# Human amblyopia and its perceptual consequences

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HUMAN   AMBLYOPIA

AND   ITS

PERCEPTUAL   CONSEQUENCES

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ABSTRACT

The presence of ocular defects of an optical or muscular nature during early childhood can cause amblyopia: a reduction in visual acuity of the defective eye. The research reported in this thesis investigated the impact of amblyopia on some aspects of visual perception by evaluating three main perceptual functions: precision of judgement of spatial relationships (in three-dimensional space), ability to detect depth in tests of stereopsis, and contrast sensitivity. In some experiments amblyopic subjects were paired with non-amblyopic subjects who had monocular acuity deficits owing to uncorrected refractive errors, in order to assess the importance of the acuity deficit as a determinant of other perceptual losses suffered by amblyopes.

In an alignment task non-amblyopes with monocularly reduced acuity performed significantly better than amblyopes, suggesting that the acuity deficit was not solely responsible for amblyopes' perceptual deficit in this task. However, in another experiment in which a greater variety of spatial cues was provided amblyopes performed as well as non-amblyopes. Thus their perceptual skills would seem to be adequate for efficient functioning in most normal environments where spatial cues are abundant.

Previous reports that amblyopes generally lack stereopsis were confirmed in two experiments with a few interesting exceptions, whose cases are discussed. The data obtained in the four experiments on space perception and stereopsis in amblyopia provided support for most current theories in these areas.

Experiments on contrast sensitivity showed that the losses

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suffered by amblyopes, as measured by interocular comparison, varied between individuals, both in depth and in bandwidth (the range of spatial frequencies affected). This variation was not directly related to the extent of acuity deficit, or to the condition which originally gave rise to amblyopia, but did seem connected with the age at which the subject first received treatment for the primary causative ocular defect. A similarity between the contrast sensitivity functions of amblyopic eyes and those of infant eyes is considered as a basis for explaining the nature of contrast sensitivity loss in amblyopia. Some preliminary attempts to measure contrast sensitivity in infancy by methods suitable for screening purposes are described in the final chapter.

The thesis includes a historical review of theories of amblyopia derived from clinical and experimental work on human subjects, and a critical evaluation of experimental work in which animals were visually deprived with a view to measuring the contributions of experience to visual development. The claims of some authors that such work may have clinical relevance for preventing or treating amblyopia are refuted, since clinical experience has already furnished sufficient evidence to achieve these ends.

The perceptual consequences of human amblyopia, as characterised in the present research have important practical implications for the amblyope, and important theoretical implications for models and mechanisms of visual perception and its development.

CONTENTS

## CHAPTER 1 : INTRODUCTION

### 1.1  OUTLINE OF THE THESIS

The first six chapters of the thesis address themselves
to the subject described by the title: human amblyopia and
its perceptual consequences.  Definitions of specialised
terms which are used throughout the thesis are to be found
later in this introductory chapter, which is followed by
a broad overview of amblyopia: its aetiology,
characteristics, theories concerning its development,
previous studies of its effects on human subjects, and a
critical review of studies in which so-called analogues
of amblyopia have been produced in animals.

The third chapter concerns experimental studies of space
perception and stereopsis in amblyopes and other subjects,
and in Chapters 4 and 5 experiments in which contrast
sensitivity was measured by various methods in a number of
different types of subjects are described and discussed.

In each of these chapters results are discussed in terms of
their practical and theoretical implications,and Chapter 6
collates all the data obtained, in order to provide a
conclusive overview.

Chapter 7 is separate from the main body of the thesis in
that it concerns visual development and the prevention of
amblyopia.  The research described in this chapter was
undertaken in parallel with the main body of research
described in the preceding chapters and it is this line
of investigation that the author is most likely to follow
in future studies.

## 1.2. DEFINITIONS

### 1.2.1. VISUAL ACUITY

Acuity means sharpness, derived from the Latin 'acus' for 'needle'. The Penguin Dictionary of Psychology (Drever, 1964) states that it is 'applied particularly to sensory perception of stimuli of low intensity, as dependent mainly on the sensitivity of the sense organ'. Its conventional application to vision is not however with reference to stimuli of low intensity but to stimuli of small size. Obviously different aspects of the size of a stimulus can be varied, and, as Pirenne (1962) points out, "there are as many different visual acuities as there are types of test objects".

Overall stimulus size can be varied to determine 'detection acuity': the smallest size at which the stimulus is still detected. This type of acuity is measured with the Catford Drum (See Chapter 7), where the stimuli are spots of various sizes.

The size of detail in the stimulus can be varied to determine 'resolution acuity'; for example the size of squares in a chequerboard stimulus, or the width of lines in a grating.

The commonest visual acuity test (Snellen, 1862) varies both the size of the stimulus and the size of detail in it, and requires detection, resolution and in addition recognition of the form, which is usually a capital letter. Thus it tests 'recognition acuity' and is held to provide a functional measure which has much more practical significance than the other two types of acuity test mentioned above, since man's visual requirements are such that detection or resolution without recognition would be of little use.

The Snellen test presents a series of rows of letters of different sizes. The test chart is white and the letters are black, so contrast approaches 100%. The surrounding luminance is usually photopic. The test is conducted at a distance of 6 metres, and this figure is the numerator of the Snellen fraction which is used to define each line of letters. The denominator gives the distance in metres at which the detail in a particular line of letters subtends 1 minute of arc. For example the width of the limbs and spaces of the letter E on the line designated 6/18 is such that they each subtend 1 min arc at 18 metres. The reciprocal of the Snellen fraction gives the angular size of the detail at 6 metres, thus the detail in a 6/18 letter subtends 3 min arc at 6 metres.

The Snellen test can be criticised on several grounds. Some letters are more easily recognised than others, while some are easily confused (e.g. H and N). These problems are quantified by Bennett (1965). Another uncontrolled variable known to influence visual acuity is luminance (Ripps and Weale 1976). The most serious shortcoming of the Snellen test, and other similar acuity tests, is that they only measure visual function for high contrast stimuli. This is comparable with an audiologist testing hearing by presenting sounds of different frequency but only at one loudness. Some information about the auditory system would be acquired but it would be a meagre representation of the total response characteristic of the system.

Taking these criticisms one at a time, I will describe other tests of visual acuity which have been devised to overcome them. The problem of differences between letters

is solved in the 'illiterate's E test'. Only the letter E
is used, its orientation being varied. The E's are
constructed on the same principle as Snellen letters, and
lines are similarly notated. The task is to report the
orientation of the E. Another test which eliminates
letter differences, and allows testing of illiterates, is
Landolt's ring test. Here the stimuli are incomplete rings,
the gap size being equal to the thickness of the ring. The
position of the gap in the ring is varied, and the task is
to locate it. Gap size and ring thickness are constructed
according to Snellen principles. These two tests are not
strictly resolution tasks because they both provide cues
other than the size of detail to facilitate recognition
of the stimulus orientation.

The most frequently used stimulus for measuring resolution
acuity is a grating; particularly valuable is a grating
with a sinusoidal luminance profile, because when blurred
it disappears into a uniform field. The size of detail to
be resolved in a grating is the width of its bars or spaces
(which are equal for sinusoidal and square-wave gratings),
and this can be specified in minutes of arc, but the
conventional notation is in terms of the number of cycles
of the sine or square wave which are contained in an arc
of one degree. The size of detail (in mins arc) can be
deduced from the number of cycles per degree by dividing
the latter by 30.

In a grating test of visual acuity the subject can be
required to detect the orientation of the grating or to
make a forced-choice decision as to its presence or absence.

In either case the task is much less complex than in the
Snellen test since far fewer choices are available.
Nonetheless, grating acuity and Snellen acuity have been
found to be highly correlated at photopic luminances both
for normal eyes (Le Grand, 1968) and for eyes with poor
vision caused by non-optical defects (Green, 1970).
The main advantage of using gratings to test visual acuity
instead of Snellen-type tests is that their contrast can
be varied while keeping mean luminance constant, thus
allowing acuity measurements to be taken at different
contrast levels.  (See Chapter 4).
In this thesis, acuities obtained by testing on a Snellen
chart are sometimes referred to in Snellen  fractions
(e.g. 6/12) and sometimes converted to give the angular
subtense (in minutes) of the detail of the letter size
just recognizable ( i.e. the reciprocal of the Snellen
fraction ).  Grating acuities, sometimes referred to as
resolution acuities, are given in cycles/degree.  Figure
1.1 shows that the relationship between the angular
subtense of one cycle of a grating and the number of
cycles/degree in the same grating is hyperbolic .  So
in order to study the relationship between Snellen acuity
and grating acuity by linear correlation procedures it has
been necessary at times to convert the reciprocal of the
Snellen fraction in mins of arc to an assumed equivalent
number of cycles/degree.  Thus a Snellen acuity of 6/18,
which represents recognition of a letter with details of
3 mins arc, is assumed to be equivalent to a grating
acuity allowing resolution of cycles subtending 6 mins
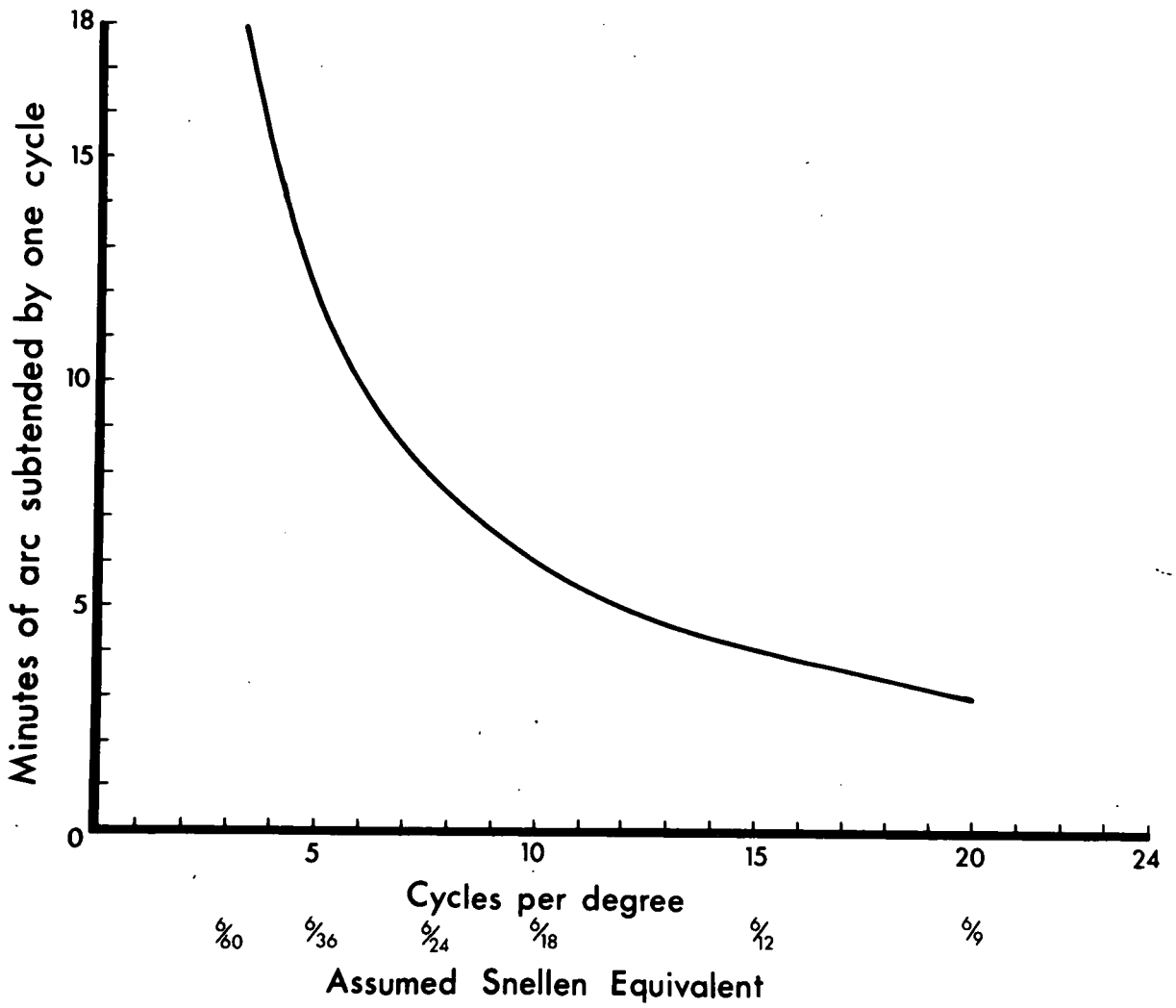
Figure 1.1.

Minutes of arc subtended by one cycle of a grating

as a function of grating spatial frequency. Assumed

equivalent Snellen fractions are shown on the abscissa.

arc each, or 10 cycles/degree. The high correlation between Snellen acuity and resolution acuity cited above is validation for this procedure, but it will be discussed further in Chapter 4.

## 1.2.2. AMBLYOPIA

This term is generally used in a restricted sense to denote reduced vision in an eye in the absence of any ophthalmoscopically detectable retinal anomaly or any disorder of the afferent visual pathways which might cause the defect; in its widest sense it may be used to include a defect of vision owing to the absence of adequate symmetrical stimuli to the two eyes so that the binocular reflexes cannot be developed (Duke-Elder and Wybar, 1973).

## 1.2.3. STRABISMUS (or squint)

This defines all conditions in which one eye deviates from the fixation point, either constantly or intermittently. It can be convergent, (also called esotropia) the deviating eye being turned nasally away from the fixation point, or divergent (exotropia) with the deviating eye turning temporally away from the fixation point. Vertical deviations are referred to as hypertropia, for an upward deviation, and hypotropia, for a downward deviation.

## 1.2.4. ECCENTRIC FIXATION

This condition which sometimes occurs with strabismus is characterised by fixation with a retinal point other than the fovea. Eccentric fixation is usually unsteady, unless the eye has deviated constantly for many years. The retinal area used for fixation does not always bear a predictable relationship to the direction of the strabismus.

### 1.2.5. EMMETROPIA

This is the ideal optical condition in which parallel rays of light are focussed clearly on the fovea while the eye's ciliary muscles are at rest.

### 1.2.6. MYOPIA

In this optical condition parallel rays of light are focussed at a point within the vitreous humour, so that the retinal image is blurred.

### 1.2.7. HYPERMETROPIA

In this optical condition parallel rays of light are focussed at a point sagittally behind the retina. The resultant blurred image can, however, be improved by exertion of the ciliary muscle (accommodation) which increases the optical power of the intraocular lens, thus moving the focal plane forward.

### 1.2.8. ASTIGMATISM

No single point focus of parallel rays exists in this optical condition which can be due to non-alignment of the optical components of the eye, or non-spherical curvature of any of the optical surfaces.

### 1.2.9. ANISOMETROPIA

This term describes optical inequality between the two eyes; for example, one eye may be more myopic than the other.

### 1.2.10. ORGANIC AMBLYOPIA

According to von Noorden (1967) "the cause of organic amblyopia is not entirely clear", and he suggests "that organic damage to the fovea or the visual pathways is present" in cases where no other explanation can be given for a reduced visual acuity.

CHAPTER 2 : AMBLYOPIA

## 2.1. AETIOLOGY OF AMBLYOPIA

Amblyopia has been briefly defined in the preceding chapter. Further details of its effects on visual functions are given in Section 2.2. Early ideas of its aetiology are reviewed in Section 2.3, and current physiological opinion is summarised in Section 2.5. This Section presents the aetiology of amblyopia according to current clinical opinion.

Amblyopia is almost invariably the consequence of some other primary anomaly of visual function. In most cases the primary defect can be easily diagnosed because it is either muscular or optical. The most common muscular defect causing amblyopia is convergent strabismus (see definition in Chapter 1.). The strabismic eye's acuity is the lower of the two, and it can only be improved if treatment is begun at an early age. The nature of the strabismus is assessed, and the type of treatment required (surgery, exercises, and/or patching) depends on the type of strabismus. Ideally treatment of the amblyopia (by patching of the good eye) begins at the same time, but in cases requiring surgery it is usually delayed by post-operative bandaging of the amblyopic eye.

The most common optical defect giving rise to amblyopia is anisometropia, particularly in hypermetropia (see definitions, Chapter 1). A difference of about 2 DS is sufficient to make the more hypermetropic eye amblyopic. Myopic anisometropic amblyopes generally have larger interocular differences. Unequal amounts of astigmatism

in the two eyes are also found in amblyopes. The treatment of anisometropic amblyopia begins with full correction of the refractive error in both eyes, and patching of the good eye. If strabismus is also present this is then treated with orthoptic exercises.

In both strabismic and anisometropic amblyopia, eccentric fixation (see definition, Chapter 1) is sometimes found, and this is treated with various pleoptic techniques in which the fovea is actively stimulated while surrounding retinal areas are 'bleached'. These two anomalies (strabismus and anisometropia) account for a large proportion of cases of amblyopia, and the remaining minority of cases are due to pathological conditions such as ptosis, congenital cataracts, corneal opacities or retinal lesions secondary to viral infection (such as measles). Where possible the obstacle to normal vision is removed as soon as possible in order to allow visual development to proceed.

Cases of amblyopia in which no primary visual anomaly can be diagnosed are now extremely rare, although in some cases the diagnosis is conjectural because precise medical history can not be ascertained.

Figures for the incidence of amblyopia average around 4% (Bock, 1960; Killen, 1961), of which about half have strabismus (with or without anisometropia) and half have anisometropia without strabismus. Figures for the incidence of amblyopia secondary to pathological defects are not available, probably because it is extremely low.

## 2.2. CHARACTERISTICS OF AMBLYOPIC VISION:
## A SUMMARY OF CLINICAL AND EXPERIMENTAL FINDINGS

The main characteristic of amblyopia is the one which its name describes: blunt sight or low visual acuity. As techniques for measuring visual function have been developed several other characteristics have been discovered. These include the following:

i) Bangeter (1953) reported that amblyopic eyes achieved better visual acuities when tested with single letters from a Snellen chart instead of lines of letters. He attributed this to 'separation difficulty', and investigated the phenomenon by varying the separation between adjacent letters on a line. He found a relationship between acuity and the separation required for recognition of a letter. His contemporaries (e.g. Ehlers, 1953 and Adler, 1959) claimed that the same 'crowding phenomenon' was found with normal eyes. Stuart and Burian (1962) attempted to resolve this controversy by testing normal and amblyopic eyes on a series of charts varying separation and letter size. They found that separation difficulty increased as visual acuity decreased, for all subjects. This result suggests that the crowding phenomenon is only a secondary characteristic of amblyopia, consequent upon the primary acuity deficit. Flom, Weymouth and Kahneman (1963) described a similar "contour interaction" which also depended on visual resolution acuity. These experimental findings illustrate the inadequacy of conventional methods of acuity testing, particularly for the evaluation of progress in amblyopes under treatment.

ii) Reinecke (1959) made a series of <u>objective acuity</u>
measurements of amblyopic eyes using an optokinetic
device consisting of drifting vertical lines. He found
that objective and subjective measures were close at low
acuities, but subjects with higher acuities (better than
6/18) achieved better subjective acuities than objective
acuities. He concluded that objective testing was more
appropriate for evaluating amblyopia, and attributed the
difference to such factors as test chart design and
experimenter bias.

iii) The contribution of technical developments to detection
of visual characteristics is dramatically demonstrated in
the case of eccentric (non-foveal) fixation (See definition,
Chapter 1). The earliest clinical technique for detecting
<u>eccentric fixation</u> required the patient to point at a
light while viewing with the amblyopic eye only. The
degree of eccentricity of pointing was used as a measure
of the eccentricity of fixation. According to Revell (1971),
Priestley-Smith (c. 1900) modified this by asking the
patient to fixate a light; the corneal reflection was
observed and its displacement or wandering was the measure
of fixation precision. Bielschowsky (1926) improved the
technique further by requiring the patient to fixate his
opthalmoscope light, while he observed the location of
the foveal yellow spot in relation to the illuminated patch
of retina. Modified ophthalmoscopes have since been designed
to improve the precision of this technique, and the following
figures (from Revell, 1971, p. 187) for the incidence of
eccentric fixation in amblyopes parallel the technological
advances: 1936=2%, 1961=23%, 1962=57%. Barnard (1962)

found that amblyopic eyes rarely fixated with a rigid
eccentric point, but wandered around in an eccentric area.
Burian and Cortimiglia (1962) found no clear relationship
between degree of eccentricity and amblyopic acuity, except
that extremely low acuities (worse than 6/60) were
associated with vertical eccentricity rather than horizontal.
iv) Burian (1969a) found no evidence linking amblyopia with
handedness or eye dominance. Burian  (1969b) reported the
following characteristics of amblyopia:
v) Dark adaptation and spectral sensitivity are unaffected.
vi) The central critical fusion frequency of flicker is
slightly reduced.
vii) The differential light threshold is raised.
viii) At low luminance levels fixation stabilises, visual
acuity approximates that of the non-amblyopic eye, and
both central critical fusion frequency and differential
light threshold are normal.
ix) The foveal spatial summation function in amblyopia is
similar to the normal eye's peripheral spatial summation
function.
x) At high luminances the amblyopic eye requires higher
contrast than the normal eye.
xi) Amblyopic visually evoked cortical responses appear
similar to those of the normal eye when it is inattentive.
Lombroso et al (1969) defined the difference between normal
and amblyopic evoked responses as a reduction in amplitude
and waveform complexity.  More recent studies of visually
evoked responses (VERs) have described several other
characteristics: Yinon et al (1974) found different waveforms,
reduced amplitude and increased latency when comparing

amblyopic eyes with their normal counterparts. Levi (1975)
reported that the VER elicited by unpatterned stimulation
was unaffected by amblyopia, but amplitude was reduced if
the stimulus was a small chequerboard pattern. He found
no relationship between visual acuity and VER amplitude,
and no differences in latency between amblyopic and normal
eyes. Arden et al (1974) found that the VERs of amblyopic
and normal eyes were out of phase with each other. Regan
(1977) described a parabolic relationship between VER
amplitude and stimulus check-size, and he claimed that
the shape of the parabola was determined by acuity, and the
difference between the normal and amblyopic eye curves was
a measure of the extent of the amblyopic deficit. Wanger
and Nilsson (1978) confirmed the amplitude and latency
differences reported previously, and also found that the
amplitude increment obtained by binocular viewing was
significantly smaller for amblyopes than for normal subjects.
xii) There have been few experimental studies of binocular
function in amblyopia. Simons and Reinecke (1974) suggest
that stereopsis is almost invariably absent. Banks, Aslin
and Letson (1975) assessed binocularity in strabismic
amblyopes by measuring interocular transfer of a tilt
after-effect, which is highly correlated with stereopsis
(Movshon, Chambers and Blakemore, 1973). They found that
the degree of binocularity present was inversely related
to the age at which the subject's squint had been surgically
corrected.
xiii) Awaya and von Noorden (1971) investigated the influence
of binocular viewing on amblyopic acuity; they concluded

that it was degraded by binocular viewing for esotropes and hypermetropic anisometropes more frequently than for exotropes and myopic anisometropes. This degradation did not occur at all in subjects whose reduced monocular acuity was a consequence of macular lesions.

xiv) Lepard's (1975) longitudinal study of <u>refractive changes</u> with growth and development showed that amblyopic eyes remain refractively constant during the first 25 years of life, while their non-amblyopic counterparts become progressively more myopic during the same period. Myopic progression was found in both eyes of non-amblyopic control subjects.

xv) The <u>accommodative responses</u> of amblyopes were studied by Wood and Tomlinson (1975). They found that the stimulus-response relationship was appropriately linear but its gradient was such that strong accommodative stimuli (i.e. near objects) failed to elicit a sufficiently strong response. Optical blurring of the stimuli elicited a similar lag in non-amblyopic subjects. They therefore concluded that this characteristic was secondary to the acuity deficit of amblyopia.

xvi) At low luminance levels amblyopes were found to have abnormal <u>brightness contrast</u> sensitivity (Levi and Harwerth, 1974).

xvii) Reduced <u>increment threshold spectral sensitivity</u> was found across the entire visible spectrum (Harwerth and Levi, 1977).

xviii) Ciuffreda, Kenyon and Stark (1978) found that amblyopic eyes had increased <u>saccadic latencies.</u>

This summary of the characteristics of amblyopia outlines the present state of knowledge of the perceptual consequences of amblyopia, with the exception of recent studies of contrast sensitivity; these will be reported in Chapter 5.

## 2.3.  A HISTORICAL REVIEW OF THEORIES OF AMBLYOPIA

The term amblyopia derives from Greek roots: 'amblyos'
meaning 'blunt' and 'ops' meaning 'eye'.  However, there
is no evidence that it was used by the ancient Greeks,
despite their knowledge of other ocular defects.  Revell
(1971) attributes its invention to Le Cat in the 18th
Century.  It was defined by Albrecht von Graefe (1828-1870)
as "the condition in which the observer sees nothing and
the patient very little" (cited in Revell, 1971, p. 164).
The ophthalmoscope, invented by Helmholtz in 1850, permitted
inspection  of the interior of the eye, including the
retinal surface.  This advance enabled ophthalmologists to
detect the causes of their patients' visual symptoms in
conditions affecting the eye itself, but not in
conditions affecting the rest of the visual pathway.  Von
Graefe's description of amblyopia alludes to the absence
of ophthalmoscopically visible abnormalities in the presence
of abnormalities of visual function, such as reduced visual
acuity.

