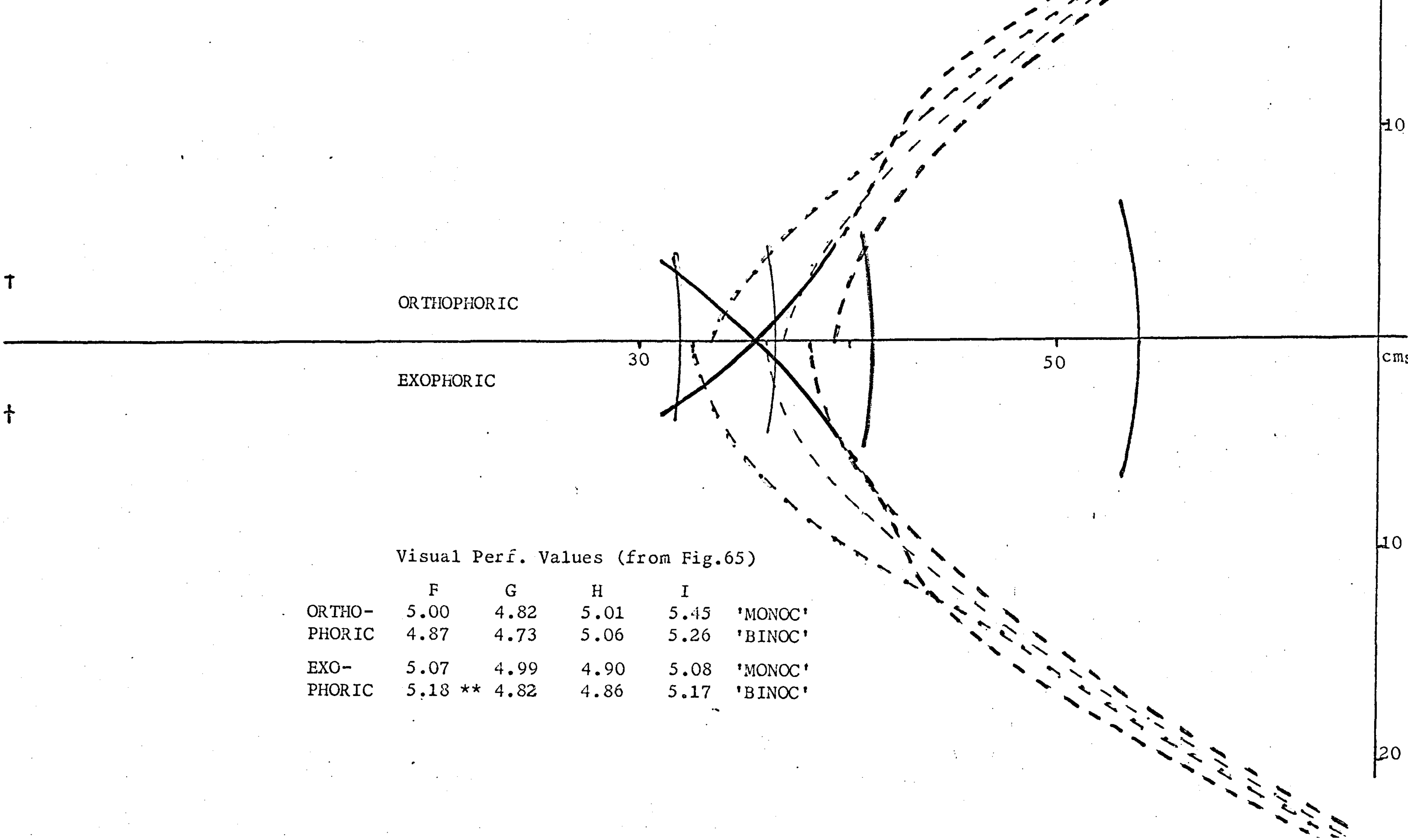
In general, most objects were recognised at locations close to the limits of the binocular overlap. This places the emphasis on the Mean Accommodative Error at these points. However, it should be remembered that the standard error on each visual performance value is $\pm$0.15 seconds, approximately and one should guard against reading too much into these figures. One method for testing the validity of this approach can be obtained from the analysis using vertical and horizontal objects. On Fig.68 the Mean Accommodative Response curves are drawn identical with those of Fig.67, but the tangential and sagittal accommodation surfaces are retained with the surface for vertical objects shown as a red broken line while the dotted red line is for horizontal objects. Unfortunately, the actual location of each object at recognition is now spread over both the binocular and the monocular regions although there is still an emphasis at the overlap limits. Comparing the Mean Accommodative Error distances with the values obtained shows overall agreement but the wide P.D. subjects are significantly worse for vertical objects on magnifier H and the narrow P.D subjects are significantly worse for horizontal objects on magnifier F. Neither of these would be predicted by the curves.

If the same approach is taken with the subjects divided according to phoria the results for 'monocular' and 'binocular' objects are shown in Fig.69. In this situation the length of the convergence surface is the same in each subject category but the effect on accommodation

FIG 69 - SUGGESTED MEAN ACCOMMODATIVE RESPONSE CURVES

Phoria against 'MONOC' and 'BINOC' objects

F - Orange	Mean Accommodation Surface - Red
G - Green	Solid - 'BINOC' Objects
H - Blue	Broken - 'MONOC' Objects



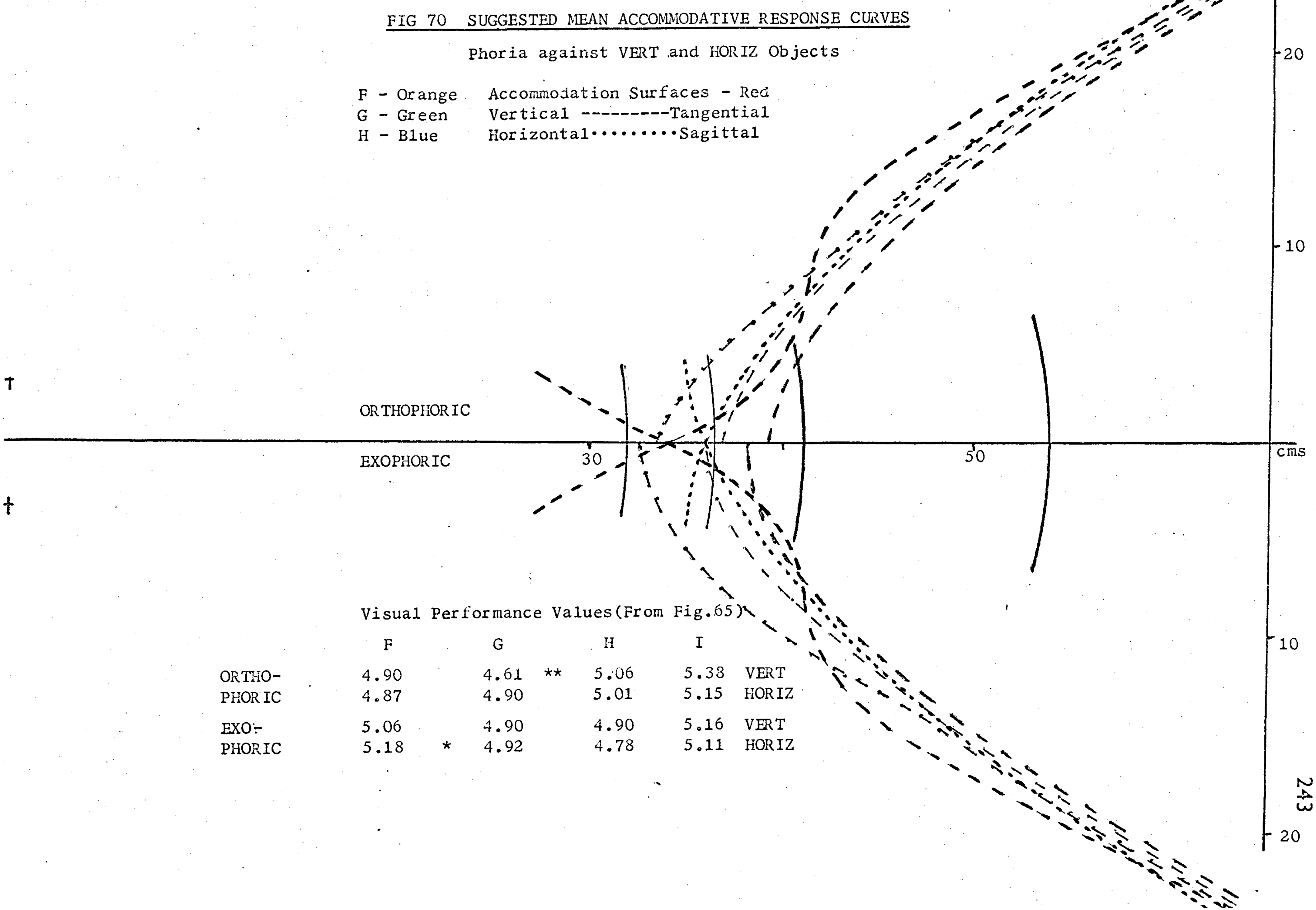
Visual Perf. Values (from Fig.65)