During the late 19th and early 20th centuries theories about
the aetiology of amblyopia began to develop.  It was almost
invariably found in patients with unilateral strabismus
(misalignment of the two eyes), and this fact produced the
two major opposing theories: that amblyopia was congenital
and caused strabismus or that it resulted from habitual
suppression of the strabismic eye's image.  Proponents of
the latter theory were further divided between those who
believed that lack of use of the eye was the causative
factor (e.g. Worth 1903), and those who believed that
"it is not for want of use that vision suffers, but through

seeing too much. The eye becomes a nuisance and the brain blinds it", (Maddox, 1907). These theories became and remain the basis of clinical teaching and practice.

Some interesting observations and explanations have been recorded by others; Swann (1931) believed that in the amblyopic eye the peripheral retina dominated the central area. He advocated occlusion of the non-amblyopic eye and the peripheral field of the amblyopic eye in order to restore the correct relationship. Duke-Elder (1949) suggested that at birth all eyes are amblyopic and appropriate facilitation of the various ocular reflexes plus the reward of clear vision were necessary for full visual development. This was compatible with Chavasse's (1939) emphasis of the influence of obstacles to normal development of binocular vision. These obstacles were classified as sensory, motor or central and their removal was the basis from which his treatment of amblyopia and strabismus began.

One possibility proposed by Alpern, Flitman and Joseph (1960) in explanation of their data on central flicker fusion thresholds in amblyopia was that rods may have encroached on the foveal area. Miller's (1955) theory for the apparent reduced photopic functioning of the amblyopic eye postulated a reduction in lateral inhibition in the foveal cones. Levi and Harwerth (1974) and Harwerth and Levi (1977) supported this model and used it to interpret evidence of reductions in brightness contrast sensitivity and increment threshold spectral sensitivity in amblyopes. In the latter study their data suggested that amblyopes suffered excessive inhibition of green cones by red ones, and reduced inhibition of red cones by green ones.

With the advent of suitable electrophysiological techniques cortical evoked response data provided another source of theoretical inspiration. Balen and Henkes (1962) linked amblyopia and inattentiveness, which they attributed to a loss of activation from the brain-stem reticular formation.

Burian's (1969b) extensive review of the characteristics of amblyopic vision (see preceding section) led him to conclude that most of them derived from the loss of foveal superiority at a physiological level. He also considered the possible roles of cortically controlled suppression, and gross fixatory nystagmus. These ideas were, on the whole, similar to those of von Noorden (1967) whose major contribution was the classification of amblyopia according to its apparent origin. The most important distinction he made was between amblyopia of suppression (as in strabismus or anisometropia) and amblyopia of disuse or amblyopia exanopsia (as in congenital cataracts or ptosis). He thought that the latter type might be retinal in origin while the former was caused by cortical suppression which he suggested was an adaptive mechanism to prevent image confusion. Later, however (1974) he emphasised the similarities between the two types, in that both were caused by a modification of normal visual experience during a period of susceptibility to such changes. This idea is compatible with Bagolini's (1976) suggestion that amblyopia was due to misuse rather than disuse of the visual system. Both von Noorden and Bagolini attributed strabismic amblyopia to abnormal binocular interactions, and von Noorden believed that anisometropic amblyopia  shared this aetiology.

Estimates of the span of the <u>critical period</u> during which the visual system is vulnerable and susceptible to misuse or abnormal visual experience have varied considerably. Worth (1903) believed that the faculty of binocular vision had to develop within the first six years of childhood, or it would not develop at all. Peter (1931) believed that amblyopia could be corrected up to the age of seven, while Chavasse (1932) favoured correction of any optical and muscular defects within the first 12 months, particularly where there was a family history of squint or amblyopia. Lyle and Foley (1957)believed that binocular vision would only be attained if the visual axes were parallel before the 30th month of life, while Bock (1960) felt that the possibility of curing amblyopia was high before the age of 5, fair between the ages of 5 and 8, and doubtful between 8 and 10. After 10 years the chances of successful treatment were nil, he said. Phillips (1966) believed that anisometropic amblyopia could be successfully treated up to 14 years of age. The estimates listed above were all based on clinical experience. The following experimental findings might be considered more reliable: Banks, Aslin and Letson (1974) demonstrated that binocularity, as measured by interocular transfer tasks, was most vulnerable to abnormal visual experience during the first three years. Hickey (1977) examined the brains of humans who had died at various ages between birth and 40 years and found that LGN cell growth continued throughout the first two years of life. He suggested that this period of cell growth might be related to the period of susceptibility, if amblyopia was a consequence of neural changes. Romano (1975)

presented data illustrating the dramatic advantages
obtained by correcting strabismus before the age of 2:
patients were far more likely to have stereopsis than those
treated later in life. Javal's (1896) policy of treating
all ocular defects at the absolutely earliest possible age
has clearly been vindicated by clinical experience and
research in the last 80 years.

Theorising about amblyopia in the last ten to fifteen years
has been strongly influenced by the work of animal physiologists
who have been exploring the effects of various types of
visual deprivation upon different components of the visual
pathways. This body of research will be reviewed later
(Section 2.4), but it is mentioned here because it has
resulted in the theoretical interpretation of most recent
studies of human amblyopes in physiological terms. Parallels
are drawn between the physiological findings in animal
visual pathways and the possible mechanisms of human
amblyopia. For example, failure of stereopsis tests or
interocular transfer tasks by amblyopes has been attributed
to their loss of cortical binocularity, (e.g. Movshon,
Chambers, and Blakemore, 1973; Wood, Fox and Stephenson,
1978; Blake and Cormack, 1979). The absence of binocular
enhancement of evoked potential amplitude has been similarly
accounted for in physiological terms (Lennerstrand, 1978).
Other authors have been more reluctant to interpret
differences in evoked potentials as direct evidence of
cortical differences (e.g. Lawwill et al, 1973; Levi, 1975;
Yinon et al, 1974). The validity of assuming parallels
between experimental animal amblyopia and human amblyopia
will be discussed later, after the animal research has

been reviewed.

Throughout this century investigations into amblyopia have provided new data and new theories. Of most pratical significance are the findings which have narrowed down the estimates of the span of the critical period during which visual experience can influence visual development. These provide a basis for successful prevention of amblyopia.

The theoretical advances of this century must be evaluated with reference to the seminal ideas of Victorian ophthalmologists. The three major viewpoints they expressed were:

i) that amblyopia was congenital and caused other ocular defects;

ii) that it resulted from lack of use of an eye;

iii) that it resulted from suppression of the image received by one eye because it was incompatible with the image received by the other eye.

In some senses the first of these opinions has been upheld by discoveries of the nature of visual development (See also Chapter 7) . At birth both eyes might be considered to be amblyopic since they have low visual acuities without any physiological defect. However a theory of amblyopia grounded upon this fact must go on to account for the progress of some eyes to normality while others remain amblyopic.

The second and third Victorian theories provide possible explanations, and these have both received some support from this century's investigative effort. Von Noorden's (1967) classification of amblyopia suggested that the two

theories described two different types of amblyopia:
the 'lack of use' theory explained amblyopia exanopsia,
while 'suppression' theory explained anisometropic and
strabismic amblyopia. He later (1974) assimilated these
two theories into one which implicated abnormalities of
visual experience during the critical period as likely
precursors of amblyopia. This position is not markedly
different from that of Chavasse (1939) who believed that
amblyopia must be treated by the removal of any sensory,
motor or central obstacles to the normal development of
binocular vision.

In conclusion, recent theoretical advances have developed
in line with early hypotheses rather than branching into
new directions. Perhaps their most valuable contribution
has been to demonstrate the compatibility between three
originally contradictory views of amblyopia.

## 2.4.  INVESTIGATIONS OF THE EFFECTS OF VISUAL DEPRIVATION
ON ANIMALS

The nature-nurture debate was the primary motivation
behind early interest in visual development outside the
clinical field.  In the 1940's various experimenters
assessed the behavioural effects of total light deprivation
during early infancy on animals of different species.
These studies were reviewed by Riesen (1950), who also
described his own studies of dark-reared chimpanzees
which demonstrated that normal usage of the visual system
was vital for normal visual behaviour to develop.
Psychologists Walk, Gibson and Tighe (1957) invented the
visual cliff for use in assessing depth perception in
normal and visually-deprived animals of various species.
Their findings suggested that early visual experience was
an important determinant of future visual perceptual
abilities.  Physiologists were consequently inspired to
search for cellular explanations of the psychologists'
behavioural results.  Pioneers in this field were D. Hubel
and T. Wiesel.  By 1962  they had mapped out the functional
architecture of the cat's visual cortex, and they turned
their attention to very young kittens (1963) who, they
found, had essentially identical cortical arrangements
before they had experienced any patterned visual stimulation.

In response to the nature-nurture question their next studies
(Wiesel and Hubel , 1963a and 1963b) involved manipulation of
the kittens' early visual experience, by monocular deprivation
(suturing the lids of one eye together or covering with a
translucent contact occluder) of varying durations.  They
concluded that abnormal early visual experience caused

atrophy of cells in the lateral geniculate nucleus (LGN) and of the cortical connections which had been present at birth, resulting in reduced cortical responsiveness to input from the deprived eye, and reduced cortical binocularity.

Hubel and Wiesel's early work has led to a dramatic proliferation of studies of the consequences of early visual deprivation, and these will now be briefly reviewed, grouped according to the type of deprivation used and the physiological measures taken.

1.  **The effects of total monocular light deprivation**
    **on the lateral geniculate nuclei (LGN)**

Wiesel and Hubel (1963a) demonstrated that monocular lid suturing of kittens led to shrinkage of cells in the layers of the LGN connected to the deprived eye. This result was confirmed by Kupfer and Palmer (1964) and was attributed to binocular competition by Wiesel and Hubel (1965a). Hubel and Wiesel (1970) determined the "critical period" during which deprivation had to occur to produce these effects; for kittens it ended about three months after birth. Guillery (1972) confirmed the role of binocular competition by lesioning areas of retina in the non-deprived eye, thus eliminating binocular competition for those areas; he found that this prevented cell shrinkage in the corresponding areas of the deprived layers of the LGN. Guillery and Seltzner (1970) demonstrated that the LGN cell changes were restricted to binocularly innervated areas of the nuclei in kittens, but von Noorden and Middleditch (1975a and 1975b) found significant shrinkage of monocular LGN cells in monkeys after monocular lid suturing during

their critical period. Sherman, Hoffman and Stone (1972)
claimed that after monocular lid suturing, recording from
the cat's binocular LGN Y-cells became more difficult while
recording from monocular cells remained unchanged. Garey
and Blakemore (1977) produced morphological evidence to
support the hypothesis that monocular lid suturing has a
specific effect upon the Y-cell system. Movshon and
Dursteler (1977) determined that the minimum period of
deprivation required to produce significant changes in
LGN cell size was 12 hours, starting on the 29th day after
birth.

Numerous other papers could be cited in this section, but
on the whole they do not add new evidence; they merely
replicate the findings described above with minor procedural
variations (e.g. in the degree of light deprivation used)
or with subjects from different species.

2.  The effects of total monocular light deprivation on
    the visual cortex.

Wiesel and Hubel (1963b) demonstrated reduced cortical
binocularity in monocularly deprived kittens and suggested
that it might be due to a disruption of the normal neural
connections which they had previously found (Hubel and
Wiesel, 1963) in normal newborn kittens. In a later study
they attributed their findings to binocular competition
(Wiesel and Hubel 1965b), because they found that reversal
of suturing within the critical period allowed some recovery
of the originally deprived eye's cortical connections. The
critical period during which monocular deprivation of light,
or just pattern, could affect the kitten's cortical
responsiveness was found to begin at the fourth week,

peak around the 6th to 8th week, and decline towards the
end of the third month (Hubel and Wiesel 1970). Several
authors demonstrated the potency of very brief periods of
monocular deprivation in reducing cortical binocularity
(e.g. Pettigrew and Garey, 1974; Olson and Freeman, 1975;
Peck and Blakemore, 1975; Movshon and Dursteler, 1977).
Schechter and Murphy (1976) confirmed that brief monocular
deprivation (3 hours) reduced cortical binocularity while
longer periods also changed ocular dominance. Blakemore
(1976) found that monocular pattern deprivation without
light deprivation had similar consequences.
Kratz, Spear and Smith (1976) found that if the non-deprived
eye was removed after the end of the critical period the
number of cells responding to stimulation of the previously
deprived eye increased, suggesting that binocular competition
occurred in the form of tonic inhibition of the deprived eye
by the non-deprived eye. However some studies demonstrated
specific physiological changes which might cause cortical
monocularity; Movshon, (1975) reported a shrinkage of
cortical columns dominated by the deprived eye, and Thorpe
and Blakemore (1975) found that in some cases loss of cortical
binocularity was associated with a loss of afferent axons
from deprived layers of LGN. Another indicator that
binocular competition might not be the only mechanism
responsible for cortical monocularity was Wilson and Sherman's
(1977) finding of reduced responsiveness of complex cells
in the monocular striate cortex; although this was in direct
contradiction to the report by Sherman et al (1974) of no
deficit in monocular cortex response.
Once again this review omits a number of references to

similar findings in different species.

3. The effects of total monocular light deprivation
   on behaviour.

Behavioural consequences of monocular deprivation were first reported by Ganz and Fitch (1968). They found deficits of visuomotor behaviour and pattern discrimination which could be improved by reversal of eye closure after the critical period. These findings were confirmed and replicated by several authors (e.g. Dews and Wiesel, 1970; Rizzolatti and Tradardi, 1971; Chow and Stewart, 1972; Ganz et al, 1972; Ganz and Haffner, 1974; Hendrickson et al, 1977). Van Hof- van Duin (1976b) reported contradictory findings: his cats showed normal pattern discrimination after monocular deprivation. He suggested that differences in test design might be responsible for the conflicting data. Sherman (1973, 1974) found normal visually guided orienting behaviour with the deprived eye if stimuli were presented in the monocular part of the visual field, but not for stimuli in the binocular field. He used this evidence to argue in support of the binocular competition theory. Packwood and Gordon (1975) found that cats with low cortical binocularity (e.g. Siamese cats and monocularly deprived cats) had no stereopsis.

4. The effects of total binocular light deprivation
   by dark-rearing or lid-suturing.

The deficits produced by binocular deprivation are less severe than those found after monocular deprivation (Wiesel and Hubel, 1965a). Rats' visual cliff performance deteriorated with increasing periods of dark-rearing, (Tees, 1974). Cortical specificity is reduced from the levels found in newborn kittens by dark-rearing from a date before eye- opening (Buisseret and Imbert, 1976), but some orientation

specificity can be restored by long periods of normal visual experience after deprivation (Cynader, Berman, and Hein, 1976).

Behavioural data are conflicting. Wiesel and Hubel (1965b) reported that kittens showed little recovery of visuomotor skills even after a year of normal visual experience, if they had been binocularly deprived throughout the critical period. But Baxter (1966), Chow and Stewart (1972), Sherman (1973) and van Hof-van Duin (1976a) all found dramatic improvements in behavioural performance. Their data, and those of Cynader et al (1976) contradict the idea of a brief early critical period of vulnerability. The recoveries reported suggest that some plasticity remains long after the critical period has ended.

## 5. The effects of strabismus on the lateral geniculate nucleus (LGN).

Ikeda and Wright (1976) investigated the cause of foveal acuity losses in strabismic amblyopia. They had previously (1972) shown that retinal ganglion cells only responded to sharply focussed stimuli, and hypothesised that disuse during the critical period might therefore disrupt the visual pathway at a point before the visual cortex. They produced convergent strabismus in one eye of each of 8 3-week-old kittens by removing the nictitating membrane, lateral rectus, superior oblique muscle and connective tissue. This drastic procedure resulted in convergent squints of 15-30 degrees, and considerably reduced the mobility of the eye. They recorded from LGN cells when the kittens were 4-5 months old, and found a loss of spatial resolution, and an increased latency of response in the 'sustained' cells receiving input from the central field

of the squinting eye, which supported the hypothesis that low visual acuity in strabismic amblyopia is a pre-cortical phenomenon.

Ikeda, Plant and Tremain, (1976) reported cell shrinkage in the LGN layers receiving input from the strabismic eye of convergent kittens, which was similar to, but less severe than, that produced by monocular deprivation (Wiesel and Hubel, 1963a). Ikeda, Plant and Tremain (1977) were unable to find any LGN cells responding to stimulation of the convergent eye's temporal retina. This area would have been deprived of stimulation because the corresponding nasal visual field would have been obscured by the kitten's nose. Cell shrinkage was also more severe for LGN layers driven by the nasal field.

Einon, Ikeda and Tremain (1977) probed the effect of inducing convergent strabismus at different ages. They found LGN spatial resolution (tested at 6-7 months) was most degraded when strabismus was created at 3 weeks (the earliest age used) and progressively less degraded as the age of operation increased up to 10 weeks. Kittens operated on at 13 and 16 weeks showed no abnormalities of spatial resolution at the LGN. A function of spatial resolution against age of operation for the strabismic kitten fitted well with a function of spatial resolution against age for a group of normal kittens aged 3-10 weeks, suggesting that convergent strabismus had arrested visual resolution development at the LGN.

6.  The effects of strabismus on the visual cortex.

Hubel and Wiesel (1965) produced divergent strabismus in kittens by cutting through the medial rectus of one eye.

This resulted in a severe reduction in cortical binocularity in area 17. Maffei and Bisti (1976) induced the same cortical result in divergent squinting kittens deprived of any visual experience by binocular lid-suturing and dark-rearing. They explained the loss of cortical binocularity in terms of the loss of symmetrical binocular eye movements as signalled to the visual cortex by oculomotor muscle proprioceptors. Supportive data was obtained by Maffei and Fiorentini (1976). They produced total immobilisation of one or both eyes of their kittens by severing the lateral rectus muscle and the oculomotor and trochlear nerves. (These nerves control the remaining five extraocular muscles.) Monocular immobilisation reduced cortical binocularity but binocular immobilisation did not, indicating that only asymmetrical eye movements degrade cortical binocularity.

7.  The effects of strabismus on behaviour.

Franklin et al (1975) measured visual acuity in both eyes of convergent squinting kittens by training them to respond to square-wave gratings. They found that visual acuity loss was dependent upon the age of onset of the squint: kittens made to squint at 3 weeks had greater acuity deficits than those who were operated on at 6 weeks. Ikeda and Jacobson (1977) demonstrated behavioural correlates with the neurophysiological findings of Ikeda, Plant and Tremain (1977), demonstrating that squinting cats could not see food morsels presented in the nasal field of the squinting eye.

8.  Effects of environmental modification.

Hubel and Wiesel's early (1962) studies of cortical specificity indicated that the preferred orientations of area17 cells were evenly distributed from 0 to 360 degrees.

Hirsch and Spinelli (1970) and Blakemore and Cooper (1970) independently discovered that kittens reared in striped environments of one orientation only 'lost' cortical cells selectively tuned to the orthogonal orientation. Hirsch and Spinelli's kittens experienced horizontal stripes in one eye and vertical ones in the other, and they lost cortical binocularity. Blakemore and Cooper's kittens saw the same orientation with both eyes and they retained normal levels of cortical binocularity. Maffei and Fiorentini (1974) and Stryker and Sherk (1975) were unable to replicate these experiments. Muir and Mitchell (1973) produced a behavioural correlate by training kittens to respond to square-wave gratings: resolution and contrast sensitivity were higher for gratings of the experienced orientation than for orthogonal gratings. Blakemore and Mitchell (1973) determined the time course of this modification of orientation specificity: only one hour of striped experience at the peak of the critical period significantly modified response properties of the cortex.

Daw and Wyatt (1976) restricted kittens' early visual experience to vertical stripes moving around a transparent cylinder in one direction only. They found this produced a change in cortical directional selectivity and that the critical period for modification of directional sensitivity peaked at 4-5 weeks. Berman and Daw (1977) confirmed that the critical period for direction deprivation terminated earlier than the critical period for monocular deprivation.

Studies of the effects of modifying the extent of visual space available during the critical period have shown that animals reared in restricted spaces develop myopia (Young,

1961 and 1963; Young and Leary, 1973; Rose et al, 1974; Belkin et al, 1977). This effect is believed to be lenticular in origin (Belkin et al, 1977).

## 9. Effects of optical modification of early visual experience.

Freeman and Pettigrew (1973) induced artificial astigmatism in kittens with cylindrical ophthalmic lenses, and found changes in orientation selectivity, the severity of which related to the power of the lens used. Cynader and Mitchell (1977) produced 12 dioptres of myopic astigmatism in kittens and recorded cortical responses at 3 months. The astigmatised eye drove fewer units than the normal eye, and binocularity was reduced; both effects were strongest for cells tuned to the blurred orientation. Cynader and Mitchell argued that the site of the changes produced in kittens and in human meridional amblyopes must therefore be in the cortex, since LGN cells are not orientation selective.

Von Noorden and Crawford (1977) produced hypermetropic anisometropia in monkeys by removing the intraocular lens from one eye. Later histological examination revealed cell shrinkage in both monocular and binocular layers of the LGN receiving input from the aphakic eye. This result is similar to that obtained by total monocular deprivation and suggests that form deprivation without light deprivation is sufficient to arrest LGN growth.

Eggers and Blakemore (1978) created myopic anisometropia of 8 or 12 dioptres in kittens and this resulted in reduced contrast sensitivity and resolving power in cortical cells driven by the myopic eye, and reduced cortical binocularity, with a bias in ocular dominance towards the emmetropic eye.

## 10. Pharmacological studies.

To explain the abundant evidence that asymmetrical early
visual experience causes loss of cortical binocularity in
the cat visual cortex, Duffy et al (1976) postulated
synaptic inhibition of input from the deprived eye. They
tested this idea by trying to reduce synaptic inhibition
pharmacologically with intravenous bicuculline, which is
believed to block inhibitory transmitters. Their findings
supported the hypothesis: after bicuculline injection 60%
of cortical cells responded to stimulation by either eye,
when previously they had been monocularly driven by the
non-deprived eye. Sillito (1976) criticised this study on
the grounds that monocular deprivation was not initiated
at eye-opening, thus affording some binocular experience .
Kasamatsu and Pettigrew (1976) retained cortical
binocularity in their monocularly-deprived kittens by
injection of a neurotoxin (6-hydroxydopamine) into the
right lateral ventricle, causing catacholamine depletion.
They speculated on the possibility of using similar treatment
to enhance plasticity outside the critical period.
A pharmocological correlate of the critical period has been
investigated by Cronly-Dillon and Perry (1976) and Perry and
Cronly-Dillon (1978). They found that changes in tubulin
synthesis in the rat visual cortex had a similar time-course
to the rat critical period as defined by neurophysiological
and behavioural experiments. Tubulin synthesis was also
susceptible to dark-rearing.

## 11. Studies of visual development in normal kittens

There have been two main areas of conflict in the literature
on normal visual development in kittens. One of these is
centred on the question of orientation selectivity; Hubel

and Wiesel (1963) reported that it was present at birth, although vulnerable to modifying experience during the critical period, while Blakemore and Mitchell (1973) and Imbert and Buisseret (1975) were unable to detect it, and Barlow and Pettigrew (1971) and others found only a few orientation-selective cells.  Sherk and Stryker (1976) confirmed the findings of Hubel and Wiesel, but there is still no conclusively accepted answer.

The other dispute arose from Freeman and Marg's (1975a) description of parallels between development of visual acuity in the kitten, as measured by evoked potential recording, and the time-course of the critical period. Flynn et al (1975) argued that their visual acuity data could be explained with reference to the improvement of optical clarity, and reduction in refractive error, and increase in accommodative power during the same period of time.  Freeman and Marg (1975b) rejected these criticisms because their kittens were compensated for refractive error and accommodation, and their own ophthalmological observations had indicated that optical clarity was satisfactory from 3 weeks onwards.

This review is by no means a complete survey of experiments involving visual deprivation of animals.  The most notable ommission is of the large body of work on monkeys by von Noorden and various associates, and Hubel and Wiesel. There are no fundamental differences between the results from monkeys and those obtained with kittens, except that the critical period covers a different age range.  A brief survey of their monkey work is provided by Hubel and Wiesel (1977), and an extensive list of references to studies

involving other species (e.g. rabbits and squirrels) is included in Phelps (1976). Barlow (1975) reviewed the cat literature and discussed the value and implications of a period of plasticity during visual development, concluding that the nature-nurture debate must be abandoned in view of the substantial amount of evidence demonstrating that both play an important role in determining adult capacities. Theoretical ideas arising from the body of research reviewed above will be described later in section 2.5.

## 2.5. THEORIES OF HUMAN AMBLYOPIA DERIVED FROM ANIMAL EXPERIMENTS.

In the early days of visual deprivation experiments neurophysiologists referred to older clinical evidence to substantiate their findings. For example, Hubel and Wiesel, (1963) discovered that kittens suffered cortical changes after monocular deprivation, whereas adults cats did not. In their concluding remarks they said that this age dependent effect was predictable from clinical knowledge of the comparative visual acuity deficits found after removal of congenital cataracts and senile cataracts from humans. Juler (1921) reported that traumatic cataracts acquired before 6 years of age (in humans) caused much greater visual loss (after extraction and optical correction) than those occurring in older children. Broendstrüp (1944) presented similar data.

So the discovery of an early critical period of vulnerability to visual deprivation (Hubel and Wiesel, 1970) was not surprising. As Hubel and Wiesel (1970) pointed out, the limits of the critical period for man were unlikely to be similar to those for the cat, since the two species are vastly different. Neurophysiological findings did however stimulate several authors to remind ophthalmologists of their predecessors' (e.g. Javal, 1896; Chavasse, 1939) advice: that obstacles to normal vision must be removed or corrected as early as possible in order to prevent amblyopia.

Barlow et al (1967) pointed out that there was no justification for assuming that their newly discovered stereopsis mechanism in cats was also responsible for

stereopsis in man, since man differs from the cat in at least two important respects: he has well-developed colour vision and finely controlled convergence movements. Either or both of these refinements might subserve an alternative stereopsis mechanism.

Reluctance in making inferences about human visual function from animal evidence soon waned however, and seemed to disappear completely in the seventies. Pettigrew et al (1968) expressed no hesitation in drawing analogies between the lack of stereopsis in human amblyopes and binocular disparity detector cells in the cat's visual cortex. Freeman and Pettigrew (1973) believed that cats wearing ophthalmic lenses provided a useful approach to studying the physiological correlates of ocular refractive error. Muir and Mitchell (1973) saw strong parallels between cats reared in striped environments and human meridional amblyopes. From their finding that falcons have stereopsis, Fox et al (1977) suggested that the mechanisms of human strabismic amblyopia could usefully be studied via other non-mammals. Franklin et al (1975) and Ikeda et al (1977) believed that the ocular condition of kittens with sectioned lateral rectus and superior oblique muscles was closely analogous to the ocular condition of human strabismic amblyopes. With similar severely squinting kittens Ikeda and Wright (1976) demonstrated a neurophysiological correlate for visual acuity loss in the LGN, and suggested that similar changes in the retina-LGN pathway were responsible for visual acuity loss in human strabismic amblyopes. Enormous optical errors induced in animals were described as simulations of anisometropic amblyopia (e.g. 12 dioptres of myopic astigmatism in kittens: Cynader and Mitchell, 1977; aphakia in monkeys: von Noorden

and Crawford, 1977; 8 or 12 dioptres of myopia in kittens:
Eggers and Blakemore, 1978). Some authors have constructed
comprehensive models of human amblyopia from animal data.
Von Noorden (1974) drew on animal evidence to support his
thesis that all three major types of amblyopia in humans
(strabismic, anisometropic and exanopsia) share the same
aetiology : visual deprivation resulting in inadequate
image formation at the fovea and/or dissimilarity between
the two retinal images. He assumed that since these events
caused neurophysiological anomalies in the cortices and
LGNs of deprived animals, similar anomalies must occur in
human amblyopes, and he felt that the animal work would
continue to make fundamentally important contributions to
further understanding of the site and mechanisms of human
amblyopia.

With reference to their own and others' earlier experiments
with cats, Ikeda and Wright (1974) summarised the main
functional differences between the so-called 'sustained'
and'transient' pathways of the visual system. The most
important of these was that the former mediated spatial
discrimination and visual acuity while the latter mediated
movement perception and eye movement control. They postulated
that only the 'sustained' pathway is deprived of adequate
early visual stimulation when the fovea does not receive
sharp images. Consequently it becomes ineffective, possibly
by failing to make adequate synaptic connections. They
concluded that amblyopia might result from the foveal
'sustained' neurones of one eye being deprived of adequate
(i.e. sharp) stimulation during a sensitive period of
development because of anisometropia or squint or occlusion.

They emphasised the difference between this theory and one
implicating active suppression of the input from one eye;
but in subsequent discussion of their paper Ikeda pointed
out that the two theories were compatible since their
'inadequate input' theory accounted for the acuity deficit
of amblyopia while 'active suppression' theory accounted
for disturbances of binocular function.

Blakemore and van Sluyters (1974) drew parallels between a
wide range of conditions produced experimentally in animals
and human amblyopia. In kittens(Wiesel and Hubel,1965a)
monocular deprivation caused loss of vision in the occluded
eye, while in human infants degradation of one eye's image
causes amblyopia. Occlusion reversal within the critical
period caused reversal of cortical ocular dominance patterns
in kittens (Blakemore and van Sluyters, 1974) while early
good eye occlusion in children causes improved visual acuity
in the amblyopic eye. Squinting kittens lost cortical
binocularity (Hubel and Wiesel, 1965) while squinting humans
lose stereopsis. Kittens reared in striped environments had
modified cortical orientation selectivity (Blakemore and
Cooper, 1970), while astigmatic infants deprived of sharp
images of one orientation have meridional amblyopia (Mitchell
et al, 1973). Blakemore and van Sluyters suggested two
possible functions for early plasticity in the visual system;
firstly that it allowed the system to adjust to facilitate
optimal functioning in its environment, and secondly that
it allowed fine-tuning of the cortical cells responsible for
detection of interocular image disparities.

The reservations of earlier authors (e.g. Hubel and Wiesel,
1970; Barlow et al, 1967) about making assumptions regarding

the human visual system from evidence obtained by animal experimentation are in stark contrast with the assertions of recent writers such as Eggers and Blakemore (1978) who believe that "the development of an animal model for the common human disorder of amblyopia offers hope for the design of more effective methods of treatment and prevention".

## 2.6. A CRITICAL APPRAISAL OF THE VALUE OF THE ANIMAL EXPERIMENTATION.

Having illustrated the changing attitudes of experimenters in animal visual deprivation towards drawing parallels between their findings and human amblyopia, I will now discuss some of my personal views on the issue.

It is unquestionable that the body of research reviewed above has provided knowledge about the roles of different parts of the visual pathway, and the ways in which they can be modified by abnormal early visual experience. These data, obtained from several different species, has inspired new theories and models of visual function and development in animals; some authors have employed the data in hypothesising about the mechanisms involved in the production of human amblyopia, and some have made claims for its practical value.

In trying to assess the practical usefulness of the animal research I considered the following questions:

1) Is it valid to draw analogies between the condition produced in experimental animals and human amblyopia?

2) If the analogies are accepted, has the animal research added to clinical knowledge of the consequences of visual deprivation in humans?

3) Has the knowledge obtained from animal research inspired any new models or theories of human amblyopia?

4) Do any of the models or theories derived from animal research suggest new methods for preventing and/or treating amblyopia?

The first question has two components: firstly, is it valid to draw analogies between animals and humans, and secondly,

is it valid to draw analogies between the conditions
produced in animals and the conditions which exist in
human amblyopes?

The first component question has been considered by some
animal experimenters (e.g. Hubel and Wiesel, 1970; Barlow
et al, 1967) and their reservations have been outlined
above. Phelps (1976) believed that "applying animal data
to humans is dangerous (because) there are many differences
in visual systems between mammalian species." One crucial
variable between species is the duration of the critical
period of visual development, and another important
consideration is the possibility that there are different
critical periods for different types and degrees of visual
deprivation. Most authors cited in preceding sections make
no mention of these factors.

The second component question requires re-examination of the
types of deprivation used in the animal experiments.
Deprivation by lid-suturing has been likened to human
conditions such as ptosis, corneal opacity, and cataract
(von Noorden, 1967). The main objection to this analogy is
one of degree: lid-suturing techniques were developed to
ensure maximal light deprivation, whereas in the human
conditions mentioned above some light is invariably
transmitted to the retina. Animal experiments using
translucent contact occluders are therefore more appropriate
analogues of the human conditions which give rise to
amblyopia exanopsia. The comparability of strabismus in
human amblyopes and experimental strabismus in animals is
also questionable on the grounds of magnitude. In order
to achieve a permanent convergent squint in their kittens

Ikeda and Wright (1976) had to sever two of the six extraocular muscles, as well as removing the nictitating membrane and connective tissue from one eye. This procedure caused far greater reductions in ocular motility than most human esotropias do. It also produced squints of 15-30 degrees, whereas amblyopia can arise from micro-strabismus of less than 2 degrees. The divergent squints produced by other workers (e.g. Hubel and Wiesel, 1965; Maffei and Bisti, 1976) required total severance of the medial rectus muscle, and the same quantitative objections to analogy apply to them. Experiments involving optical modification of animals' early visual experience have also imposed much larger defects than are normally found in anisometropic amblyopes. Animals have been given around 10 dioptres of astigmatism or myopia or hypermetropia (see preceding section for details) whereas 3 dioptres are enough to cause human amblyopia.

In summary animal 'amblyopia' has usually been produced by imposing far greater deprivation than is known to be necessary to produce human amblyopia. It seems possible therefore that the conditions produced, are far more severe than human amblyopia and they might even differ qualitatively. With this possibility in mind the validity of drawing analogies between the animal data and the human condition is doubtful, but the practice evidently appeals to medical grant awarding bodies who finance much of this research.

Proceeding now to the second question: has animal research added to clinical knowledge of the consequences of visual deprivation in humans? At the time when animal deprivation

experiments were starting (around 1963) clinicians were aware that visual defects present during childhood often resulted in amblyopia (see sections 2.3. and 7.2.). The known characteristics of amblyopia (summarised in section 2.2) included reduced visual acuity and poor stereoscopic vision. Animal research has shown that the behavioural consequences of visual deprivation are deficits of visual acuity, pattern discriminiation and visuomotor behaviour, none of which would be unpredictable from clinical knowledge, if visually deprived animals are in any way similar to human amblyopes.

It is interesting to note that in the late 19th century the Association for the Advancement of Medical Research (the authority responsible for deciding whether proposed animal research should receive a Home Office licence) required an applicant to specify the "utility of endeavouring to prove experimentally a fact which he (the Secretary of State) is given to understand has long been established clinically" (from French, 1975). Faced with a similar request, recent investigators of visually deprived animals could not possibly claim to have added to clinical knowledge of the functional consequences of amblyopia.

Has knowledge from animal research inspired any new models or theories of human amblyopia? The most notable impact that animal research has had on human amblyopia is that it has led to a proliferation of physiological models for the site and mechanism of amblyopia. For example, Ikeda and Wright's (1974) model proposed functional degeneration of the 'sustained' pathway as the mechanism responsible for reduced visual acuity in amblyopia. Other examples of

physiological models have been outlined above (section 2.5).
These mechanistic approaches to the study of amblyopia have
certainly determined some of the physiological corollaries
of the conditions created in animal subjects, but speculative
application of the animal findings in constructing
mechanistic models of human amblyopia are of dubious validity.
Inferential 'knowledge' of the probable sites and mechanisms
responsible for human amblyopia has not changed the position
of our understanding of its functional aetiology. Von
Noorden (1974), Ikeda and Wright (1974) and Blakemore and
van Sluyters (1974) all agree with Chavasse (1939) that
  inappropriate early visual experience is the fundamental
cause of amblyopia. So despite the efforts of the
neurophysiologists, the clinical theories of amblyopia,
which developed during the first half of this century, have
not been superceded or significantly modified.
The fourth and last question to be answered is 'do any of
the models derived from animal research suggest new methods
for preventing and/or treating amblyopia?'. Eggers and
Blakemore (1978) believe that they do, or may in the
future, as witnessed by their statement: "the development
of an animal model for the common human disorder of amblyopia
offers hope for the design of more effective methods of
treatment and prevention", and their ·        · research
is financed by the Medical Research Council because they
too accept this claim.
Taking the two issues of prevention and treatment separately,
I would argue that the answer to this question must be
negative. Clinical knowledge that amblyopia can be prevented
by early correction of any type of visual defect has accumulated

throughout this century, and several clinical studies have demonstrated the advisability of establishing a large-scale visual screening programme for infants. The evidence is presented in section 7.2. A means by which amblyopia could be totally eliminated has been known by clinicians since at least 1954, when Gunderson described it as a preventable form of blindness. Even earlier Duke-Elder (1949), in discussing the incidence of amblyopia pointed out that "66% of all cases of uniocular visual loss in young adult men" were due to amblyopia, and felt "that (this) should be tolerated with complacency is an unpleasant reflection of the neglect shown by modern civilisation towards its human material".

Clinicians have also long known that for treatment of amblyopia to be effective, it must be undertaken during early childhood. When this criterion is fulfilled, available methods of treatment are successful in restoring good visual acuity to the amblyopic eye, and in maintaining binocular single vision. Wesson (1961), provided equal right eye and left eye acuities for 64% of children whose treatment started before the age of two years, but only 38% of children examined after their 2nd birthday, (see section 7.2 for further data).

One new apparatus for the treatment of amblyopia has been developed as a result of animal experimentation. The 'Cam Stimulator' is described by Banks et al (1978). During a brief 7 minute period of conventional (good eye) occlusion the amblyopic eye views rotating square wave gratings, and immediately afterwards the amblyopic eye shows improvements in visual acuity and contrast sensitivity. The method of

stimulating the amblyopic eye was inspired by knowledge of the spatial response characteristics of the visual cells in various animals' brains. Unfortunately the report of Banks et al (1978) does not compare the results obtained with the Cam stimulator and those obtained with other methods of active stimulation of the amblyopic eye during occlusion (reviewed in Revell, 1971, p. 180), so it is impossible to know whether the reported success of the Cam stimulator is specifically due to the aspect of its design which derived from animal work or more generally due to the known effects of active stimulation of the amblyopic eye. Recent (1979) personal communications with practicing orthoptists who are using the Cam stimulator as well as other methods of active stimulation suggests that there is no difference in success of treatment, so it seems that the contribution of animal research to the design of the Cam stimulator has not been specifically helpful. However, further extensive clinical trials with the new apparatus might contradict this opinion.

The foregoing analysis of research into the consequences of visual deprivation of animals has been included at this point in order to demonstrate that its contribution to the specific problems of understanding, preventing and treating amblyopia has been minimal. The author therefore feels justified in conforming with her personal ethical standpoint by omitting detailed discussion of animal data in the remainder of this thesis.

CHAPTER 3:   SPACE PERCEPTION AND STEREOPSIS

## 3.1. Introduction:   Definition of terms

Space perception can be defined as the interpretation
and comprehension of three-dimensional information, to
facilitate interaction with the environment.
In the visual modality, the sensory information available
for space perception is entirely two-dimensional, because
it is coded upon the two-dimensional surfaces of the retinae.
Some features of this two-dimensional information can be
employed to make spatial interpretations.  These features
are referred to as spatial cues.
Many spatial cues are monocular: the necessary information
is available in one retinal image.  For example, when a
familiar object produces a retinal image of a certain size,
the distance of the object from the observer can be
inferred from the image size.  Thus the retinal image size
is a monocular cue to spatial location.  Similarly, the
shape of a retinal image produced by a familiar object can
be a cue to its orientation.  For example, a circular plate
producing an elliptical image will be perceived as being
inclined from a vertical plane.  Other monocular retinal
image cues are interposition or overlay, aerial perspective,
illumination gradients, texture gradients, and motion
parallax.  Ogle (1962b), Gibson(1969) and Hochberg (1972)
present extensive accounts of these, some of which will
also be discussed later.
Owing to the lateral separation between the two eyes, the
two retinae receive slightly different or disparate images.
The magnitude of the disparity between points of two retinal
images is determined by the spatial configuration of the

field of view, relative to the fixation point. Thus inter-retinal image disparity is a spatial cue.

Recent investigations of space perception have concentrated upon studying disparity cues in isolation, by eliminating all monocular cues. Perception within these constraints is referred to as stereoscopic perception or stereopsis. Stereopsis was discovered by Charles Wheatstone in 1833. Early stereoscopic presentations in which two seperate pictorial images were viewed, via mirrors or prisms, by each eye, were unsuitable for the experimental evaluation of stereopsis because they retained many monocular cues. Similarly, stereo-images produced photographically, by using two different camera positions, usually contained some pictorial monocular information. Wirt (1947) (cited in Duke-Elder and Wybar, 1973) designed a clinical test of stereopsis (to be described in more detail later) in which monocular information was minimised by using simple rings as stimuli. The only remaining monocular cue was the slight lateral shift of each image from a central position.

Julesz (1960) perfected the elimination of monocular cues using computer-generated random dot stereograms. Two identical random dot patterns were generated, but one area of one of them was laterally displaced. Monocularly this displacement has no significance and is not distinguishable, but binocularly it functions as a disparity cue, and the displaced area appears in a different depth plane from the random-patterned surround.

Visual cues are not the only source of ocular information used in space perception. Berkeley (1709) suggested that convergence and accommodation might provide muscular

<u>proprioceptive cues</u>.  Psychophysical evidence, reviewed
by Hochberg (1972),has produced nothing conclusive about
their efficacy as spatial cues for judgement of absolute
distance, but Ono and Comerford (1976) cite several studies
in which oculomotor adjustment <u>has</u> been found to provide
distance information.  Brindley and Merton (1960)
demonstrated the absence of any sense of eye position,
but, by using more sensitive response measures and techniques,
Skavenski (1972) demonstrated the existence of a non-visual
mechanism capable of controlling eye movements and conveying
information about eye position.  He eliminated the conjunctiva
and eyelids as possible sensory sources of information.
Stretch receptors have been found in the extra-ocular muscles
(Whitteridge, 1960) and Skavenski (1972) suggests that these
might be responsible for the mechanism he isolated.[*]
In summary, space perception utilises monocular pictorial
cues, binocular disparity cues and possibly muscular
proprioceptive cues.

[*] Alternatively, efferent information on eye movement control can
contribute to knowledge of eye position.

## 3.2.  Theories of space perception and stereopsis.

It is not the purpose of this section to present detailed descriptions of the various theories of space perception and stereopsis, but merely to indicate their various approaches, and to indicate sources from which more information can be obtained.

The earliest theories of space perception (e.g. those of Kepler, 1604, and Descartes, 1673, as cited by Epstein, 1976) proposed that cues listed above as monocular cues, e.g. image size, were 'processed' by means of conventional geometrical rules to provide information about spatial configurations.  Helmholtz (1890) emphasised that the 'processing' was "unconscious".  Theories of this type are referred to by Epstein (1976) as taking an "algorithm approach".

Gibson (1950) and Wallach (1939, 1948, 1959), hypothesised that space perception is based on relative measures such as ratio and gradient, thus accounting for the psychophysicists' discovery of various constancy phenomena. Theories of this type are referred to by Epstein (1976) as taking a "proximal stimulus approach".

Other more recent theoretical treatments are presented in Epstein (1976) who concludes that they seem to demonstrate that the "algorithm" and "proximal stimulus" approaches are both still valid and complementary, rather than competitive.

The theoretical frameworks mentioned above include proposals regarding the utilisation of binocular cues for space perception.    A slightly different approach   is that proposed by Richards (1975)  whereby inter-retinal comparisons are made globally, to detect whether disparities are convergent or divergent or nil.  Richards (1970) reported

finding some subjects who could not detect disparities in one direction, thus providing psychophysical support for his hypothesis.

The invention of random-dot-stereograms (Julesz, 1960) confirmed the existence of a mechanism whereby depth perception could arise from binocular disparity cues alone, and recent physiological research has suggested that various species possess cortical neurones specifically tuned to detect inter-retinal disparities (see review by Pettigrew, 1978).

## 3.3 Experiments to measure space perception and stereopsis

Much of space perception research has been directed towards isolating and evaluating individual cues (reviews in Ogle, 1962b and 1962c and Hochberg, 1972). Developmental aspects of stereoscopic vision have also received some attention. Romano, Romano and Puklin (1975) reviewed this field, and reported their own results from stereoscopic assessments of over 300 children aged 1½ - 13 years. Stereoscopic acuity was found to develop gradually attaining adult levels at 9 years.

There have been a few reports of the effects of ocular defects on spatial perception; for example, Birnbaum (1975) evaluated peripheral stereopsis in strabismus, testing at different distances. He found that it was present in 47% of his sample of 61 strabismics, and demonstrated that it could be developed by training. Frisby et al (1975) assessed random-dot-stereogram perception in strabismus and found it was related to the degree of bifoveal single vision present.

Amblyopia has long been suspected of interfering with binocular functions such as stereoscopic vision; Javal (1839 - 1907) advised the use of lengthy binocular exercising on a Wheatstone stereoscope as part of his scheme of treatment for amblyopia (cited in Cibis, 1975). However, a survey of 2500 children by Kohler and Stigmar (1973) failed to show a significant correlation between performance of standard stereo-tests and presence of amblyopia. Simons and Reinecke (1974) provided a possible explanation for this finding by describing an inadequacy in the test used; and suggest that pure stereopsis is almost invariably absent in amblyopes.

The aim of the following experiments was to expand understanding of the spatial perceptual abilities of amblyopes using two measures of pure stereopsis and two measures more closely comparable with normal spatial configurations. The first experiment required subjects to make a simple two-way forced-choice distance discrimination between a string and a bead: did the bead fall behind or in front of the string? Several monocular cues were available as well as binocular disparity and proprioceptive cues. Performance was rated according to number of errors made. Three groups of subjects were used: amblyopes, myopes and emmetropes. The amblyopes and myopes were arranged as acuity-matched pairs for analytical purposes (see Section 3.3.1 for detailed explanation). The second experiment required subjects to match the distance of one mobile rod with that of two fixed ones situated over 6 metres away. Performance was assessed binocularly and monocularly over several trials, and quantified in terms of the mean error of setting. There were fewer cues available than in the first task, and the measure was more directly related to conventional stereo-acuity which is taken to be the angular separation between two just-discriminable points on a sagittal axis from the viewer, (Ogle, 1962c). Again, three subject groups were used: amblyopes, acuity-matches, and a third group of other non-amblyopes which covered a wide range of acuities.

The third experiment simply measured stereopsis using the clinically-popular Titmus stereo-test. This purports to isolate disparity as the only cue presented but in fact includes a monocular cue of lateral displacement. Subjects

were classified as amblyopes, strabismic non-amblyopes and non-amblyopes.

The fourth experiment was another pure measure of stereopsis, using random dot stereograms from the new clinical test designed by the Netherlands National Institute of Perception. These succeed in isolating the disparity cue. The subject categories were the same as for experiment three, but numbers were severely depleted since the test was difficult to obtain and several subjects left the university before it arrived.

By analysing and comparing the results from these four measures of space perception I hoped to answer the following questions:

1) Is the amblyope's world two or three dimensional?

2) Is the acuity deficit of amblyopia a significant contributor to any deficit of space perception or stereopsis?

3) If amblyopes can correctly perceive spatial configurations, what cues do they use?

4) If amblyopes can correctly perceive spatial configurations, which of the above tests is most appropriate for predicting their performance in a normal environment, e.g. assessing suitability for a job?

5) Which test is most appropriate for screening for amblyopia?

6) Are the results compatible with current theories and models of space perception and amblyopia?

## 3.3.1. Experiments in space perception

Experiment 3.1: Measurement of space perception with the falling bead test.

This experiment was designed to evaluate the precision of space perception using a task which presented as many cues as possible and thus approximated a normal environment. Subjects were required to make a simple two-way forced-choice distance discrimination. The only constraining factor was the brevity of presentation (70 to 85 msecs) which, according to Stigmar's (1971) data would be expected to reduce the precision of space perception by a factor of 10.

The apparatus is based on Hering's (1865) "Fallversuch" (falling bead test). Three main groups of subjects were tested: amblyopes, myopes, and emmetropes.

Subjects

Subjects were obtained by screening a population of about 150 undergraduates for visual acuity. Measurements were taken on a standard Snellen chart at 6 metres. Monocular acuities with refractive correction, if worn, were taken first. Any eye failing to read the smallest line was then re-tested with a 1mm pinhole, in order to eliminate any uncorrected refractive errors. All participants who failed to achieve equal right and left acuities despite pinhole-viewing, and all subjects whose refractive errors were significantly undercorrected were fully examined ophthalmoscopically and their ocular defects were investigated in detail.

This screening procedure produced only 7 amblyopes; this percentage agrees with previously reported figures (e.g. Cole, 1959). In addition, two strabismic non-amblyopes were found. These were included in the experiment as a separate

group.  One had a partial third nerve palsy and the other had a concomitant esotropia.

Each amblyopic subject was paired with a non-amblyopic uniocular myope who was accustomed to being uncorrected or undercorrected, so that the pair had approximately equal monocular acuities. For expedience this group will be referred to as the myopic group.

The two members of each of these matched pairs had experienced approximately identical acuity deficits for a considerable period of time.  Some of the myopes had been prescribed optical corrections in the past, but none had been regular wearers within the preceding two years.  The amblyopes had presumably suffered their acuity deficits since childhood. Thus the effects of acuity-deficit were counter-balanced for these two groups.  It was assumed that any difference in performance between the two groups would be attributable to other deficits of amblyopia, such as impaired binocular function.

A third group consisted of 7 subjects with high acuities in both eyes.  They were either emmetropic or fully corrected ametropes.  These will be referred to as emmetropes, for brevity.