	F	G	H	I	
ORTHO-	5.00	4.82	5.01	5.45	'MONOC'
PHORIC	4.87	4.73	5.06	5.26	'BINOC'
EXO-	5.07	4.99	4.90	5.08	'MONOC'
PHORIC	5.18 **	4.82	4.86	5.17	'BINOC'

FIG 70 SUGGESTED MEAN ACCOMMODATIVE RESPONSE CURVES

Phoria against VERT and HORIZ Objects

F - Orange   Accommodation Surfaces - Red
G - Green   Vertical ---------Tangential
H - Blue   Horizontal·········Sagittal



Visual Performance Values(From Fig.65)

	F		G		H	I	
ORTHO-PHORIC	4.90		4.61	**	5.06	5.38	VERT
	4.87		4.90		5.01	5.15	HORIZ
EXO-PHORIC	5.06		4.90		4.90	5.16	VERT
	5.18	*	4.92		4.78	5.11	HORIZ

is different so that the broken Mean Accommodative Response lines do not meet on the axis. Once again it is possible to draw lines which give agreement with the values of Fig.65. When the same curves are transferred to Fig.70 showing the vertical and horizontal object curves the same sort of general agreement is obtained but again the curves do not predict the relative vertical and horizontal performances of the exophoric subjects on magnifier F or the orthophoric on H although the latter values are too close to be distinguishable.

7.3 Conclusions

During this study four particular visual aberrations have been formulated and two parameters of the visual apparatus have been investigated. Obviously, others may have an influence on visual performance particularly with magnifiers having different amounts of the visual aberrations. The effect in different parts of the field of view has only been touched upon and the whole analysis has been confined to the horizontal plane through the magnifier.

Within these limitations it has been shown that gross parallax error generated for one type of object by astigmatism is reflected in a reduced recognition ability of observers. With some magnifiers a shift in the disassociated phoria of the observers is found and this can be related to visual performance rather than visual aberrations. Other effects with time include a difference in visual performance when interrupted viewing is adopted which could suggest that any learning process adopted by the visual apparatus gives poorer visual response while it is taking place. It is also possible to suggest that the phoria shift is related to the successof the learning process without conflicting with these results.

Although fatigue effects were anticipated with high-powered magnifiers very little evidence of this was found. No subject failed to complete his trials and acknowledgement of minor headaches could only be prised out of a few subjects.