Apparatus

The black box (50x50x80 cm.) illustrated in fig. 3.1 was internally illuminated by means of a tungsten tube situated in the upper front corner, and its luminance was approximately 1.5 cd/m$^2$.  All interior surfaces were painted matt black. A 2 mm.wire painted matt white was attached to the inner lateral surfaces so that it was taut and horizontal and central in all three orthogonal planes.  Six 10 mm.holes were spaced 50 mm.apart along the central  sagittal axis

PLAN VIEW OF TOP

50cm

50cm

80cm

6 o
5 o ] 5cm
4 o
3 o
2 o
1 o
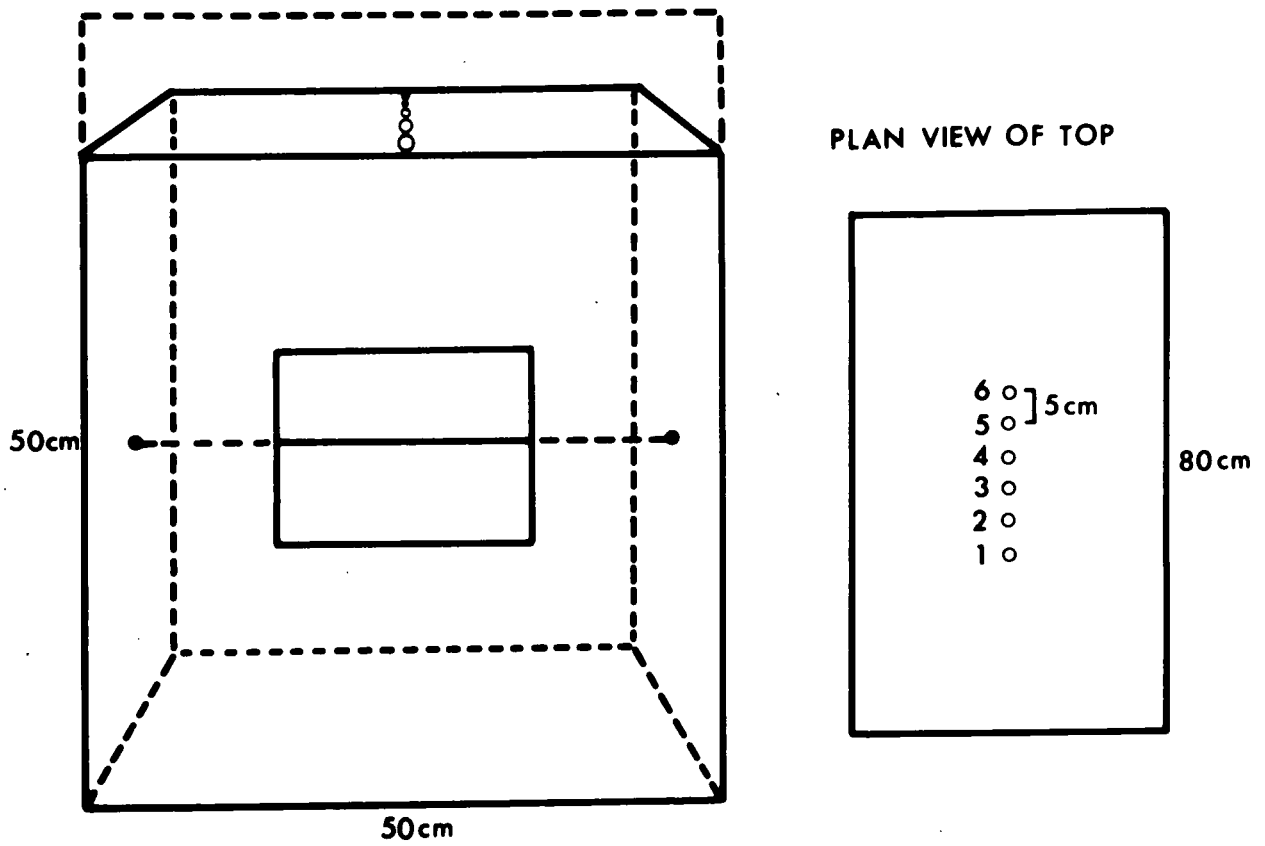
Figure 3.1.

Apparatus for the falling bead test.  See text for

description.

in the roof of the box. They were arranged centrally
about the mid-frontal plane, such that three were in front
of the vertical plane incorporating the wire, and three
were behind it. Thus the centres of the holes were 25,
75 and 125 mm. in front of or behind the plane of the white
wire. The base of the box was damped to prevent bouncing
and ramped so that the beads rolled into a trough at the
back of the box where the experimenter could retrieve them
for further use. The aperture at the front of the box
concealed all inner surfaces and corners from the subject's
view. A small screen concealed the experimenter's hand.

Procedure

The subject was seated 1 m. from the front of the box, with
the white wire at eye level. Room illumination was reduced
to a minimum with black-out blinds, and the subject was
given 10 mins. to dark adapt. He/she was instructed to sit
perfectly still throughout the experiment, and to watch the
central area of the white wire with both eyes open. The
experimenter stood at the side of the box and dropped the
beads, singly, through the holes in the roof. The subject
was required to detect whether each bead had passed in front
of or behind the wire, and to respond "front" or "back"
accordingly. Each drop was preceded by a warning so that
the subject was always ready to watch. Six practice trials
preceded the experimental block of 36 trials, in which the
6 holes were used in random order. Responses were recorded
as correct or wrong on a 6 x 6 grid, each hole being used
6 times. After the experimental trials subjects were
asked to report on the cues they felt they had been using
to make their decisions.

| HOLE | 1 | 2 | 3 | 4 | 5 | 6 | |
|---|---|---|---|---|---|---|---|
| ERROR SCORE | 3 | 2 | 1 | 1 | 2 | 3 | |
| TRIALS | | | | | | | |
| 1 | ✓ | ✓ | x | ✓ | ✓ | ✓ | |
| 2 | ✓ | x | ✓ | ✓ | ✓ | ✓ | |
| 3 | ✓ | x | ✓ | ✓ | ✓ | ✓ | |
| 4 | x | ✓ | x | ✓ | ✓ | ✓ | |
| 5 | ✓ | x | x | x | ✓ | ✓ | |
| 6 | x | x | x | ✓ | x | ✓ | |
| NO. OF ERRORS | 2 | 4 | 4 | 1 | 1 | 0 | |
| ERRORS SCORE | 6 | 8 | 4 | 1 | 2 | 0 | Σ = 21 |

Table 3.1.

Sample score sheet from falling bead experiment.

## Results

Performance on the bead test was evaluated by means of an error score. This was computed by giving each wrong response a weighted score according to the hole position it occurred in. Thus the distance of the hole from the wire was taken into account. The two easiest holes (1 and 6) scored 3 and the two hardest ones (3 and 4) scored 1. Maximum error score possible was 72, and chance level performance, that is three errors for each hole, would produce an error score of 36. (See Table 3.1).

Table 3.2 shows the monocular acuities and bead test error scores for each subject. Snellen acuity is given as the reciprocal of the Snellen fraction, in decimal form which is conventionally assumed to represent resolution in mins. of arc (Ogle, 1962a). Subjects are divided into 3 main groups: amblyopes, myopes and emmetropes, as defined previously. Acuity-matched pairs of amblyopes and myopes are listed adjacent to each other in their respective columns. Strabismics are listed seperately.

<u>TABLE 3.2</u>  (Continued overleaf)

| | AMBLYOPES | | | | ACUITY-MATCHED MYOPES | | |
|---|---|---|---|---|---|---|---|
| NAME | BETTER ACUITY | WORSE ACUITY | ERROR SCORE | NAME | BETTER ACUITY | WORSE ACUITY | ERROR SCORE |
| HE | 0.7 | 1.5 | 32 | JP | 0.7 | 2.0 | 3 |
| MB | 0.7 | 3.0 | 19 | GR | 0.7 | 4.0 | 8 |
| MR | 0.8 | 1.0 | 11 | UP | 0.8 | 1.0 | 25 |
| AM | 0.8 | 1.5 | 10 | PE | 0.8 | 1.0 | 22 |
| PS | 0.8 | 2.0 | 36 | SC | 0.8 | 2.0 | 33 |
| BC | 1.5 | 2.0 | 10 | CS | 1.0 | 2.0 | 11 |
| ME | 1.5 | 3.0 | 22 | JC | 1.0 | 4.0 | 13 |

TABLE 3.2 Continued

| EMMETROPES | | | | STRABISMICS | | | |
|---|---|---|---|---|---|---|---|
| NAME | BETTER ACUITY | WORSE ACUITY | ERROR SCORE | NAME | BETTER ACUITY | WORSE ACUITY | ERROR SCORE |
| DB | 0.7 | 0.8 | 4 | GD | 1.0 | 1.5 | 7 |
| BO | 0.7 | 1.0 | 17 | MS | 1.5 | 20.0 | 39 |
| CJ | 0.7 | 0.7 | 9 | | | | |
| BM | 1.0 | 1.0 | 36 | | | | |
| AP | 0.7 | 0.8 | 15 | | | | |
| SP | 1.0 | 1.0 | 5 | | | | |
| MS | 0.7 | 1.0 | 6 | | | | |

Table 3.3 shows correlation coefficients (Spearman $\rho$) between worse eye acuity and error score for each subject group and for all subjects together, none of which reach significant levels.

TABLE 3.3

| GROUP | SPEARMAN $\rho$ |
|---|---|
| AMBLYOPES | 0.24 |
| MYOPES | -0.47 |
| EMMETROPES | 0.24 |
| ALL INCLUDING STRABISMICS | 0.24 |

Fig.3.2 shows the same comparison as a scatter plot. Comparisons of error scores between groups are shown in Table 3.4. The only difference approaching significance is that between amblyopes and emmetropes.
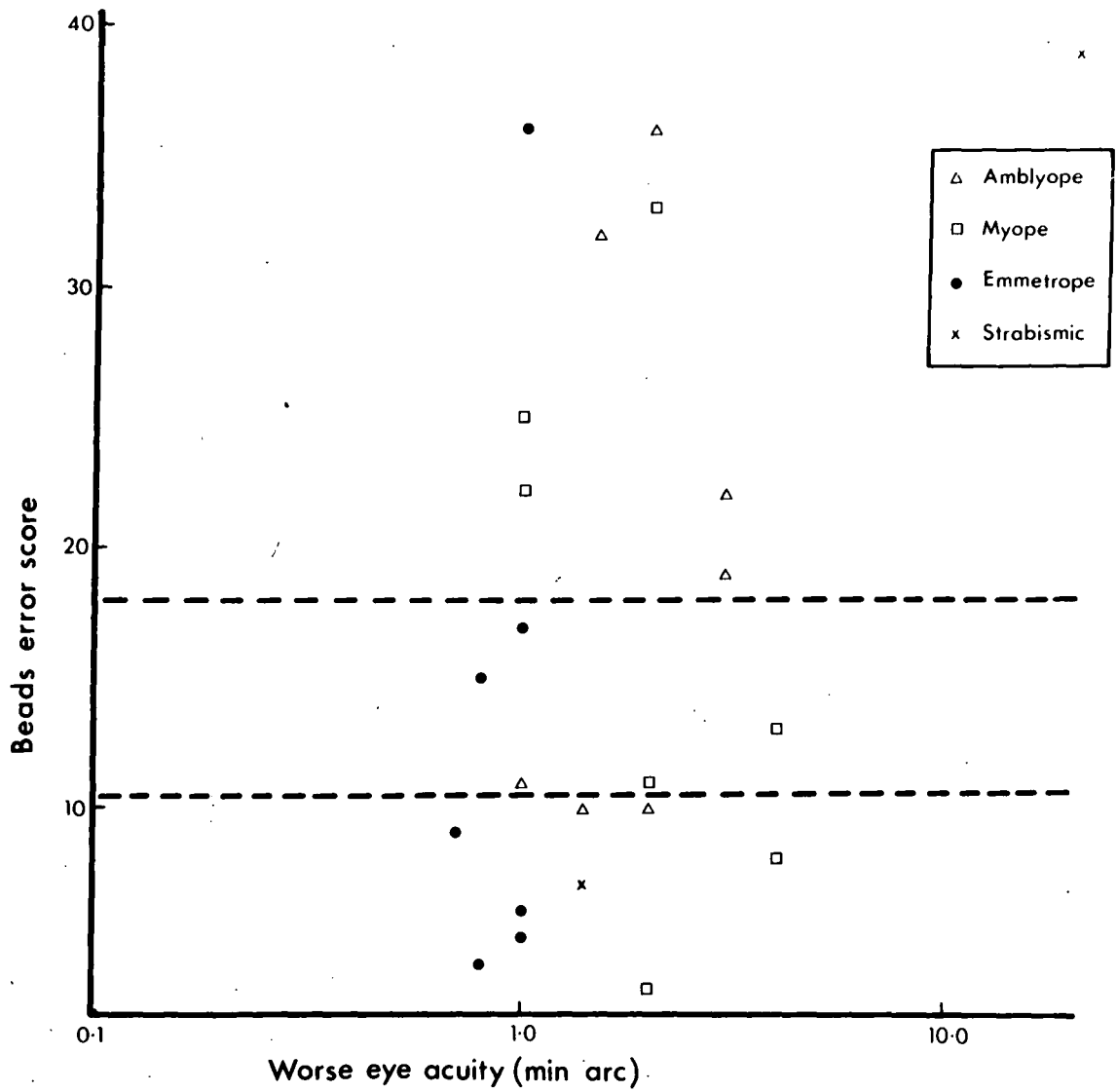
Figure 3.2.

Scatter plot of error scores on falling bead test against worse eye acuity.

## TABLE 3.4

| GROUPS | STATISTIC | SIG. LEVEL |
|---|---|---|
| AMBLYOPES VS MYOPES | WILCOXON T = 12 | NOT SIGNIFICANT |
| MYOPES VS EMMETROPES | MANN WHITNEY U = 20.0 | P = 0.31 |
| AMBLYOPES VS EMMETROPES | MANN WHITNEY U = 20.5 | P = 0.08 |

Table 3.5 classifies the cue descriptions of each subject into six catagories.  These were as follows:

1) Watching the central portion of the wire and noting whether it disappeared momentarily as the bead passed, in which case they responded "front".

2) Noting the apparent diametrical difference between nearer and further beads.

3) Noting the different luminances which resulted from front beads being nearer to the light source than back beads.

4) Noting the different times taken for beads to traverse the aperture.  Front beads appeared to be travelling faster than back beads because a shorter portion of their descent was visible.

5) Some subjects were unable to explain how they had arrived at their decisions even though they had found the task easy.

6) Some subjects admitted that they found the task impossible and had resorted to guessing.

In Table 3.5 these cues are given names, which are self-explanatory.  Some subjects reported using more than one cue.

TABLE 3.5

| NAME | CUES | OVERLAY | SIZE | ILLUM- INATION | MOTION | NO CONSCIOUS STRATEGY | GUESS |
|---|---|---|---|---|---|---|---|
| **AMBLYOPES** | | | | | | | |
| HE | | | | | | | X |
| MB | | X | | | | | |
| MR | | X | X | | | | |
| AM | | | | | | X | |
| PS | | X | | | | | |
| BC | | | | | | X | |
| ME | | X | | | | | |
| **MYOPES** | | | | | | | |
| JP | | | | | | X | |
| GR | | | | | | X | |
| UP | | X | | | | | |
| PE | | X | | | | | |
| SC | | X | | | | | |
| CS | | X | | | X | | |
| JC | | | X | X | X | | |
| **EMMETROPES** | | | | | | | |
| DB | | | | | | X | |
| BO | | | X | X | | | |
| CJ | | | | | | X | |
| BM | | X | | | | | |
| AP | | | X | X | X | | |
| SP | | | | | | X | |
| MS | | | | | | X | |
| **STRABISMICS** | | | | | | | |
| GD | | | | | | X | |
| MS | | | | | | | X |

The cue classification was simplified into 4 groups to facilitate analysis and Table 3.6 shows bead test error scores as a function of cue employed, and ocular defect.

## TABLE 3.6

| GROUP | AMBLYOPES | MYOPES | EMMETROPES | STRABISMICS |
|---|---|---|---|---|
| CUE | | | | |
| OVERLAY ONLY | 19, 36, 22 | 25, 22, 33 | 36 | |
| NO CONSCIOUS STRATEGY | 10, 10 | 3, 8 | 4, 5, 9, 6 | 7 |
| SEVERAL CUES | 11 | 11, 13 | 17, 15 | |
| GUESS | 32 | | | 39 |

Comparison of the error scores in the three main cue categories (omitting the two guessers) showed a very significant difference between categories.

## TABLE 3.7

| | MANN-WHITNEY U | P |
|---|---|---|
| OVERLAY X NO STRATEGY | 1.0 | $< 0.001$ |
| NO STRATEGY X SEVERAL | 0 | $< 0.001$ |
| OVERLAY X SEVERAL | 5 | 0.015 |

Histograms in figs.3.3, 3.4, and 3.5 illustrate the error patterns grouped according to cue category. Ocular defects and error scores are included. The differences between the three groups are also delineated by dotted lines in fig.3.2.

## Discussion

Performance of the dropped-bead test appears to be independent of worse-eye-acuity (fig.3.2 and Table 3.3). Neither is it determined by type of ocular defect, since error scores did not differ significantly between amblyopes, myopes and emmetropes (Table 3.4). However, the three main
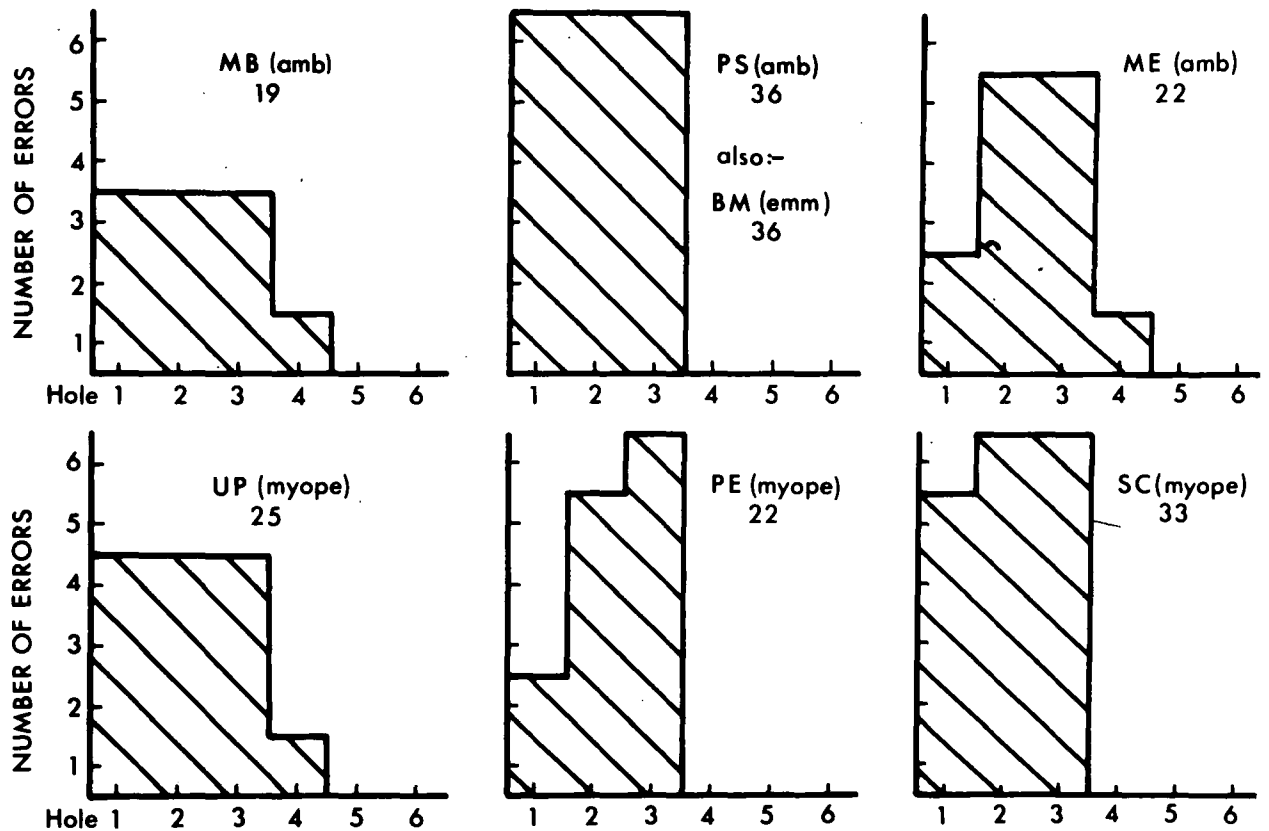
Figure 3.3.

Histograms of errors of subjects who reported using the
overlay cue. Subjects' initials and error scores are also
given, with abbreviated descriptions of their ocular
conditions: KEY    amb = amblyopic

emm = emmetropic

myope = myopic

strab = strabismic

Figure 3.4.

Histograms of errors of subjects who reported using no conscious strategy. See fig. 3.3 for key.

Figure 3.5.

Histograms of errors of subjects who reported using

a variety of cues.  See fig. 3.3 for key.

groups arising from classification according to post-experimental strategy reports (Table 3.6) showed highly significant differences in performance. Subjects using no conscious strategy and unaware of any of the monocular cues per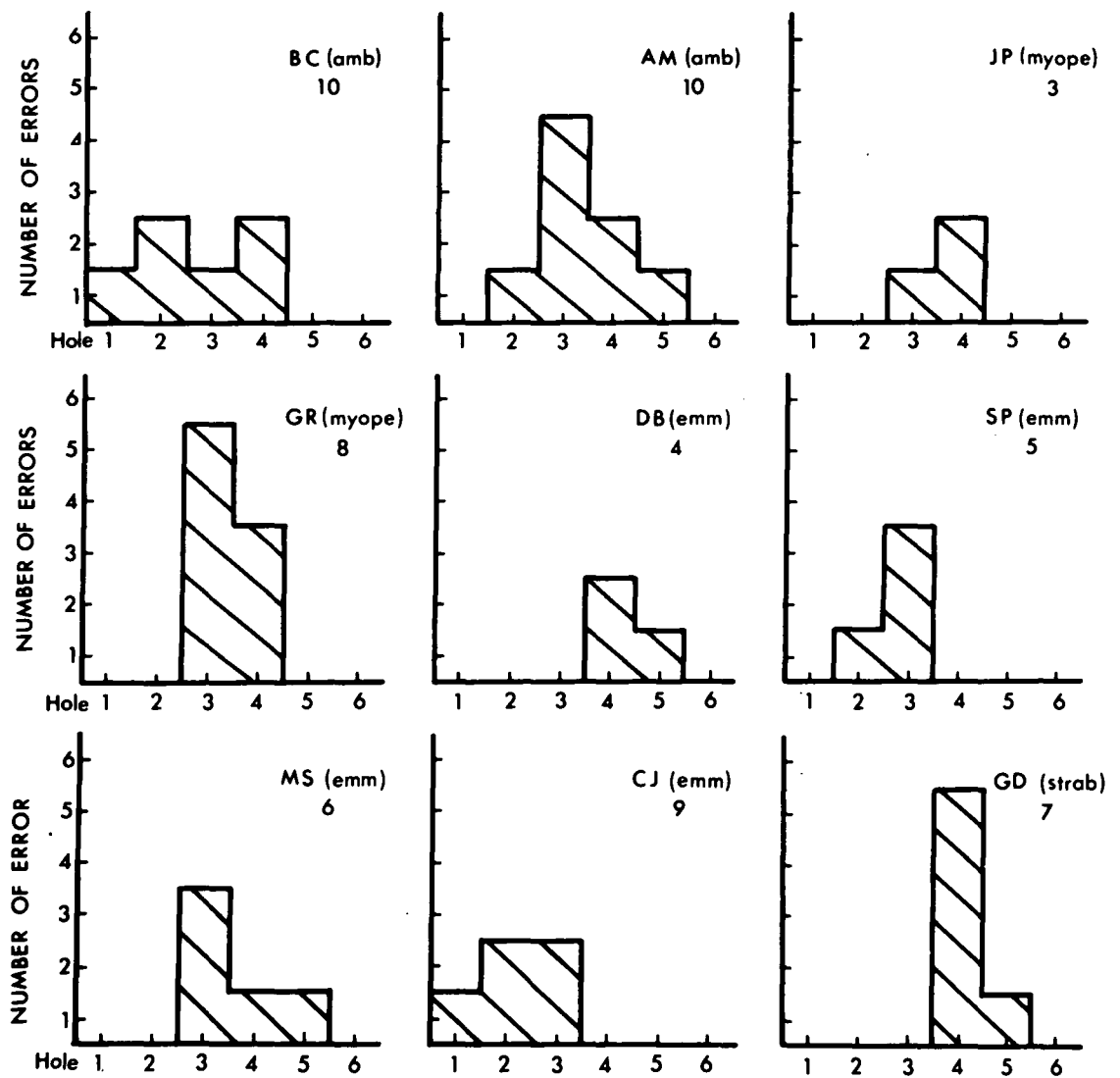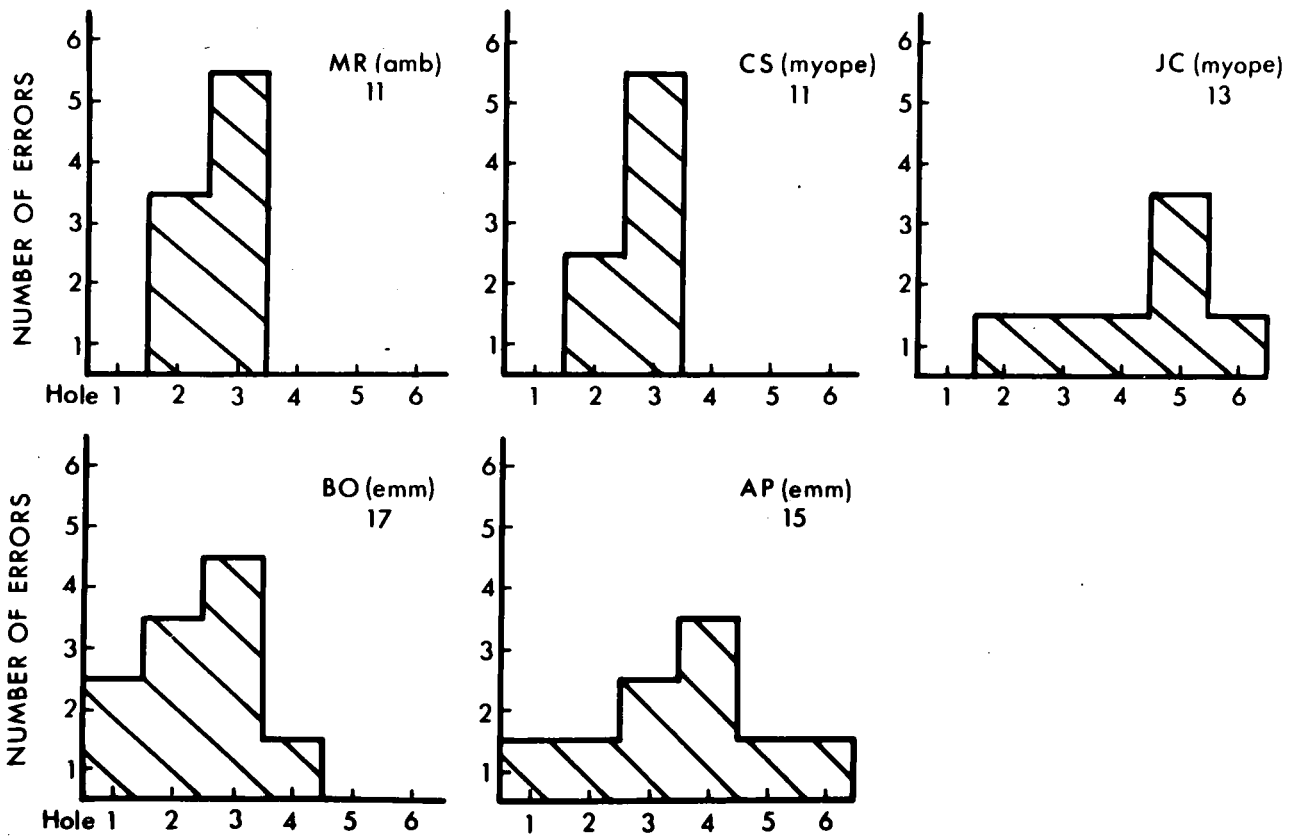formed best. Those relying upon the overlay cue alone performed worst. The intermediate group attempted to use a variety of monocular cues. The high-performance group (using no conscious strategy)show errors clustered around the central (i.e. hardest) holes (fig.3.4). The group using a range of monocular cues show a diversity of error patterns (fig.3.5). The low-performance group, using only overlay, show errors concentrated at holes 1, 2, and 3 (fig.3.3). These subjects were reluctant to respond "front" unless they were sure that the wire had disappeared momentarily behind the bead. In cases of doubt they responded "back". Thus they made few errors on holes 4,5 and 6. The two guessers (one strabismic amblyope and one strabismic non-amblyope) performed around chance levels across all hole positions.

Two members of the overlay strategy group (BM and SC) were asked to repeat the experiment. They were instructed to avoid the overlay strategy and to look for size, illumination and motion cues. Neither of them could comply with these instructions and both re-produced their original error histograms.

Since the only significant determinant of performance seemed to be the cue strategy employed, these were evaluated quantitatively . Both absolute and relative measures were calculated, since the former is relevant to algorithm theories and the latter to proximal stimulus theories.

Attempts to measure the illumination cue were fruitless since the spot matching photometer was not sensitive enough to detect any differences in the luminances of beads at different distances, which all appeared to be around 2 cd/m$^2$.

Table 3.8 shows the angular subtense of a bead at each position, and the difference in angular size between adjacent beads, and the ratio of the angular sizes of each bead to the wire.

Table 3.8

| Position | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Bead subtense (mins arc) | 26.96 | 25.95 | 25.0 | 24.13 | 23.31 | 22.54 |
| Bead: wire ratio | 5.4 | 5.2 | 5.0 | 4.8 | 4.7 | 4.5 |
| Difference between adjacent beads (secs arc) | 61 | 57 | 52 | 49 | 46 | |

Table 3.9 shows the duration of bead visibility for each hole position (calculated with the assumption that air resistance was negligible) and the apparent angular velocity (distance/time) of each bead, based on the angular size of the viewing aperture = 6.867 degrees.

Table 3.9

| Position | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Duration (msecs) | 70 | 73 | 76 | 78 | 81 | 84 |
| Velocity (degs/sec) | 98.1 | 94.1 | 90.4 | 88.0 | 84.8 | 81.8 |

Table 3.10 shows angular disparities between the wire and each bead,                      assuming interpupillary distance

*However it is unlikely that subjects could converge or accommodate precisely on to a featureless horizontal wire, so the usefulness of this disparity cue was probably negligible.

= 60mm. These values also represent the change in
convergence angle required to transfer binocular fixation
from the wire to the bead or vice versa.[*]

Table 3.10

| Position | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Angular disparity (secs arc) | 76 | 44 | 14 | 14 | 39 | 63 |

Several other possible cues were considered: the different
sounds made by beads at different positions when they hit
the base of the box seemed indiscriminable to the
experimenter; the sound of the beads rolling backwards
into the trough was inaudible so the duration of roll
could not have been a cue; the beads made no sound when
they fell into the trough because it was lined with foam
rubber; the beads had very smooth surfaces so there was
no texture cue.

Algorithm theories would suggest that one or more of the
absolute cues was being used by subjects performing better
than chance. Absolute cues were: size differences between
beads at different positions; differences in the time for
which beads were visible or differences in the apparent
velocity of beads at different positions.

Proximal stimulus theory would suggest that one or more of
the relative or comparative cues was being used by subjects
performing better than chance. Relative cues were: the
size ratio of bead to wire and the disparity in angular
subtense between the bead and wire.

Table 3.11 summarises the magnitudes of differences in
these cues for three pairs of positions:

Table 3.11

| | ABSOLUTE CUES | | | RELATIVE CUES | |
|---|---|---|---|---|---|
| Positions | Absolute size difference (secs arc) | Absolute time difference (msecs) | Apparent velocity difference (degs/sec) | Size ratio difference | Angular disparity (secs arc) |
| 3 and 4 | 52 | 2 | 2.3 | 0.2 | 14 |
| 2 and 5 | 158 | 8 | 9.2 | 0.5 | 39-44 |
| 1 and 6 | 265 | 14 | 16.2 | 0.9 | 63-76 |

The absolute cues required detection of non-simultaneous and often non-consecutively presented stimuli, and would therefore require use of a memory store for size or time or velocity. The existence of a mechanism for size memory is suggested by data from experiments in which familiar size is found to be a cue to spatial configuration (reviewed in Hochberg, 1972, pp 495-6). The literature does not specify the precision of size memory, and presumably it is governed by the degree of familiarity. In this experiment the subjects did not really have time to familiarise themselves with the size of the beads; they were only given six practice trials before beginning the experiment proper, and there did not appear to be an improvement in performance with practice, so the evidence is against the possibility that absolute size difference was a usable cue.

The absolute cue of duration of visibility or apparent velocity is another one which has not been reported in the literature. The differential threshold for stimulus velocity for simultaneously presented stimuli was reported as 1 to 2 mins arc/sec by Aubert (1866) and 30 secs arc/sec by Graham et al (1948). The differences in apparent velocity in this experiment were all much greater than

either of these figures, so despite the fact that stimuli were not simultaneously presented, it seems possible that the absolute temporal cue was usable. The possibility of a relative velocity cue is suggested by Rock, Hill and Fineman's (1968) report of speed constancy, which they found was facilitated by either a frame of reference or knowledge of distance. It was not governed by duration of visibility, but was related in precision to size constancy.

The relative cue of size ratio (bead:wire) did not vary much in this experiment: for the nearest hole the bead was about 5½ times larger than the wire (in angular subtense) and at the farthest hole it was 4½ times larger. As with the absolute size cue, familiarity with the size ratios at different hole positions would be necessary to allow a response decision to be made on this basis alone.

The other relative cue, disparity of angular subtense between the wire and the bead, does not necessarily require familiarity, whether it operates via retinal disparity or via change in convergence angle. However, according to Rashbass and Westheimer (1961) reaction time for disjunctive eye movements is 160 millisec. It is possible that some subjects who reported using a size cue were in fact using this angular disparity cue, and those who were not aware of having used any strategy at all might have been making use of the proprioceptive cue available from convergence angles, or the inter-retinal disparity detector system hypothesised by neurophysiologists (e.g. Barlow, Blakemore and Pettigrew, 1967). (See addition to p.73)

Having considered the various cues available in this experiment, it is necessary to determine why all subjects

with the same visual states did not make equal use of all of them. This question is particularly intriguing for the emmetropic group. The only possible explanatory factor was elicited by further questioning of the subjects: the high-performance group included seven (out of nine) keen sports-players (1 tennis, 5 squash, 1 rugby), while the poor-performance group included only 2 footballers (out of seven). It is impossible to determine whether the poor-performance group's lack of interest in sport was due to their poor space perception, or whether their poor space perception was due to lack of practice in tracking fast-moving balls.

Experiment 3.2: Measurement of space perception with
the three-rods test

## Introduction

The second experiment in which space perception was
investigated (as opposed to stereopsis) was based on
Helmholtz's (1866) three-needle test.  The apparatus to
be described presented subjects with an alignment task
which they attempted both binocularly and monocularly.
The only usable monocular cues were based on size and
luminance gradients.  Binocular disparity and proprioceptive
cues were also available.

The main difference between this experiment and the preceding
one was the reduction in the number of monocular cues
available.  Originally it was intended to eliminate all but
one monocular cue (size gradient), and to evaluate the
relative contributions of this and binocular and
proprioceptive cues to space perception for different groups
of subjects.  But, as described later, elimination of the
luminance gradient cue proved impossible, so the experimental
task provided two monocular cues.

The results of this experiment were presented originally in
Kani (1978).

## Subjects

The 23 subjects used in the previous experiment were
supplemented by one further amblyope, making a total of 8
amblyopes and 16 non-amblyopes.  Each amblyopic subject
was matched for visual acuities with a non-amblyopic subject,
as in the previous experiment.  The remaining eight non-
amblyopes formed a third group whose acuities covered a wide
range.  The two strabismic subjects without amblyopia were
not classified seperately (as in the last experiment) but
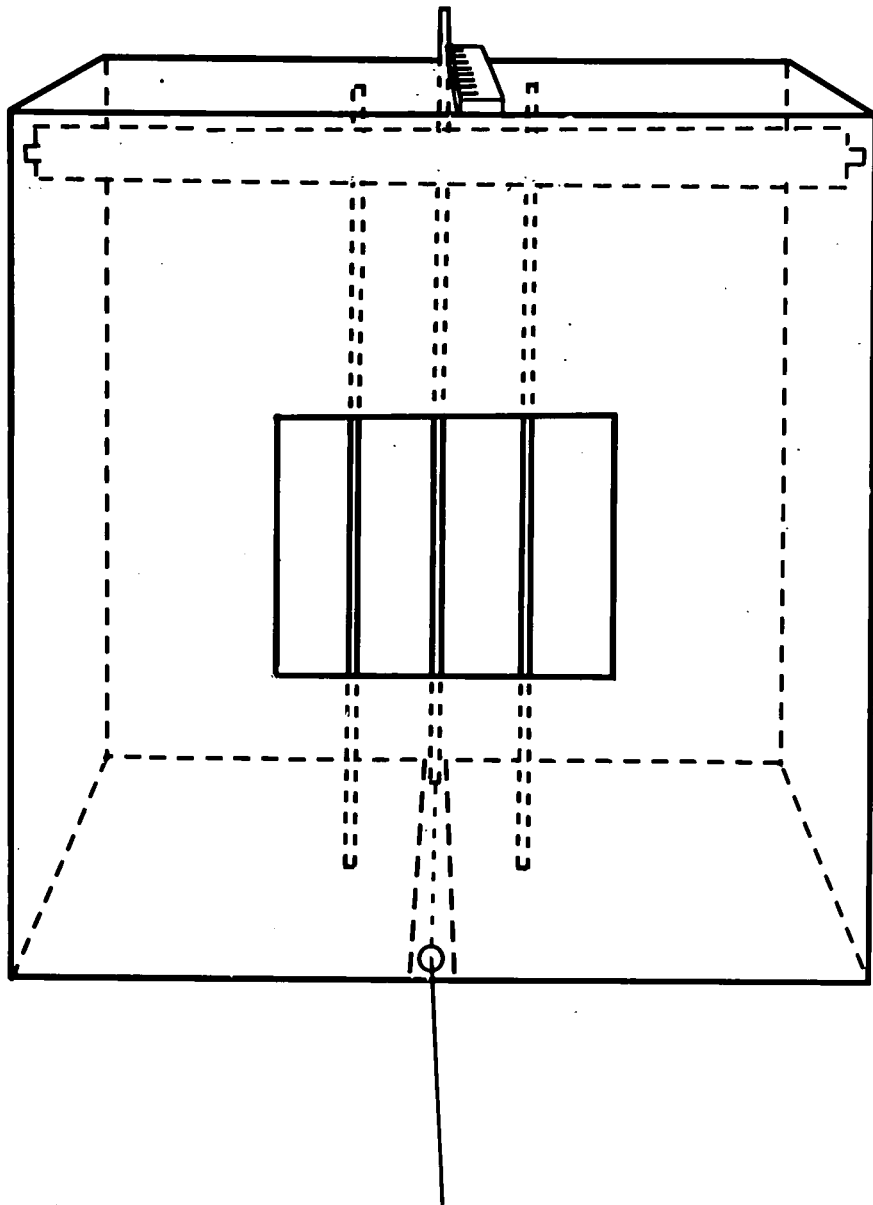were simply treated as non-amblyopes.  Consequently some

Figure 3.6.

Apparatus for the three rods test.

See text for despription.

of the acuity-matched pairs differ from those used in the previous experiment.

Apparatus

The three-rods apparatus used is shown in fig. 3.6. The two outer white rods were fixed inside the black box, (50 x 50 x 70 cm) and the central white rod was free to travel sagittally in a groove in the base of the box. The position of the central rod was indicated by the pointer attached to it which protruded through a slit in the top of the box. A millimetre scale lay along the slit so that the position of the pointer could be precisely recorded. The box was internally illuminated by a fluorescent tube in the upper front corner. All interior surfaces were painted black, and the luminance of the box interior was about 1.5 cd/m$^2$. The mobile central rod was attached to a pulley system such that it could either be pulled forward by a subject, or allowed to slide backwards under the weight of the pulley system.

The diagram shows the subject's view of the apparatus. The ends of the three-rods were not visible through the rectangular frontal aperture at any time.

In designing the three-rods apparatus it became apparent that the central rod's position along the sagittal axis determined its luminance: as it approached the front of the box, where the light source was situated, it appeared brighter. This cue could be utilised in making alignments by matching the luminance of the mobile central rod to that of the two fixed rods.

To assess the effect of this cue 12 subjects performed the three-rods test twice, on two slightly different versions of the apparatus. One version was exactly as described above. The other had all interior surfaces of the box

painted white except the back wall which was black, to provide a background for the white rods.  This increased the amount of internal reflection from walls and minimised the directionality of illumination within the box.  Internal luminance was about 2.5 cd/m$^2$.

## Procedure

Subjects were seated six metres away from the apparatus with instructions to keep as still as possible, thus minimising the motion parallax cue.  For each trial the subject was required to align the central mobile rod with the two fixed rods twice.  The first alignment was made by pulling the rod forwards with a single smooth movement. The position of the pointer was then recorded by the experimenter and the subject was instructed to prepare for the second alignment by pulling the central rod right up to the front of the box.  The second alignment was made by allowing the rod to regress under the weight of the pulley system, again with a single smooth movement.  The new position of the pointer was recorded, and the subject was instructed to prepare for the next trial by allowing the rod to return to the back of the box.  There were no time constraints imposed upon the trials.  Pointer positions were recorded as errors in mms.  (i.e. distance from the correct alignment position).  Six trials (pairs of alignments) were made in each of four conditions in the following order:

Condition 1 = Both eyes open, room lights on (illuminance = 174 lux )

Condition 2 = Only RE open, room lights on  (illuminance = 174 lux )

Condition 3 = Only LE open, room lights on  (illuminance = 174 lux )

Condition 4 = Both eyes open, room lights off (illuminance <0.01 lux)

Thus each subject made a total of 48 alignments.

Results

Table 3.12 shows Snellen acuities, converted to minutes of arc for all subjects. The three columns distinguish the subject groups 1) amblyopes; 2) non-amblyopes with acuities closely matched to those of the amblyopes, matched pairs being adjacent in columns 1 and 2 of the table; 3) non-amblyopes with a wide range of acuities. In each group subjects are listed in order of decreasing better eye acuity.

Table 3.12    (Continued overleaf)

| | Amblyopes | | | Non-amblyopic acuity-matches | |
|---|---|---|---|---|---|
| Name | Snellen acuity (min arc) | | Name | Snellen acuity (min arc) | |
| | Better eye | Worse eye | | Better eye | Worse eye |
| HE | 0.7 | 1.5 | JP | 0.7 | 2.0 |
| CJ | 0.7 | 1.5 | IM | 0.7 | 1.5 |
| MB | 0.7 | 3.0 | GR | 0.7 | 4.0 |
| MR | 0.8 | 1.0 | UP | 0.8 | 1.0 |
| AM | 0.8 | 1.5 | PE | 0.8 | 1.0 |
| PS | 0.8 | 2.0 | SC | 0.8 | 2.0 |
| BC | 1.5 | 2.0 | GD | 1.0 | 1.5 |
| ME | 1.5 | 3.0 | CS | 1.0 | 2.0 |

Table 3.12 (continued)

Other non-amblyopes

| Name | Snellen acuity (min arc) | |
|------|------------|-----------|
|      | Better eye | Worse eye |
| DB | 0.7 | 0.8 |
| BO | 0.7 | 1.0 |
| MS | 0.7 | 1.0 |
| JC | 1.0 | 4.0 |
| BM | 1.0 | 1.0 |
| SP | 1.0 | 1.0 |
| SD | 1.0 | 2.0 |
| MS | 1.5 | 20.0 |

Table 3.13 shows the errors, in cms, made by each subject
on the white painted version of the three-rods apparatus.
Subjects are grouped as in the preceding table.  The first
four columns of errors in each group's data shows the means
of errors made on the 12 trials in each of the four
conditions.  These are headed C.1, C.2, C.3 and C.4.  Means
of errors made in all 48 trials are also given, both in cms
and in seconds of arc of disparity between the angle
subtended by the mean selected position of the central rod
and the angle it would subtend if correctly positioned, in
alignment with the fixed rods.  This angular disparity is
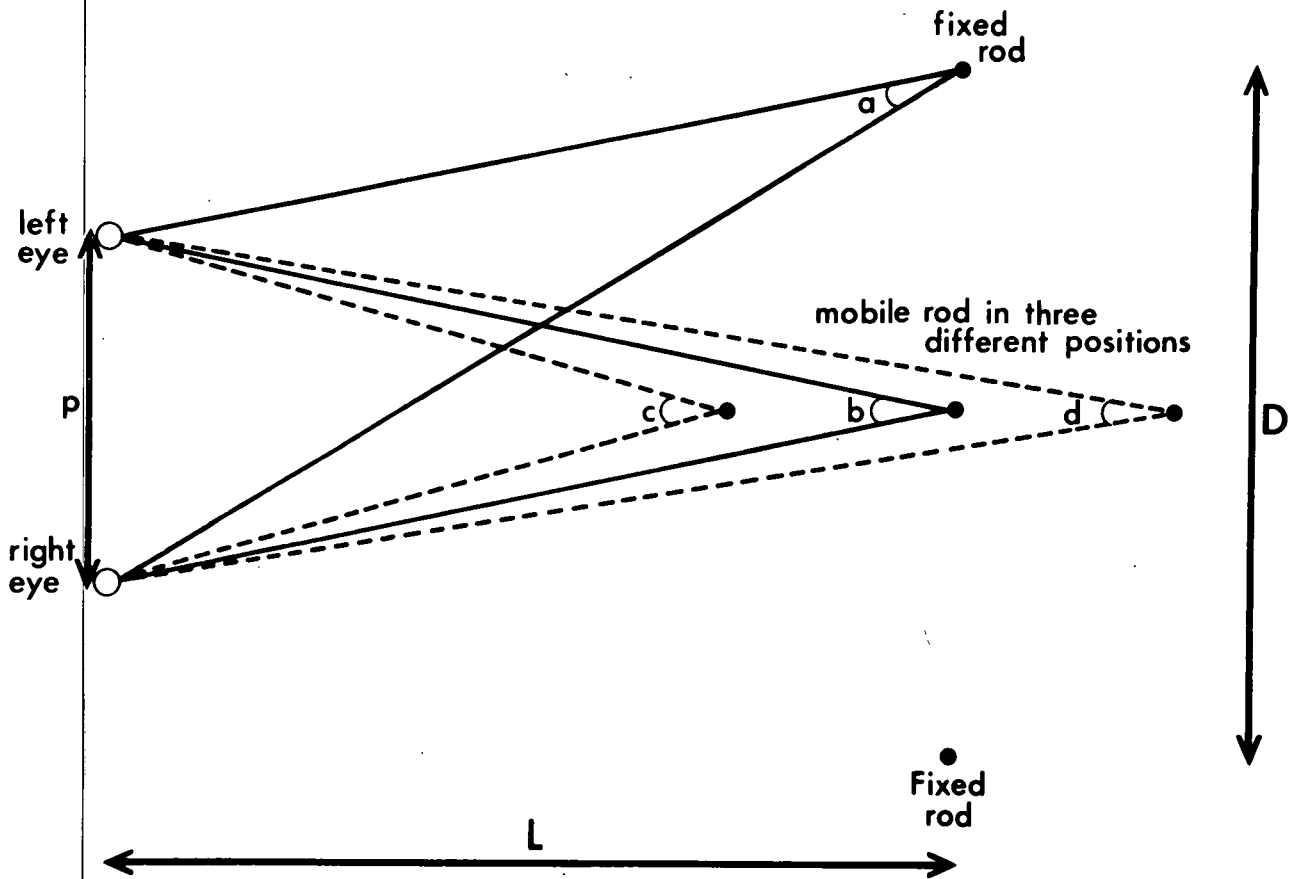illustrated in fig. 3.7.

Figure 3.7.

Diagram showing the angular disparity cue in the

three rods test.

KEY  p = interpupillary distance; assumed to be  60 mm.

L = distance from eyes to fixed rods = 6350 mm.

D = distance between fixed rods = 150 mm.

a = angle subtended by the fixed rod = 32.48 min arc.

c = angle subtended by mobile rod when in front of
fixed rods plane.

b = angle subtended by mobile rod when in fixed rods
plane = 32.48 min arc.

d = angle subtended by mobile rod when behind fixed
rods plane.