When the effects of time are ignored by taking mean values of the 20 minute viewing time it is possible to obtain a crude explanation of the average visual performance values using the concept of a Mean Accommodative Response surface located as suggested by known physiological effects. The major problem with this is that it fixes a single value to the accommodative response for any given field point. As it is known that accommodative response is influenced by the immediately previous demands on the accommodation it may be necessary to formulate a Mean Probable Accommodative Response which takes into account the effects of fixation shifts to each point in the field from all other points in the field.

The anticipation effect found by Wildt et.al (1974) (Page 78) also needs to be included. This effect would explain a general learning effect if the visual aberrations are too small to give conflicting stimuli or general eyestrain. It could also support the results of Expt.2 where interrupted viewing seemed to destroy the effect. Wildt et.al reported that some confusion could be generated in subjects and the 'worse before better' effect of Expt.2 might possibly be related to this.

Pending the somewhat intimidating amount of work to supply evidence and figures for these last two concepts, the Mean Accommodative Response leading to the Mean Accommodative Error is the best candidate so far for a Merit Function for use in the auto-design of biocular magnifiers. The next section suggests areas of work required to allow calculation of this surface from the optical parameters of the design.

7.4 Future Work

At the outset of this study the greatest concern lay in the possible fatigue-generating characteristic of high-powered magnifiers. As the work progressed it became apparent that visual fatigue was not a major problem even on trials lasting 80 minutes. In the search for criteria to use when designing magnifiers the interest shifted to visual performance. The visual task had been designed to maintain interest in the event of fatigue. However, the data reduction methods devised still allowed a relatively accurate assessment of performance and the interest of a real work scene is important when many subjects are being used so that few of them have any sympathy with the investigation.

However, the meaning in optical terms of the extra time needed for recognition of the target is difficult to obtain with such a task. Perhaps the major understanding to come from the study lies in the ability to specify the sort of artificial visual aberrations which should be used to investigate the visual response to non-normal stimuli using low-powered optical elements and actual objects in a laboratory environment. Visual performance measurements using these could be obtained over large numbers of subjects using a mobile laboratory to visit suitable institutions. Work of this nature while not in the higher echelons of research is still very necessary and it is to be regretted how rarely it is carried out in the field of physiological optics. Research studies on the chemical and physical properties of new materials is a common practice in the technology-related sciences.

As well as visual performance measurements, direct measurements of the visual response to non-normal stimuli must be undertaken. At the same time it is clear that accommodation is the component of the triad response which should be monitored. This is not easy to carry out objectively and no subjective method would give a sufficiently fast response or sufficient accuracy. Existing infra-red optometers are limited to a particular line of sight and require tracking if the effects of fixating different parts of the field are to be investigated. It is possible that a sufficient accuracy of tracking in the horizontal plane through the magnifier may be obtainable from the EOG potentials from the subject.

The future work therefore divides into four areas using real magnifiers or simulated aberrations and making psycho-physical or physiological measurements. These should be aimed at understanding the accommodative response and in establishing that correctness in this response relates to better visual performance. Specific values are best obtained from the results of Chapter 6 applied to the particular experiment chosen. The range of work is best presented by the following two lists. The first suggests types of magnifier and simulated aberration while the second suggests psycho-physical and physiological measurements which may be made. As almost any magnifier/aberration can be studied using any method of measurement there are 24 possible experiments!

Magnifier(A)/Aberration Simulation(B)

A1	Existing magnifiers with small add-on modifications giving stepped ranges of visual aberrations.
A2	Wider field magnifiers with poorer overall corrections.
A3	Completely different magnifier designs giving different mixes of aberrations.
B4	Curvature of field variants using low-powered systems having replaceable field flatteners.
B5	Specific aberration conditions at the limits of the binocular overlap.
B6	Very large (100%) binocular overlap systems.

Measurements - Psycho-physical (C)/Physiological (D)

C1	Visual performance measurements on objects increasing in contrast but not in size.
C2	Visual performance for traversing objects in different parts of the field.
D3	Monitor accommodation with tracking eye movements as well as fixation shifts.
D4	Monitor pupil size with fixation in different parts of the field.