Table 3.13 (continued overleaf)    84

## Amblyopes

| Three-rods-test errors (mean of 12 trials for each condition in cms.) | | | | Mean error of 48 trials (cms) | Mean error of 48 trials (secs arc) |
|---|---|---|---|---|---|
| C.1 | C.2 | C.3 | C.4 | | |
| 11.70 | 12.30 | 10.07 | 8.89 | 10.74 | 36.5 |
| 0.93 | 5.49 | 5.53 | 1.18 | 3.28 | 11.2 |
| 3.65 | 5.86 | 4.84 | 3.95 | 4.58 | 15.6 |
| 2.33 | 3.43 | 4.83 | 4.36 | 3.74 | 12.7 |
| 4.49 | 6.18 | 7.76 | 4.98 | 5.85 | 19.9 |
| 5.39 | 9.15 | 7.68 | 2.44 | 6.17 | 21.0 |
| 5.07 | 6.26 | 7.52 | 6.15 | 6.25 | 21.3 |
| 5.11 | 5.98 | 5.96 | 2.44 | 4.87 | 16.6 |

## Non-amblyopic Acuity matches

| Three-rods-test errors (mean of 12 trials for each condition in cms.) | | | | Mean error of 48 trials (cms) | Mean error of 48 trials (secs arc) |
|---|---|---|---|---|---|
| C.1 | C.2 | C.3 | C.4 | | |
| 2.11 | 4.73 | 3.22 | 1.18 | 2.81 | 9.6 |
| 2.27 | 3.04 | 3.05 | 3.46 | 2.96 | 10.1 |
| 2.11 | 6.37 | 1.97 | 4.23 | 3.67 | 12.5 |
| 2.29 | 4.21 | 5.09 | 3.01 | 3.65 | 12.4 |
| 6.23 | 7.28 | 6.48 | 3.88 | 6.00 | 20.4 |
| 0.71 | 1.76 | 2.75 | 1.95 | 1.79 | 6.1 |
| 2.23 | 4.10 | 4.70 | 1.80 | 3.21 | 10.9 |
| 2.13 | 3.65 | 1.53 | 3.62 | 2.73 | 9.3 |

.Table 3.13 (continued)

## Non-amblyopes

| Three-rods-test errors (mean of 12 trials for each condition in cms.) | | | | Mean error of 48 trials (cms) | Mean error of 48 trials (secs arc) |
|---|---|---|---|---|---|
| C.1 | C.2 | C.3 | C.4 | | |
| 2.77 | 2.84 | 2.74 | 3.07 | 2.86 | 9.7 |
| 3.09 | 4.64 | 9.24 | 4.23 | 5.03 | 17.1 |
| 2.36 | 2.43 | 3.18 | 2.04 | 2.49 | 8.5 |
| 7.38 | 2.29 | 5.63 | 4.83 | 5.03 | 17.1 |
| 7.18 | 7.10 | 14.94 | 4.60 | 8.46 | 28.8 |
| 1.27 | 3.86 | 5.37 | 1.80 | 3.09 | 10.5 |
| 3.13 | 4.39 | 3.95 | 2.00 | 3.37 | 11.5 |
| 3.73 | 2.24 | 3.39 | 4.10 | 3.37 | 11.5 |

Several different analyses and comparisons were made and these are now described. All given significances are for two-tailed distributions.

## i) Effect of the luminance cue

Fig. 3.8 shows the mean errors, in cms, made by the 12 subjects who were tested on both versions of the three-rods apparatus. Mean errors were significantly greater ($t=3.04$, $0.01<p<0.02$) on the white-painted version in which the luminance cue was smaller due to a reduction in the directionality of illumination.

## ii) Effect of visual acuity

Correlations between acuity and performance on the three-rods-test were not significant for amblyopes or non-amblyopes. They are shown in Table 3.14.
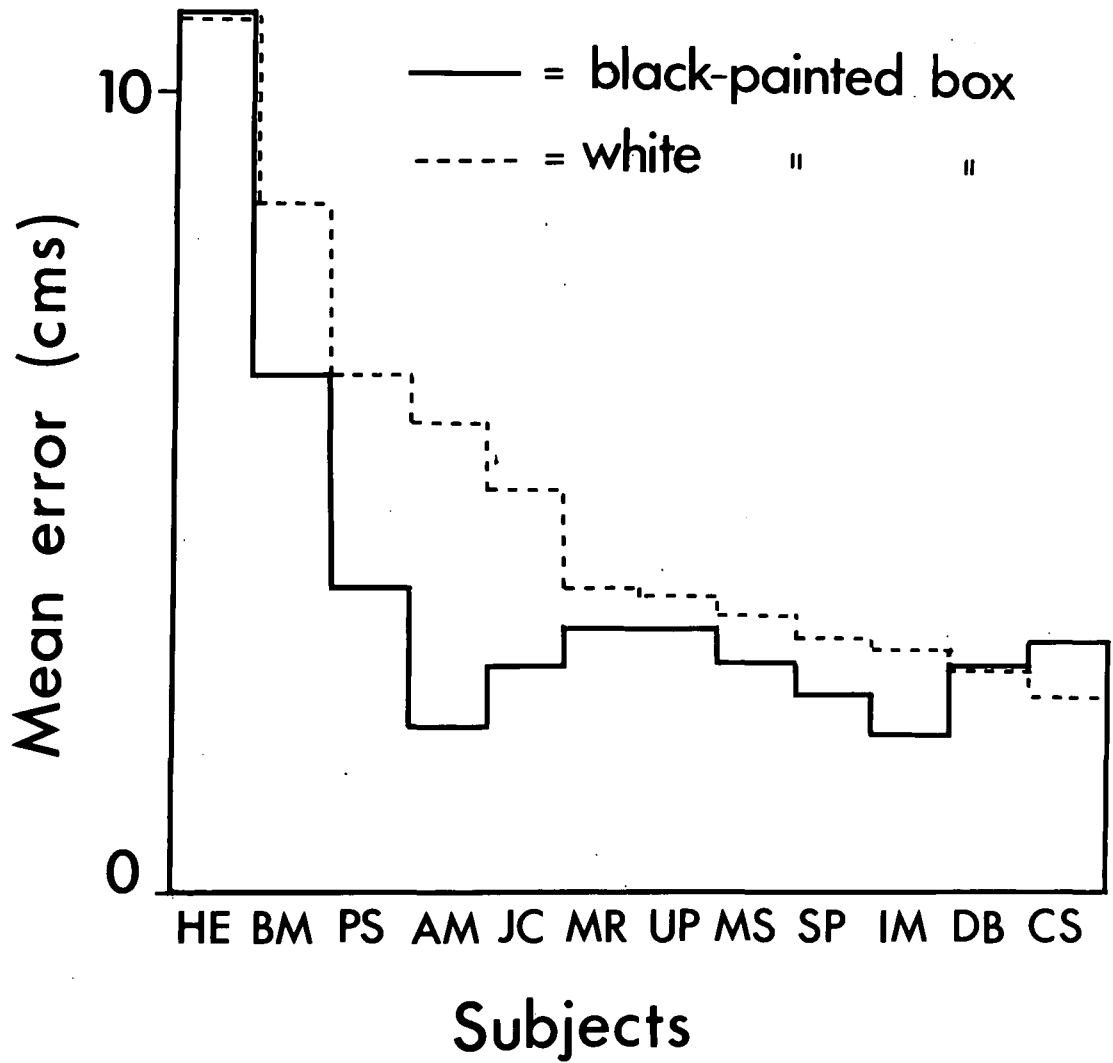
Figure 3.8

Histograms of mean errors on two versions of the three rods test:
with internal walls painted black (solid lines) or white (dotted
lines). Mean errors over 48 trials on each version are shown for
12 subjects.

## Table 3.14

### Spearman correlation coefficients ($\rho$)

Amblyopes
(n = 8)

|  | Overall performance (48 trials) | Monocular performance (12 trials) |
|---|---|---|
| Better eye acuity | 0.24 | 0.10 |
| Worse eye acuity | 0.15 | -0.04 |

Non-amblyopes
(n = 16)

|  | | |
|---|---|---|
| Better eye acuity | 0.23 | 0.13 |
| Worse eye acuity | 0.06 | -0.11 |

## iii) Comparison between test conditions

Better eye performance was compared with worse eye performance, that is conditions 2 and 3 were compared. The worse eye tended to make larger errors than the better eye but the difference did not attain statistical significance (t = 1.4, $0.1 < p < 0.2$). The effect of the level of room illumination was determined by comparing conditions 1 and 4, and these too were not significantly different (t = 0.68, $p \gg 0.3$).

Each subject's better binocular performance (condition 1 or 4) was compared with his/her better monocular performance (condition 2 or 3). Histograms of mean errors, in cms, are shown in figure 3.9. Binocularity improved performance significantly for amblyopes (t = -4.1, $p < 0.01$) and for non-amblyopes (t = -2.4, $0.02 < p < 0.05$). The amount of
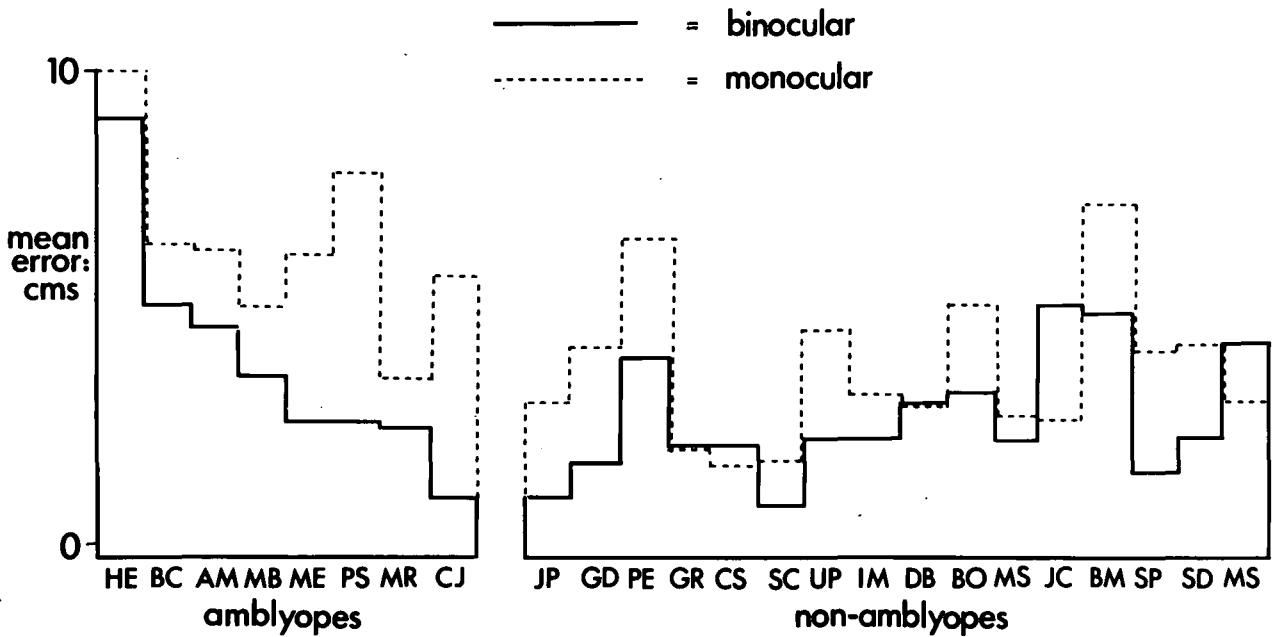
Figure 3.9.

Histograms of mean errors on the three rods test, internal walls painted white, for all 24 subjects. The solid lines show each subject's smaller binocular error (i.e. performance in either condition 1 or 4), and dotted lines show smaller monocular error (i.e. performance in either condition 2 or 3).

improvement, i.e. the reduction in error was calculated for amblyopes and for their acuity-matched non-amblyopic counterparts (subject groups 1 and 2). A comparison of their improvement scores showed no significant difference ($t = 1.4$, $p = 0.2$).

## iv) Effect of amblyopia

Figure 3.10 shows the mean errors, in cms, of amblyopes and their acuity-matched non-amblyopic counterparts. Amblyopes errors were significantly greater ($t = 2.4$, $0.02 < p < 0.05$). However there was no significant difference at the 5% level between their performances in the binocular conditions only ($t = 1.6$).

## Discussion

The precision of alignments in the three-rods-test was found to be independent of visual acuity (see Table 3.14) or room illumination. The latter finding is in conflict with Luria's (1971) report that the presence of peripheral visual information during testing on a similar apparatus enhanced performance, probably by providing cues for more precise accommodation, (Luria and Kinney, 1973). However in the present study a testing distance of 6 metres required very little accommodational effort, whereas Luria's testing distance of 1.5 metres required four times more. Significant determinants of performance were the luminance cue (fig. 3.8), binocularity (fig 3.9) and the type of visual defect (fig. 3.10). Attempts were made to quantify the cues available and these are tabulated below. The changing luminances of the central rod as it travelled through the box could not be measured with the only available spot-matching photometer since the differences were too small. It was therefore impossible to tell
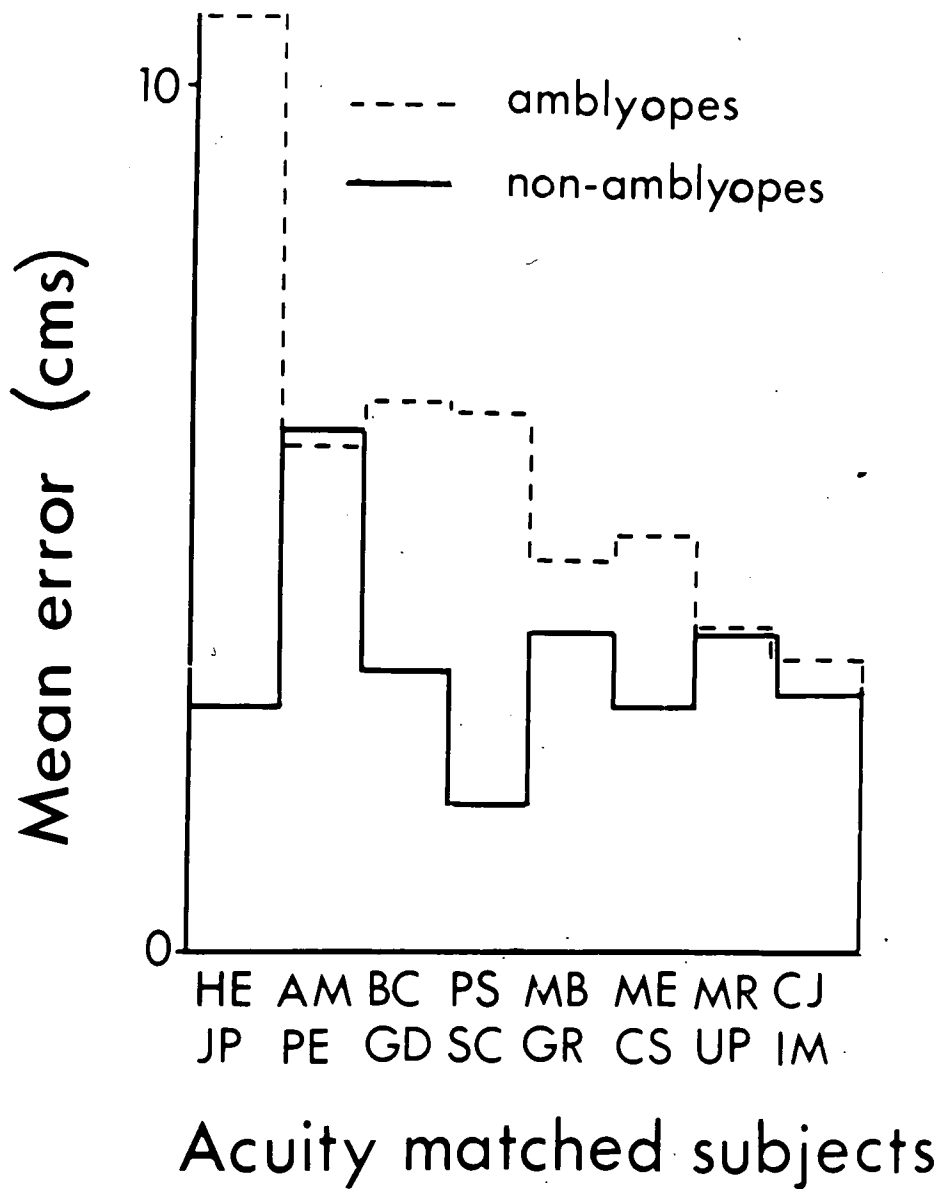
Figure 3.10.

Histograms of mean errors of 16 subjects, presented

as acuity-matched pairs of amblyopes and non-amblyopes.

Mean errors over all 48 trials are plotted for each

subject.

whether the white-painted version of the apparatus still
provided a residual luminance cue, or whether the only
remaining monocular cue was the apparently changing width
of the central rod as it travelled through the box.
The angular subtense of the central rod was calculated for
several positions, as tabulated below.

Table 3.15

| Distance of central rod from subject's eye (metres) | 6.0 | 6.1 | 6.2 | 6.3 | 6.4 | 6.5 | 6.6 | 6.7 |
|---|---|---|---|---|---|---|---|---|
| Angle subtended by central rod at the eye (mins arc) | 4.58 | 4.51 | 4.43 | 4.37 | 4.30 | 4.23 | 4.17 | 4.10 |

The fixed rods each subtended a fixed angle of 4.33 mins arc,
so the monocular cue provided by apparent changes in the size
of the moving rod was extremely small, the largest difference
in apparent size between the fixed and moving rods being
only 15 secs arc.

The binocular angular disparity cue (see fig. 3.7.) was
evaluated, assuming an interpupillary distance of 60mm, and
the change in convergence angle required to shift bifoveal
fixation from a fixed rod to the moving rod in various
positions is tabulated below.

Table 3.16

| Distance of central rod from subject's eye (metres) | 6.0 | 6.1 | 6.2 | 6.3 | 6.4 | 6.5 | 6.6 | 6.7 |
|---|---|---|---|---|---|---|---|---|
| Binocular angular disparity between fixed & moving rods (sec arc) | 114 | 80 | 47 | 16 | 15 | 45 | 74 | 101 |

Thus the binocular cue of angular disparity was approximately 8 times greater than the monocular cue of apparent size change, and this might account for the advantage provided by binocularity, as illustrated in figure 3.9.

The finding that amblyopes' mean errors were significantly greater than those of their acuity-matched non-amblyopic counterparts when all trials were taken into consideration, but not when only binocular trials were compared, suggests that the amblyopes were less able to utilise the available monocular cues than the non-amblyopes, Separate comparisons of their good eye and bad eye mean errors showed that both were signigicantly greater for the amblyopic group (good eyes: t = 2.68; bad eyes: t = 2.69; 0.02<p<0.05).

Levi and Harwerth (1974) reported that amblyopes had abnormal brightness contrast sensitivity at low luminances in an experiment requiring brightness matching of a comparison field presented to one eye and a test field surrounded by an inducing field presented to the other eye. They suggested that amblyopic eyes might have enlarged retinal receptive fields causing abnormal retinal interactions. Some such defect could have prevented the amblyopic group from using any available luminance cue when tested with their amblyopic eyes alone. This explanation does not however account for their poor performance with their non-amblyopic eyes.

The two findings that both groups of subjects gained an advantage from binocularity, and that the matched pairs did not have significantly different errors for binocular trials suggest that amblyopes were able to use binocular cues as well as non-amblyopes. Or that both groups benefited from binocular summation. It is impossible, at this

stage, to determine whether they used retinal disparity, or proprioceptive information from accommodation and convergence, or both.

Comparison of the data obtained in these two experiments will be found later in this chapter, after descriptions of two experiments measuring stereopsis.

## 3.3.2. Experiments to measure stereopsis

## Experiment 3.3: Measurement of stereopsis with
### The Titmus stereotest.

## Introduction

The preceding two experiments have tested the precision of
space perception in two situations.  In the first, a wide
range of cues was available but they were only briefly
visible, and in the second, exposure time was unlimited
but only a few cues were available.  The results of the
first experiment suggested that precision was primarily
dependent upon the subject's use of cues, but no distinction
was found between those cues which non-amblyopes could
detect and those which amblyopes could detect.  In the second
experiment, acuity-matched pairs of amblyopes and non-
amblyopes were found to differ in their ability to perform
an alignment task monocularly.  Their binocular performances
were essentially similar, suggesting that they were making
equal use of binocular cues.  This last result was rather
surprising, since Simons and Reinecke (1974) reported that
amblyopes have no stereopsis, and Blakemore and van Sluyters
(1974) suggested that they have reduced binocularity at
the cortical level.

This experiment required subjects to attempt a widely used
clinical test of stereopsis: the Titmus stereotest (Titmus
Optical Co. Inc., Petersburg, Virginia).  This was the test
used by Simons and Reinecke (1974).  It approaches an ideal
test of stereopsis by presenting the two eyes with two
identical images with a small lateral displacement between
them.  This displacement is interpreted as a disparity cue
which triggers perception of depth in the image.  The only
weakness of the Titmus stereotest lies in the fact that
the lateral displacement can be detected monocularly as a

slight decentring in some of the stimuli.

Some of the data presented here were reported in Kani (1978).

## Subjects

For three years, several undergraduate populations were
screened in order to find amblyopic subjects to take part
in the various experiments described in this thesis.
Anyone with unequal right-eye and left-eye Snellen acuities
was then given a full ophthalmological examination, including
refraction.  From a total of about 250 undergraduates
screened, the following subjects took part in this experiment:
28 non-amblyopic anisometropes, 4 non-amblyopic strabismics
and 10 amblyopes.  A further 11 amblyopes obtained from
other sources (eye hospital, ophthalmic practice and chance
encounters) also participated.  Amblyopic subjects wore
full optical corrections during this experiment and non-
amblyopes were tested either with or without optical
corrections depending upon their normal wearing habits.

## Apparatus and Procedure

The Titmus stereo-test stimuli are ten pairs of superimposed
Polaroid images.  When  viewed through a pair of special
Polaroid spectacles, in which the two lenses are orthogonally
orientated Polaroid material, each eye sees only one of the
pair of images.  There is a small lateral displacement
between the two images in each pair which translates to a
small horizontal inter-retinal disparity.  Ten different
degrees of disparity are presented in the 10 test targets.
Each stimulus (pair of images) shows a cluster of four rings,
one of which is laterally displaced so that it appears, to
a viewer with stereopsis, to be in a plane above the plane
of the page.

Subjects viewed the test from 33 cms in a normally
illuminated room (174 lux) and were required to make a
forced choice between the four rings in each stimulus
to report the position in the cluster of the 'raised'
ring.  Subjects who claimed they were unable to detect
a raised ring were encouraged to guess.  All subjects
started with the stimulus with the largest lateral
displacement, and proceeded through the series in order
of decreasing displacement.

The Titmus stereotest instruction manual specifies the
displacement in each stimulus in seconds of arc, for a
testing distance of 33 cms.  The last correctly located
raised ring was taken to represent each subject's stereopsis
threshold, which was recorded in secs arc, and this value
will be referred to as Titmus stereo-acuity.

Results

Titmus stereo-acuities in secs arc are plotted against
worse eye Snellen acuities in mins arc in figure 3.11.
Clearly, the amblyopes performed much less well on the
Titmus test than the non-strabismic non-amblyopes ($z = -6.2$,
$p \ll 0.0003$, from Mann-Whitney U test).  Correlations
between worse eye Snellen acuity and Titmus stereo-acuity
were:- amblyopes: Spearman $\rho = 0.015$; non-strabismic
non-amblyopes: Spearman $\rho = 0.258$, neither of which is
significant at the 5% level.

Discussion

There are some noteworthy points in fig 3.11:  two of the
non-amblyopic strabismics whose Titmus stereo-acuities
are as bad as those of most of the amblyopes both had
marked alternating exotropia with hypertropia, and the
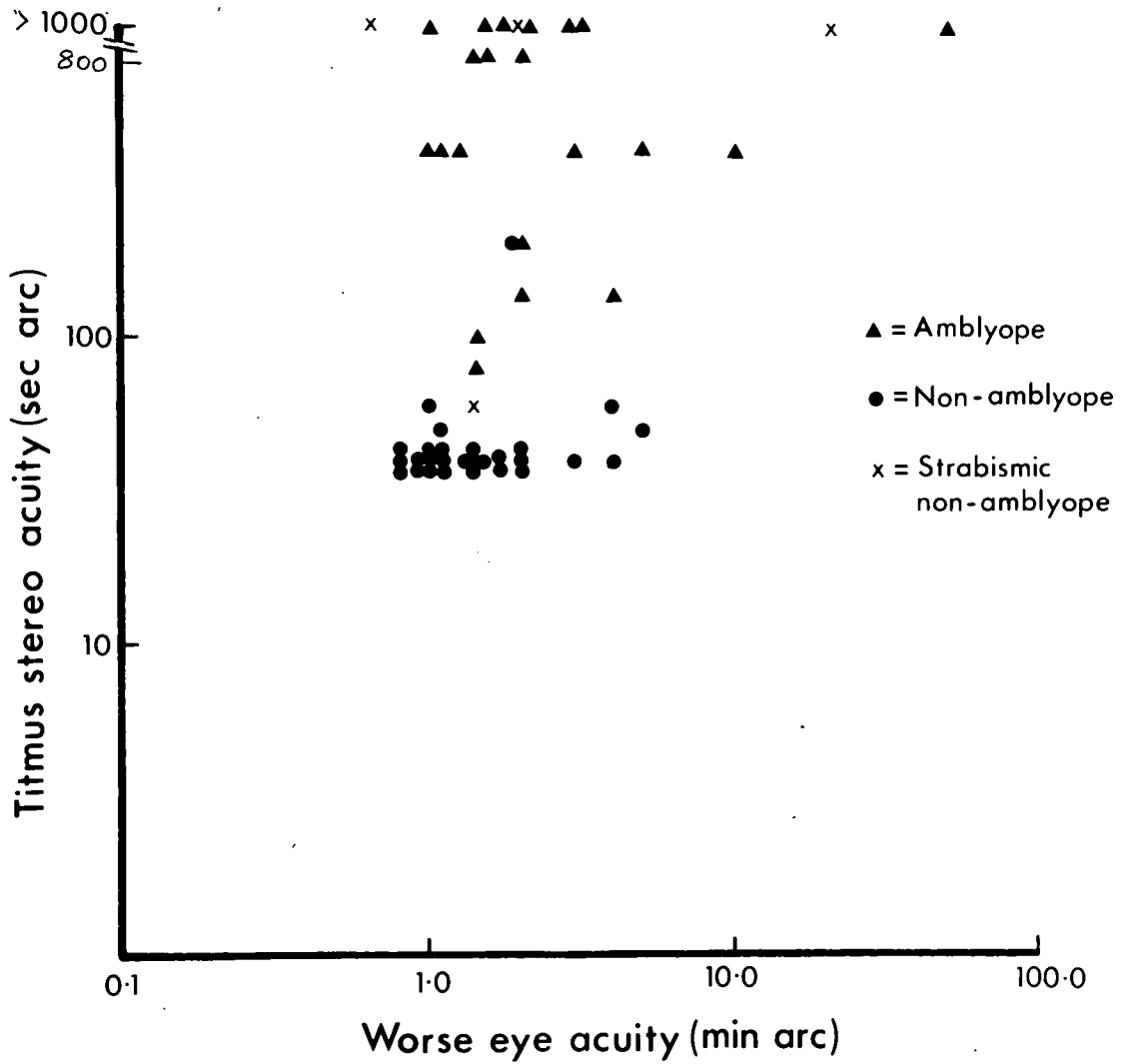third had a large esotropia.  Consequently, they were not

Figure 3.11.

Scatter plot of Titmus stereo-acuity against worse eye

Snellen acuity.

The ordinate is broken above 800 sec arc because this was the

largest disparity used.  Subjects not detecting any disparity are

shown at > 1000 sec arc.

able to fixate anything bifoveally at any fixation distance. The fourth non-amblyopic strabismic, whose stereo-acuity is high, had a noncomitant intermittent esotropia caused by a partial third nerve palsy which only affected the left eye's lateral and medial recti. He was capable of bifoveal fixation and coordinated binocular eye movements within a central visual field of about 5 degrees radius. Outside this area his stereo-acuity fell to < 800 sec arc. All three of these subjects had equally high right-eye and left-eye Snellen acuities so they were not amblyopic, but their responses to stereoscopic tasks were identical to those of amblyopes if the stimuli were presented to non-binocular parts of their visual fields.

Four amblyopes achieved Titmus stereo-acuities better than 400 secs arc, but on questioning they all admitted using the monocular cue of lateral displacement to facilitate their forced-choice responses. This tactic could produce erroneous diagnosis in a clinical situation, and as Simons and Rienecke (1974) concluded, the presence of the monocular cue of lateral displacement detracts from the reliability of the Titmus stereo-test as a screening device for amblyopia or stereo-blindness.

The failure of this study to find significant correlations between stereo-acuity and Snellen visual acuity conflicts with Levy and Glick's (1974) finding of a linear correlation (r = 0.83, N = 10). Their subjects were all non-amblyopes who could detect the apparent depth in the most difficult Titmus stimulus when fully corrected optically. They were tested with various degrees of monocular blurring by convex lenses. This artificially-induced myopia degraded their stereo-acuity linearly. In Levy and Glick's study

visual acuities were not measured on a standard Snellen chart but on a reduced chart at 35 cms, the distance at which they administered the Titmus stereo-test. In the present study Snellen acuities were measured at 6 metres, and since most of the non-amblyopic subjects were myopes their visual acuities at this distance were considerably worse than their acuities at the Titmus testing distance of 33 cms. Only those with more than 3 DS of myopia would be expected to have reduced visual acuity at 33 cms, and since most of the non-amblyopic group were less myopic than this, their Titmus stereo-acuities were unaffected.

The worst Titmus stereo-acuity obtained by a non-amblyopic subject was 200 sec arc; this subject had myopic astigmatism in both eyes which her glasses did not fully correct. With full optical correction her Titmus stereo-acuity improved to 100 secs arc, which is still lower than any other non-amblyope, even though her Snellen acuities were both better than 6/6.

Further discussion of the results of this experiment will follow after the fourth experiment has been described.

Experiment 3.4.   Measurement of stereopsis with the
                         TNO test

## Introduction

The TNO test is another stereopsis testing device designed

for clinical use.   It differs from the Titmus stereotest

in one important respect, which is that the two eyes are

dissociated by anaglyph presentation of random dot patterns,

so that there is no monocular information available to

either eye.   Thus it constitutes a test of pure stereopsis:

the ability to perceive depth from binocular disparity cues

alone.

## Subjects

The TNO test was difficult to obtain because when this

study was started it was not widely used by clinicians.

Consequently the total subject pool employed for the

preceding study was no longer available for testing.   The

remaining 26 subjects were: 16 amblyopes, 3 strabismic

non-amblyopes, and 7 other non-amblyopes.

## Apparatus and Procedure

The TNO test stimuli comprise pairs of red and green

anaglyphs which are viewed through red/green spectacles.

Monocularly, each anaglyph appears to be a random speckled

pattern.   When viewed binocularly by a subject with stereopsis,

a lateral shift which is incorporated in each pair provides

a binocular disparity cue which results in perception of a

raised area.   The TNO test begins with three screening

plates in which the lateral shift produces a binocular

disparity of about 33 mins arc at a testing distance of 40

cms.   A series of graded test plates follow, in which the

disparities range from 8 mins arc to 15 secs arc.   For the

screening plates the subject is required to detect the

location of certain specified shapes which should appear

raised above the plane of the plate. In the series of test plates one shape is repeated at different orientations, and the subject is required to report the orientation. Only four orientations are used in the 12 test plates.

As before, amblyopes were tested with their full optical corrections and non-amblyopes were tested either with or without their optical corrections, according to their normal wearing habits. The red/green spectacles were worn on top of ordinary spectacles, rather than vice versa, so that the distance between the eye and its correcting lens was not changed. Subjects viewed the TNO test from 40 cms in a normally illuminated room (174 lux). They were instructed to keep the test plates parallel to their faces to facilitate detection. Subjects who were able to detect some or all the shapes in the screening plates were asked to make forced-choice reports of the orientations of the series of test plates. Most subjects were reluctant to guess for the plates on which they could not detect a raised shape. TNO stereo-acuity was recorded as the disparity of the last test plate correctly perceived.

Results

TNO stereo-acuities are plotted against worse eye Snellen acuities in fig.3.12. Amblyopes' TNO stereo-acuities were significantly lower than those of non-strabismic non-amblyopes ($z = 3.29$, $p = 0.0006$). Correlations between TNO stereo-acuity and worse-eye Snellen acuity were not significant for amblyopes (Spearman $\rho = 0.41$, one-tailed $p = 0.1$) or non-strabismic non-amblyopes (Spearman $\rho = 0.28$, one-tailed $p > 0.1$).

Discussion

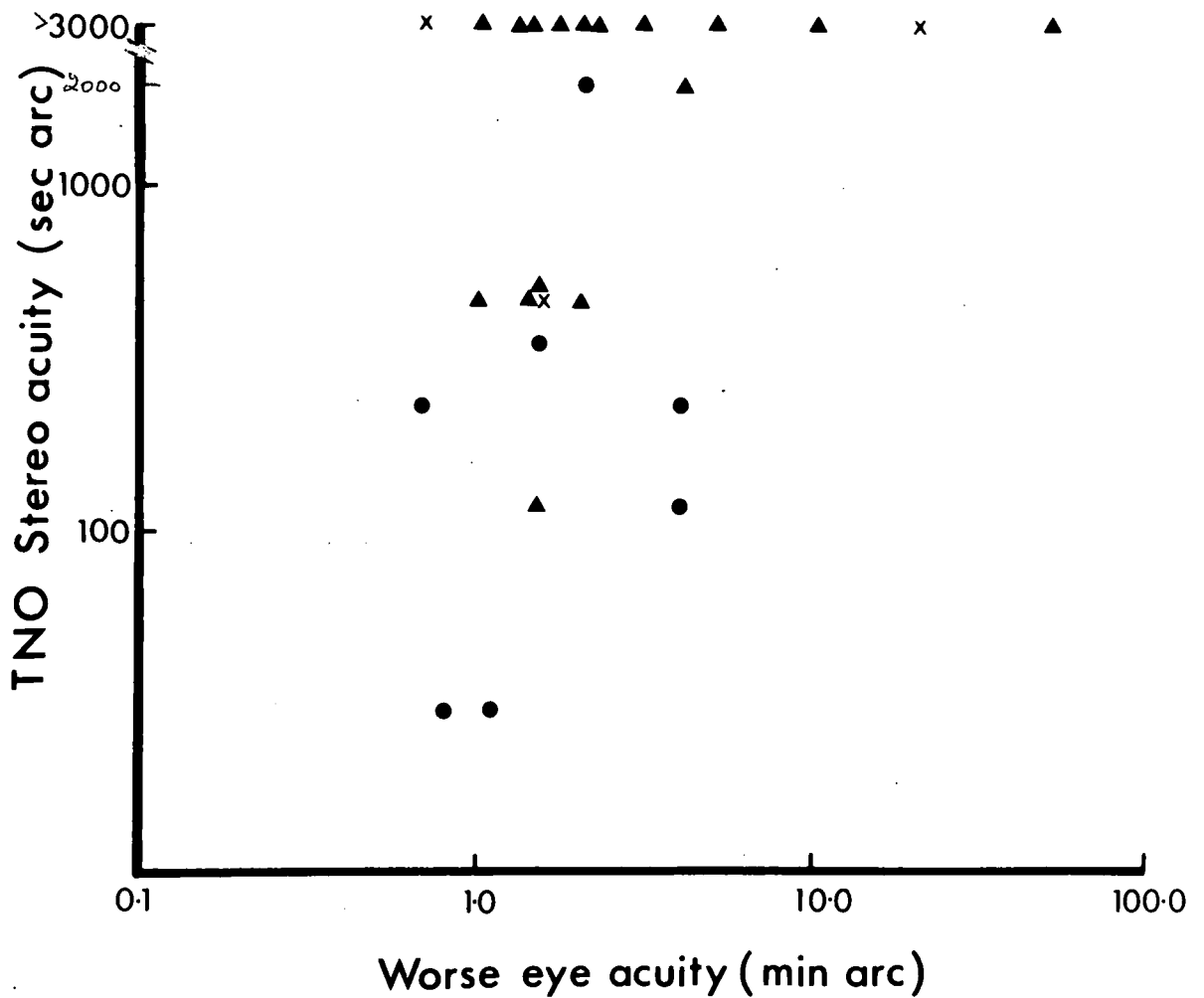As in the Titmus stereo-test the strabismic non-amblyope
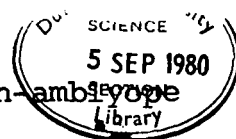
Figure 3.12.

Scatter plot of TNO stereo-acuity against worse eye

Snellen acuity.  Key as in Fig. 3.11.

The ordinate is broken above 2000 sec arc because this was the largest

disparity used.  Subjects not detecting any disparity are shown at

> 3000 sec arc.

with a partial third nerve palsy performed better than the other strabismic subjects, and an explanation has already been given for this. One amblyopic subject achieved a TNO stereo-acuity of 120 secs arc. She was one of the four amblyopic subjects who scored well on the Titmus stereo-test as well. She underwent orthoptic treatment (glasses and patching) between the ages of 5 and 12 years, and although this did not result in equalisation of her Snellen visual acuities (which were 6/5 and 6/9) it seems to have preserved her stereopsis.

One non-amblyope's stereo-acuity was very low; she managed to pass on all the screening plates but was unable to detect any shapes in the test plates at all. This subject also had the worst Titmus stereo-acuity of the non-amblyopic group in the previous experiment, despite having equally high corrected visual acuities.

These individual cases demonstrate that not all amblyopes are stereo-blind and not all stereo-blind subjects are amblyopes, but the overall data support Walraven's (1975) conclusion that the TNO test provides an excellent means of screening for amblyopia.

### 3.4. Comparison of data from experiments measuring space perception and stereopsis.

In this section the results of the four experiments described above will be compared with a view to answering the questions set out in the introduction to the preceding section. Unfortunately different subjects had to be used in each experiment according to their availability, so in some comparisons the number of subjects was rather small.

22 subjects took part in both the space perception experiments (3.1 and 3.2); these were 7 amblyopes, 2 strabismic non-amblyopes, and 13 other non-amblyopes. In fig.3.13 their mean error of setting in the three-rods test is plotted against their bead test error score as defined previously. The latter measure was not ordinal, so non-parametric statistical tests were used. These two measures were found to be significantly correlated for non-amblyopic subjects (both strabismic and non-strabismic subjects were included in this group) at the 5% level (one-tailed; $\rho$ = 0.461), but not for amblyopic subjects ($\rho$ = 0.223). In the figure there is no distinct separation between the data points of amblyopic and non-amblyopic subjects.

In the falling bead test performance was found to be dependent on the strategy the subject reported having used. Best performers were 9 subjects who reported using no conscious strategy at all; they scored between 3 and 10 on the falling bead test. The seven non-amblyopes in this group also performed well on the three rods test with mean errors of between 2.49 and 3.67 cms, as shown in fig.3.13. The two amblyopes who used no conscious strategy in the beads test had greater mean errors on the three rods test (5.85 and 6.25 cms). It seems probable from inspection
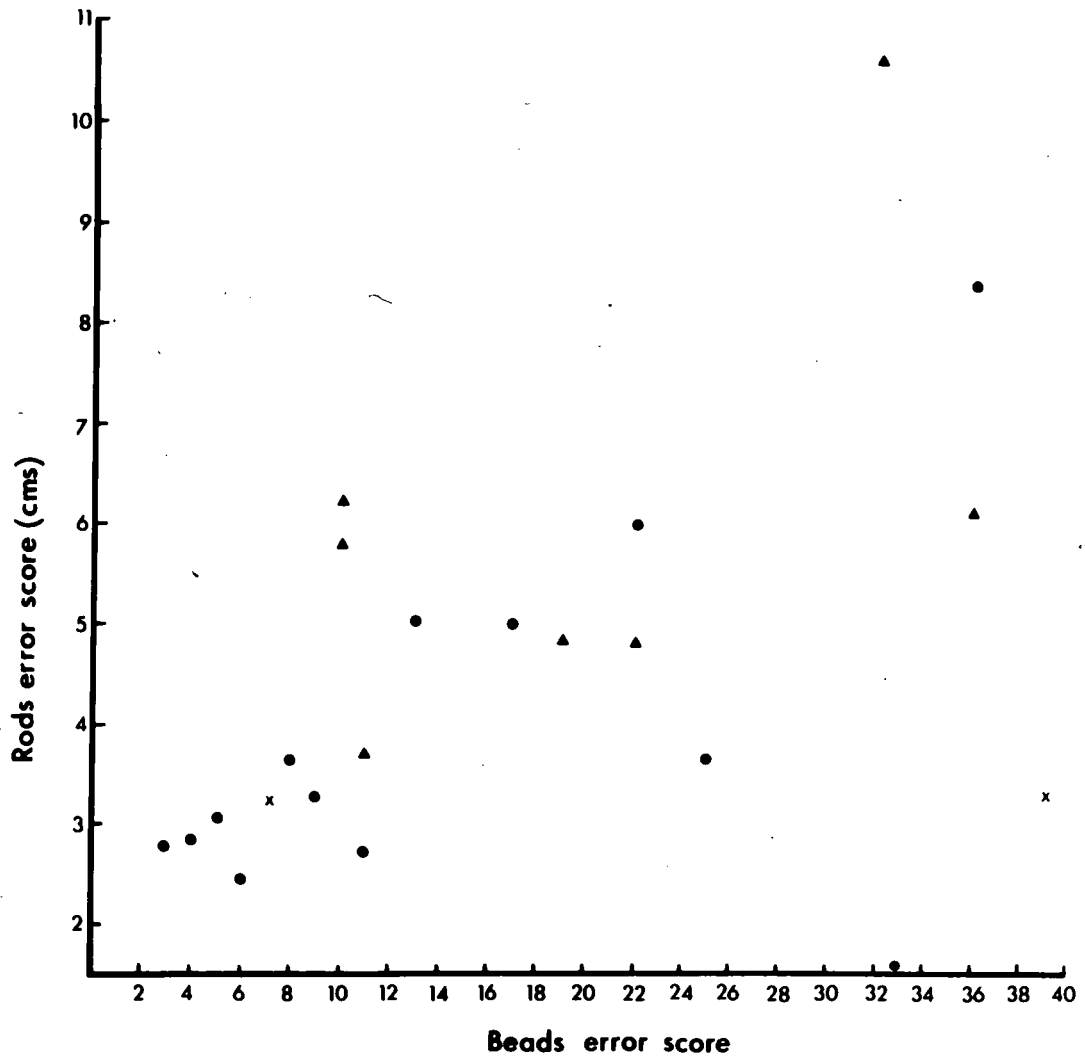
Figure 3.13.

Scatter plot of mean error on three-rods test against error score on falling bead test.  Key as in Fig. 3.11.

of fig.3.13 that this group of subjects lends most weight
to the significant correlation coefficient found between
non-amblyopes' performances on these two tests.

The most notable deviant point in fig.3.13 is that of an
uncorrected uniocular myope (-0.50 DS) who scored 33 on
the falling bead test, using the overlay cue only, and yet
achieved the smallest mean error on the three rods test
(1.79 cms).  One might have expected his myopia to hinder
performance on the three rods test rather than the falling
bead test, since the former was conducted at 6 metres and
the latter at 1 metre.  The possibility that he had simply
selected a poor strategy was investigated by asking him to
repeat the falling bead test, but his second performance
was identical to his first, and he found it impossible to
avoid using the overlay cue strategy.  His point in fig.
3.13 and that of the strabismic subject who scored 39 on
the falling bead test and yet only had a mean error of
3.37 cms in the three rods test might be explained in
terms of their idiosyncratic vulnerability to certain types
of cue limitation: brief stimulus presentation in the falling
bead test might have been a greater handicap for them than
the absence of cues such as overlay and motion parallax in
the three rods test.

Two amblyopic subjects in fig.3.13 seem to have a bias in
the opposite direction:  having performed well on the beads
test (both scoring 10) they made errors of around 6 cms
on the three rods test.  There is no clear relationship
between the type of visual defect a subject has and the
direction of his/her bias in performance between these two
tests, and the most parsimonious explanation rests in
idiosyncratic differences as proposed above.  No account

can be given for how such differences in cue dependence might
arise, but data obtained from the three rods test suggested
that the presence of amblyopia was a determining factor
(see fig. 3.10), whereas data from the falling bead test
did not (fig. 3.2).

All 26 subjects who tried the TNO stereo-test also tried
the Titmus stereo-test. Their results on these two tests
are compared in fig. 3.14. The dotted line represents a
perfect correlation, and most data points lie above it,
indicating that most subjects' stereo-acuities as measured
on the TNO test were lower than those obtained from the
Titmus test. Pearson product-moment correlations were:
0.69 for amblyopes and 0.93 for non-amblyopes both of which
indicate significant correlation at the 0.5% level (one-
tailed). In the figure there is some separation between
the amblyopes and non-amblyopes in the expected direction,
with all amblyopes except one (KD) lying in the upper right
quadrant and all non-strabismic non-amblyopes except one
(SD) lying in the lower left quadrant.

The high stereo-acuities of amblyope KD have been previously
attributed to her early orthoptic treatment. The validity
of this proposition was checked by inspection of the case
histories of the other 18 amblyopic and strabismic subjects
who took part in both stereopsis experiments. Only one
subject had been treated at an earlier age than KD. He
had worn glasses to correct a large anisometropia between
the ages of 4 and 8 years, but had been given no treatment
for a constant convergent squint. KD, on the other hand,
had no oculomotor problems and only a small amount of
anisometropia. This meagre amount of evidence cannot be
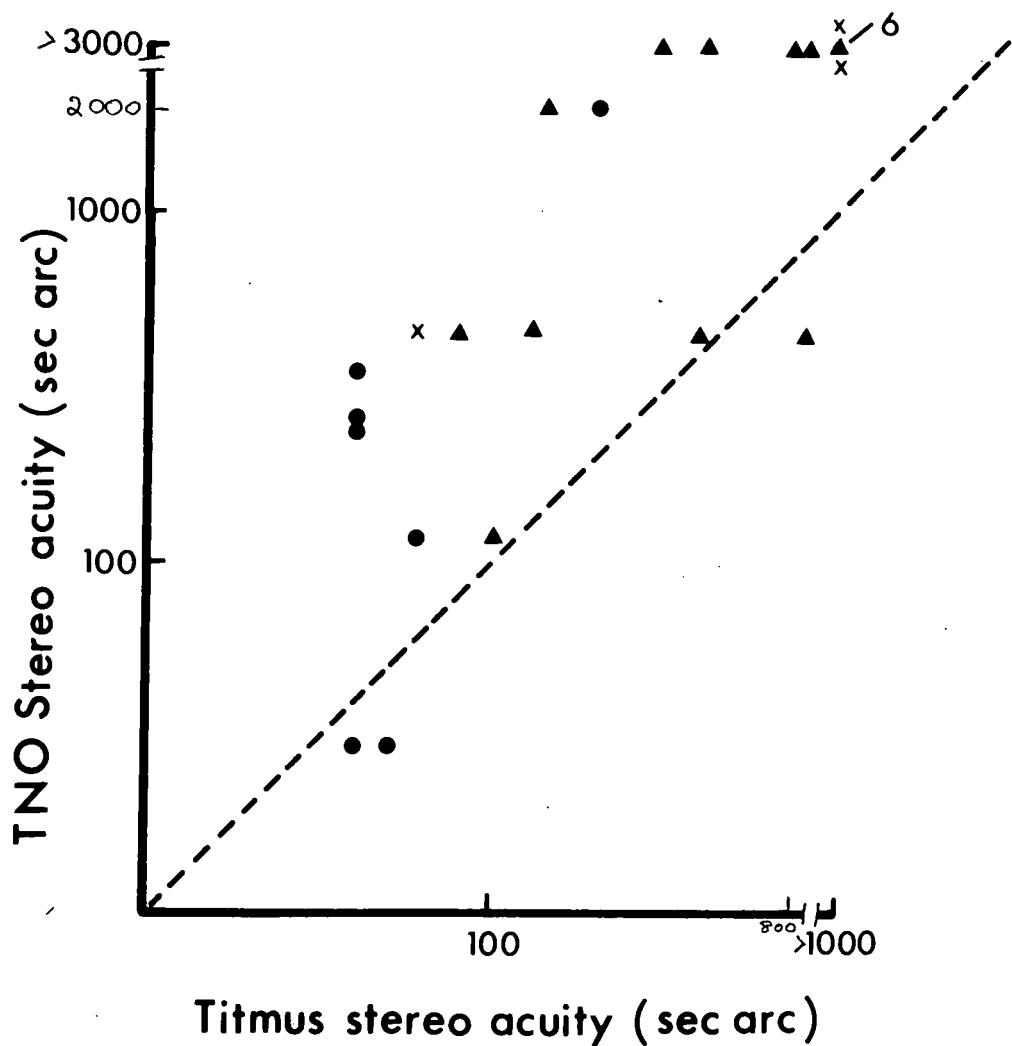regarded as conclusive, but it seems to suggest that early

Figure 3.14.

Scatter plot of TNO stereo-acuity against Titmus

stereo-acuity.  Key as in Fig. 3.11.

The axes are broken above 800 and 2000 sec arc respectively, since these

were the largest disparities used.

treatment of anisometropia can preserve stereopsis even if equal visual acuities are not attained. Current clinical opinion (as explained to me by a practising orthoptist) is that stereopsis is most likely to be maintained if a squint arises after 12 months of age, and if it is treated soon after onset with full refractive correction and/or surgery as necessitated by the type of squint. Data supporting this view can be found in Parks (1968) and Taylor (1972) who both report a higher incidence of stereopsis in children whose strabismus was corrected before 2 years of age than in children corrected after 2 years of age.

The anomalous non-amblyopic subject (SD) with low stereo-acuities first had her myopic astigmatism corrected at 10 years of age. It seems that her abnormal early visual experience prevented normal development of stereopsis but failed to affect development of equal visual acuities, even though the two eyes were probably not equally deprived: her refractive error at 18 years of age was found to be: RE: -2.25/-3.00 x 5;  LE: -3.50/-4.00 x 175. Her poor stereopsis might be a congenital deficiency caused by hereditary factors (Worth, 1903; Richards, 1970), but according to Richards (1970) lack of appropriate responses to disparity information would disrupt fusional mechanisms and cause strabismus, which this subject definitely did not exhibit.

Julesz (1971) suggested that similar subjects that he encountered might improve their stereopsis with training (as confirmed by Ramachandran, 1976), or that they were too dependent on monocular cues, or that they had a strongly dominant eye. SD has been available for repeated stereopsis testing over a period of 3 years, but her stereo-acuities have not improved at all despite all attempts to train her.