GLOSSARY OF TERMS

(coined or used specifically in this thesis)

Accommodation Surface - Page 30

That surface in the image space of a magnifier to which an eye must accommodate for best visual acuity. See Visual Aberrations.

Astigmatism (Visual) Page 41

The difference between accommodation surfaces for vertical and horizontal objects. See Visual Aberration.

Binocular Overlap Page 41

The region of the field of view or image which can be seen with both eyes, measured in angular or linear dimensions respectively. See Visual Aberration.

Biocular Page 11

Adjective describing a single optical system designed for two eye viewing.

Convergence Surface Page 30

That surface in the image space of a magnifier to which the eyes must converge to obtain fusion. See Visual Aberration.

Curvature of Field (Visual) Page 41

The change in accommodative surface with field position. See Visual Aberration.

Disassociated Heterophoria Page 95

As normally defined but restricted in this study to measurements at 50cms viewing distance.

Interpupilliary Distance Page 161

As normally defined and measured with relaxed convergence.

Magnifier Module Page 161

Framework carrying rear-projection screen and photo-cells to which specific magnifiers may be attached at their normal conjugate with the screen.

GLOSSARY OF TERMS

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Convergence Surface Page 30

That surface in the image space of a magnifier to which the eyes must converge to obtain fusion. See Visual Aberration.

Curvature of Field (Visual) Page 41

The change in accommodative surface with field position

F/Number Page 23

Although numerical aperture terminology is more applicable to these lenses F/Nos are used. F/0.5 is equivalent to N.A.1 for aplanatic lenses where the relevant pupil is spherical.

Framework carrying rear-projection screen and photo-cells to which specific magnifiers may be attached at their normal conjugate with the screen.

Mean Accommodative Error Page 236

Difference between Accommodation Surface of Magnifier (or Sagittal or Tangential Surfaces) and the Mean Accommodative Response.

Mean Accommodative Response Page 236

The mean state of accommodation for a given field point over multiple fixations of that point during normal usage of a magnifier.

Mean Probable Accommodative Response Page 246

As Mean Accommodative Response but including an indication of the range of variation of the Mean Accommodative Response.

P.D.

see Interpupilliary Distance.

Parallax (Visual) Page 41

The difference between the accommodation surface or surfaces and the convergence surface. See Visual Aberration.

Phoria Page 103

Used as abbreviation for Disassociated Heterophoria.

Phoria Shift

The change in value of Phoria of subject obtained before and after a trial.

Registration Film Page 123

Specific film carrying stationary image of resolution chart and format lines. Used to set up apparatus with running projector.

Sagittal Surface Page 42

Best Accommodation Surface for light rays in a plane through the pupil of the eye and the fixation point which is orthogonal to the tangential surface. (See Visual Aberrations).

Sub-Trial Page 175

Five minute viewing period.

Tangential Surface — Page 42

Best Accommodation surface for light rays in a plane through the pupil of the eye and the fixation point and also containing the optical axis of the magnifier. (See Visual Aberration)

Trial — Page 175

Continuous period of viewing (usually 20 minutes)

Visual Aberrations — Page 41 et seq.

A scheme of magnifier defects related to the occular adjustments which has been defined and developed for the restricted case where the eyes of the observer are located symmetrically in a horizontal plane through the optical axis of the magnifier.

See Accommodation Surface
Astigmatism (Visual)
Binocular Overlap
Convergence Surface
Curvature of field (Visual)
Parallax (Visual)
Sagittal Surface
Tangential Surface

Visual Comfort (Discomfort) — Page 111

Subjective State of Eyes

Visual Compliance — Page 111

Alteration of range or rest states of adjustments of the visual apparatus.

Visual Task — Page 130 et seq.

A dynamic scene presented to subjects from whom a deliberate response is required.

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