During testing on the TNO stereograms she was asked to report whether one of the anaglyph colours was dominating her perceived image, but she reported normal rivalry phenomena. So both learning and dominance explanations must be rejected. In order to discover whether she was strongly dependent on monocular cues data from the three-rods test was examined: figure 3.9 and table 3.13 show that her binocular performance was better than her monocular performance, and that her monocular performance was not noticeably better than that of other subjects, so it seems unlikely that she was abnormally dependent on monocular cues. Her stereopsis deficiency remains unexplained. Having discussed the comparisons of both pairs of similar tests, it only remains to look at the four dissimilar pairings, i.e. beads x Titmus, beads x TNO, rods x Titmus, and rods x TNO. Scatter plots of these four comparisons are presented in fig. 3.15, and no significant correlations were found. In some comparisons there were few subjects who took part in both tests (e.g. beads x TNO and rods x TNO). In the two comparisons where the three rods data is included, mean error on the three rods test is converted to seconds of arc of disparity (see fig. 3.7) and both scatter plots include equivalence lines joining points of equal disparity on the two scales. In both these scatter plots all points lie to the right of the equivalence line indicating that performance of the stereopsis tests was worse than performance on the three rods test, both for amblyopes and non-amblyopes. The presence of a greater number of cues to facilitate the alignment task of the three rods test must account for this finding.

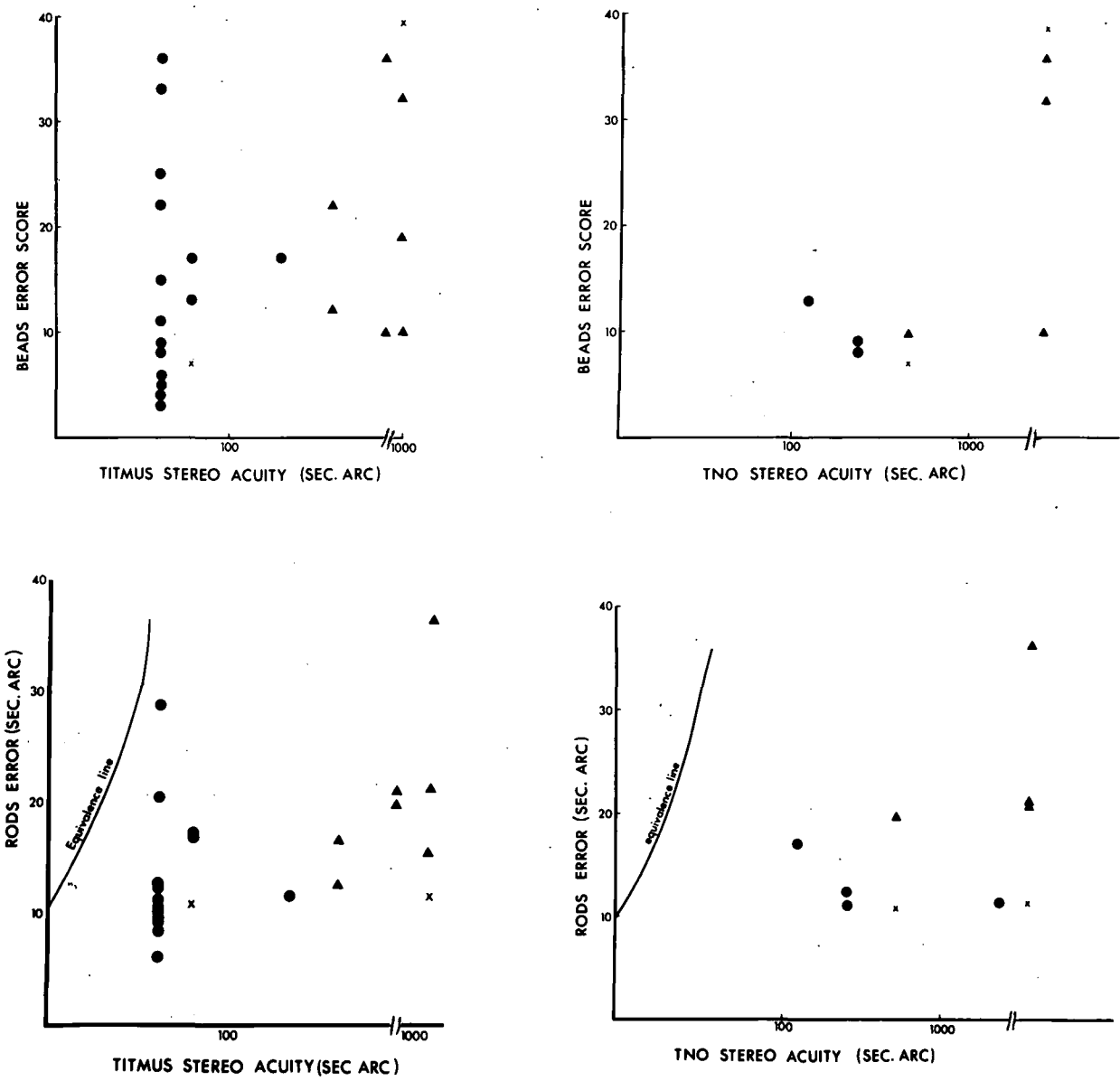In summary, the data from the four experiments described in

Figure 3.15. - Key as in Fig. 3.11.

Top left: scatter plot of beads error score against Titmus stereo-acuity.

Top right: scatter plot of beads error score against TNO stereo-acuity.

Bottom left: scatter plot of angular error on rods test against Titmus stereo-acuity.

Bottom right: scatter plot of angular error on rods test against TNO stereo-acuity.

this chapter suggest that amblyopes are more handicapped for stereopsis tasks than for other space perception tasks, and that factors other than acuity deficit affected their performance.

## 3.5. Conclusions

Having considered the data quantitatively, it remains to evaluate their contributions to answering the questions set out in the preceding section. Firstly, is the amblyope's world two or three dimensional? In the three rods test the amblyopic group of subjects made a mean error of alignment of 5 cms at a testing distance of 6 metres, which, by simple linear transformation corresponds to inaccuracies of about 15 yards at one mile. This would seem to represent an order of accuracy which is adequate for most perceptual tasks normally encountered, with the possible exception of those in which high speed or unusual surroundings necessitate greater precision. Even in the falling bead test, in which a decision was required from a stimulus presentation of only 70 - 85 millisecs, two amblyopes performed well above chance levels. These results suggest strongly that the perceptual world of amblyopes is three dimensional.

Is the acuity-deficit of amblyopia a significant contributor to any deficits of space perception or stereopsis? In all four experiments correlation coefficients between visual acuity of the worse eye and the performance measure were not significant for amblyopes or non-amblyopes. In the falling bead test amblyopic subjects were each paired with myopic subjects with similar acuity deficits and no significant differences were found between the error scores of matched pairs (Table 3.4). However differences between (amblyopes and emmetropes) and (myopes and emmetropes) also failed to achieve significance, so in this experimentmneither amblyopia

*However in the three rods test the accommodative range required to focus on the moving rod was only 0.149 to 0.167 dioptres.

nor acuity deficit were significant determinants of the precision of space perception.

In the three rods test, acuity-matched pairs of amblyopes and non-amblyopes did show significant differences, with the amblyopes making larger alignment errors than the non-amblyopes (fig.3.10). This result suggests that the acuity deficit was not the only determinant of performance, and that some additional aspect of amblyopia was hindering precise alignment. Comparison of the performances of matched pairs of subjects in binocular testing conditions only yielded no significant difference, implying that the additional aspect was not a specifically binocular feature.

Nonetheless amblyopes clearly did lack the ability to detect the cue of binocular (or interocular) disparity in the two stereopsis tests. Recently, Wolfe, Held and Owens (1979) have demonstrated that there may be more than one binocular process in man; by presenting subjects with rotating dichoptically illuminated targets, they discovered that stereoblind subjects were unable to see a so-called 'tilt' effect but did manage to detect a 'torsion' effect. They do not discuss the nature of the proposed secondary binocular process, but one possible mechanism which would account for the remarkably good alignment precision attained by amblyopes in the three rods test is suggested by another recent paper by Kenyon, Ciuffreda and Stark (1979). They found that amblyopic and strabismic subjects did not make normal fusional vergence movements when tracking a moving object, but instead used accommodational vergence and a saccade to achieve fixation with the dominant eye.[*] The roles of accommodation and convergence in providing information for space perception have been debated for centuries,

and recent data seem to support theories such as Sperling's
(1970) in which they are given some importance.

The answer to the question of whether the acuity deficit
of amblyopia is a significant determinant of the precision
of space perception or stereopsis must be negative.

The third question asked what cues amblyopes used to make
judgements of three dimensional configurations.  In the
falling bead test they seemed to use the same variety of
cues as non-amblyopes.  In the three rods test they seemed
less able to utilise monocular cues than the non-amblyopes.
In the stereopsis tests they were unable to use disparity
as a cue to depth.  These results imply that, apart from
disparity, all cues are available to amblyopes.  They
gained as much advantage from binocularity as non-amblyopes
in the three rods experiment, suggesting that they have
other intact binocular systems despite their inability to
detect disparity when it is presented as the sole cue.

Two questions as to the suitability of the above tests for
a) predicting performance in a particular task and b)
screening for amblyopia are easily answered.  The ideal
method of predicting an amblyopic subject's ability to
perform a specific visual task would be designed to replicate
the task as closely as possible.  The lack of correlation
between amblyopes' performances on the first two tests
demonstrates the unpredictability of the consequences of
their deficits.  The ideal screening test is clearly the
TNO stereo-test which unlike the Titmus test, defied any
'cheating' by detection of monocular cues.

The data presented provide support for most current theories
of space perception and stereopsis.  Algorithm theories are
compatible with the results of the falling bead test.

Theories taking the 'proximal stimulus approach' would account for the results of the three rods experiment in which comparison objects were always available. Amblyopes' inability to detect depth in the stereopsis tests supports theories that they lack a system for disparity detection, while their improvement on the three rods test when viewing binocularly supports Wolfe, Held and Owens' (1979) proposal of a secondary binocular process.

Further discussion of the results presented in this chapter will be found in Chapter 6, where they will be considered alongside results from contrast sensitivity studies.

CHAPTER 4:   CONTRAST SENSITIVITY

## 4.1.   Introduction

Understanding of the functional capacities of the human
visual system has been closely linked to the development
of techniques for their measurement.   This interdependence
has been discussed in Chapter 2 with reference to the
detection of eccentric fixation in amblyopia.

Technical progress combined with conceptual advances has
led to new methods for the analysis of optical systems,
including the human visual system (Schade, 1956).   These
are described in detail by others (e.g. Cornsweet, 1970),
so this outline will be brief.

The relationship between an object and its image is determined
by the properties of the optical system between them, and
the properties of the object.   A poor optical system will
degrade a fine-detailed object to produce a blurred image,
while it may produce a satisfactory image of a coarse-detailed
object.   This aspect of the performance of an optical system
can be described by the modulation transfer function (MTF):
a graph of the amount of change (or degradation) produced
as a function of the size of detail in the object.
Degradation is conventionally measured in terms of the
reduction in amplitude, or attenuation, of the luminance
profile of the object or stimulus;   gratings with a
sinusoidal luminance profile are used as stimuli when
studying the MTF of an optical system, because they undergo
no changes other than amplitude attenuation.   Size of detail
is represented by the frequency of the sine-wave. In the case
of the human visual system the absolute MTF cannot be
measured since the contribution of neural factors cannot be

assessed. It is necessary instead to measure the qualities of stimuli which are on the threshold of detectability. These stimuli are modulated by the visual system just too much to remain perceptible. Threshold stimuli can be defined by the spatial frequencies and amplitudes of their luminance profiles, but conventionally amplitude is measured in terms of contrast which is defined as the ratio (Imax - Imin)/(Imax + Imin), where I = luminance. Hence the modulation transfer function is converted to a contrast sensitivity function when the visual system is the optical system under consideration, contrast sensitivity being the reciprocal of contrast.

Two factors influence the contrast sensitivity of the human visual system: the quality of the optical components and the resolution of the retina-cortex pathway. Campbell and Green (1965) measured the contrast sensitivity of the latter in isolation by projecting sinusoidal interference fringes onto the retina using neon-helium gas lasers. They found that the contrast sensitivity of the retina-cortex pathway decreased exponentially as spatial frequency increased above 10 cycles/deg, as did the contrast sensitivity of the whole visual system. Calculations of contrast ratios indicated that the optical components reduced the contrast sensitivity of the visual system and had a greater detrimental effect at high spatial frequencies. However with a 2mm diameter pupil the optical components did not differ much from an aberration-free diffraction-limited optical system, indicating that the contrast sensitivity function is primarily determined by the properties of the retinal-cortex pathway, and it has consequently become an important measure in the study of mechanisms of visual perception.

## 4.2. THEORETICAL APPLICATIONS OF CONTRAST SENSITIVITY STUDIES.

### 4.2.1. Theories of visual perception arising from contrast sensitivity studies on humans.

Campbell and Robson (1968) interpreted the results of a series of experiments using different luminance profiles (sine, square, rectangular and saw-tooth) by breaking the complex waves down into their sine-wave components by Fourier analysis. The conclusions they derived were i) that the contrast thresholds of a complex wave are determined by its fundamental Fourier component; ii) that the complexity (e.g. squareness) of a waveform cannot be distinguished until its higher harmonic components reach a contrast above their own threshold. They explained these results by postulating the existence of linear independent mechanisms, or channels, which were selectively sensitive to a narrow range of spatial frequencies. The overall contrast sensitivity function might be, they proposed, an envelope resulting from combination of the responses of these narrow channels. They drew support for this hypothesis from the physiological evidence produced by animal experimentation; this will be discussed later. Further support came from experiments by Blakemore and Campbell (1969) who demonstrated that adaptation to a particular spatial frequency increased the contrast threshold for gratings of closely similar($\pm$ one octave) spatial frequencies. However they were not able to substantiate the existence of narrow channels by plotting a detailed contrast sensitivity function (with 31 points between 5 and 40 cycles/deg); although they found 'bumps' in the function which approximated the bandwidth of the hypothetical channels, they failed to replicate the 'bumps' in a second plotting. These studies led to an ongoing controversy regarding visual processing mechanisms.

Supportive evidence for a visual system composed of narrow-band spatial frequency analysers continued to accumulate in the 70's (e.g. Kulikowski and King-Smith, 1973; Sansbury, 1977) but contradictory evidence was also emerging. Legendy (1975) re-interpreted Campbell and Robson's (1968) data without assuming Fourier analysis, and found that it was compatible with a model of Gaussian receptive fields with convergence and summing of the outputs from similarly shaped fields. Legge (1976) found that Fourier theory failed to predict adaptation responses to a bright bar, and proposed a receptive field model. Henning, Hertz and Broadbent (1975) demonstrated interactions between low and high spatial frequency gratings which were incompatible with the hypothesis of narrow-band frequency analysis. Stromeyer and Klein (1975) found a non-linear medium-band hypothesis more compatible with their data and with the visual system's need to analyse phase and position information, and Mostafavi and Sakrison (1976) assumed that frequency channels were not narrowly tuned in their analysis of the response characteristics of a single channel.

To date there is no universally accepted conclusion to this debate, and it has become confounded with another issue: Keesey (1972), Tolhurst (1973) and others proposed the existence of two distinct classes of channels differing in their temporal properties and in the range of spatial frequencies over which they operate; they were referred to as the transient and sustained mechanisms by Kulikowski and Tolhurst (1973). Examples of experimental evidence supporting this idea are found in Tolhurst (1975), Vassilev and Mitov (1976) and Legge (1978). This and other evidence was interpreted by Watson and Nachmias (1977) to support a serial model of spatio-temporal visual analysis in which transient

and sustained responses were at opposite ends of a single range of response characteristics and were determined by spatial frequency alone. The importance of detection criteria used in psychophysical experiments from which visual processing models are derived was considered by Watson and Nachmias (1977), and they found their serial model compatible with both pattern detection and flicker detection criteria. Arend and Lange (1979) presented data showing that spatial frequency tuning curves were not significantly dependent on exposure duration and they too rejected the proposed existence of two different mechanisms of visual processing.

It is traditional to appeal to physiological evidence from animal experiments for support when a perceptual model is derived from psychophysical data. The following section therefore consists of a brief review of the appropriate area of the animal literature.

["

and Bisti and Maffei (1974). Bisti and Sireteanu (1976) demonstrated that the cat's superior collicular cells have similar contrast sensitivity functions but with lower spatial frequency ranges. These cells remained responsive after cortical ablation, indicating the possible existence of a non-cortical mode of pattern processing. Tolhurst and Movshon (1975) produced electrophysiological support, in the form of a cellular dichotomy, for the sustained/transient division by recording from the cat striate cortex, but Lennie's (1979) findings indicated that the cells did not respond as predicted by the sustained/transient model. He suggested that any differences were therefore quantitative rather than qualitative.

Thus the animal research appears to be paralleling human psychophysical research in providing conflicting models of visual perception. It seems that most of the proposals of psychophysicists can find some support from animal physiology, but neither research area has as yet provided an acceptable conclusion to the contentious points which have arisen within both of them.

## 4.3. EXPERIMENTAL VARIABLES IN CONTRAST SENSITIVITY STUDIES.

### 4.3.1. Introduction

The production of a human contrast sensitivity function is complicated by ocular and stimulus parameters. Studies of the effects of some of these factors are reviewed here.

The effect of <u>pupil size</u> upon contrast sensitivity measurement was evaluated by Campbell and Green (1965). A 2mm pupil produced a contrast sensitivity function close to that of the retina-cortex pathway in isolation; larger pupils reduced contrast sensitivity across the entire spatial frequency range by a factor of approximately 0.7 per 2mm increase in pupil size. The largest pupil size used was 5.8mm. The shape of the contrast sensitivity function was not noticeably changed within this range of measurements.

The influence of <u>testing distance</u> was considered by Schober and Hilz (1964). Their data suggested a shift in the function towards higher spatial frequency as distance was increased up to 5m. Thus sensitivity was lower for low spatial frequencies and higher for high spatial frequencies. Campbell and Robson (1968) studied the same phenomenon using two testing distances: 57cm and 285 cm. Their data led them to the conclusion that testing distance does not influence the contrast sensitivity function but the angular subtense of the stimulus field does. This variable has been investigated by the writer and results will be described later (section 4.3.3).

<u>Temporal characteristics</u> of the display have been varied by several experimenters (e.g. Schober and Hilz, 1965; Nachmias, 1967; Watanabe et al, 1968; Tolhurst, 1975; Arend, 1976; Lupp, Hauske, and Wolf, 1976; Tulunay-Keesey and Jones, 1976). Their somewhat contradictory findings will be described later

(in section 4.3.2.), with the results of a pilot study.
Mean luminance has been shown to influence the contrast
sensitivity function. Patel's (1966) and Van Nes and Bouman's
(1967) data illustrated that small reductions of mean luminance
reduced contrast sensitivity to high spatial frequencies and
shifted the peak of the function progressively from 5 cycles/
deg to 1 cycle/deg. Further reduction of mean luminance then
abolished the peak and reduced contrast sensitivity across
the entire spatial frequency range. Watanabe et al (1968)
reported that contrast sensitivity to high spatial frequencies
increased with increased mean luminance while sensitivity to
low spatial frequencies was unaffected. This apparent
discrepancy is explained by the ranges of mean luminances used:
van Nes and Bouman's experiment covered a range of 0.0003
$cd/m^2$ to 300 $cd/m^2$, while Watanabe et al only used 10 to 170
$cd/m^2$. Van Meeteren and Vos (1972) demonstrated that
disappearance of the peak of the function occurred when mean
luminance fell below 0.1 $cd/m^2$.

At low spatial frequencies a grating stimulus may consist of
only a small number of cycles if testing distance and stimulus
area are held constant over a range of spatial frequencies.
Findlay (1969) discovered that the detectability of gratings
with few cycles depended upon the number of cycles. Hoekstra
et al (1974) suggested that stimulus displays with small
numbers of cycles had artificially lowered contrast sensitivity
in many previously published experiments. They found that
the critical number of cycles was around 7. Below this
critical value contrast sensitivity was determined
independently of spatial frequency in the low spatial frequency
range. Savoy and McCann (1975) and van der Wildt et al (1976)
presented similar data. Kelly (1975) explained these findings

with reference to similar results obtained when measuring
optical systems other than the eye, and concluded that the
low spatial frequency decline in the contrast sensitivity
function was not entirely an artifact of grating design.
Estevez and Cavonius (1976) demonstrated that the luminance
of the area surrounding the grating could be responsible for
low frequency attenuation: low surround luminances flattened
the peak of the contrast sensitivity function, so that the
low frequency decline disappeared.

The influence of psychophysical method upon contrast sensitivity
functions was reported by Kelly and Savoie (1973).  They
compared a forced-choice staircase method with a method of
adjustments.  Contrast sensitivity functions obtained by
these two methods were essentially the same shape.  The
former method elicited higher sensitivities than the latter
in most subjects.  Variability between runs was random for
the forced-choice staircase method and systematic for the
method of adjustments.  The authors attributed the second
finding to systematic changes in the subject's criterion.
Furchner, Thomas and Campbell (1977) found similar differences
between these two psychophysical methods.  Other variables
capable of influencing contrast sensitivity measurements
include: the region of retina stimulated, the steadiness of
the subject's fixation and the type of oscilloscope phosphor
used.  The first two will not be considered since in the
studies to be described the gratings were presented to central
retina throughout, and none of the subjects had unsteady
fixation.

The problem created by the properties of the oscilloscope
phosphor is due to electron scatter.  If the scatter across
the oscilloscope screen is sufficient to brighten the dark

half-cycles of a grating, contrast cannot be predicted from attenuation voltage. This occurs when high spatial frequency gratings are being presented, and it becomes impossible to present a high contrast grating of high spatial frequency. If the spatial frequency at which scatter becomes significant is lower than the subject's resolution threshold spatial frequency, then the high spatial frequency end of the subject's contrast sensitivity function is artificially lowered. One solution to this problem would be to measure the contrast produced by each level of voltage attenuation for each spatial frequency used, but this too is difficult for high spatial frequency gratings since one would require a photometer with a minute head (< half-cycle width) with known frequency response characteristics.

In order to minimise the effects of as many of these variables as possible I decided to use individual subject's interocular differences in contrast sensitivity as the primary measure, thus variables such as pupil size, mean luminance, surround luminance, number of cycles in the display, etc would not require careful consideration. Previous authors (e.g. Hess and Howell, 1977) have shown that there are individual differences in contrast sensitivity even between subjects with perfectly normal vision. By measuring interocular differences each subject acts as his/her own control and this seemed particularly appropriate for subjects with one normal eye and one with defective vision, which most amblyopes have.

Some of the other variables mentioned above were investigated in order to select procedures for obtaining contrast sensitivity data, and findings are described in the following series of pilot studies.

### 4.3.2. Pilot Study 4.1: to investigate the effects of the temporal characteristics of the display on interocular differences in contrast sensitivity.

<u>Introduction</u>

Sensitivity to the contrast of a grating is known to be dependent upon the duration of presentation of the display. This interaction has received much experimental attention and there are some areas of conflict in the literature. Nachmias (1967) found that contrast sensitivity to square wave gratings of low spatial frequency (0.7c/deg) was optimised at a display duration of 50 - 100 msecs. Shorter durations reduced contrast sensitivity, and longer ones did not improve it. In the case of high spatial frequency gratings (17.5 c/deg) contrast sensitivity improved with display duration continuously from 11 msec to 500 msec. The data of Schober and Hilz (1965) and Watanabe et al (1968) suggested that brief exposure duration decreased contrast sensitivity in the middle frequency range (1.2 - 12 cycles/deg) more than in the high and low ranges, and therefore flattened the peak of the contrast sensitivity function. Spitzberg and Richards (1975) presented a range of spatial frequencies at two display durations (20 and 1000 msecs) and found that the longer display improved contrast sensitivity to low spatial frequency gratings (0.5 c/deg) by a factor of 2, and high spatial frequency gratings (10 c/deg) by a factor of 10. Tulunay-Keesey and Jones (1976) found no differential effect of spatial frequency when measuring contrast sensitivity with a range of display durations. However their lowest spatial frequency was 1.5 c/deg which may have been too high to show the effects reported by previous authors. Breitmeyer and Ganz (1977) found a critical duration of display associated with each of three spatial frequencies (0.5,2.8 and 16 c/deg),

and the relationship between critical duration and spatial frequency was monotonic rising to 200 msec at 16 c/deg.

Some of the contentious points in this body of data are accounted for by Legge (1978). The controversial issues have little bearing upon this study, since as stated before, interocular differences are the measure of choice. The primary reason for investigating the effect of brief presentations in this pilot study was that they might permit a forced-choice design to be used instead of a staircase procedure, without significantly increasing the total duration of the testing sequence, as implied by Lupp, Hauske and Wolf's (1976) finding that simple reaction time to suprathreshold gratings was shortest for brief exposure durations. The improvement in contrast sensitivity obtained with a forced-choice design has already been mentioned (Kelly and Savoie, 1973; Furchner et al, 1977).

## Apparatus

Sine wave gratings were generated on a Telequipment D52 oscilloscope with a 12 cm diameter circular screen in the conventional manner (Campbell and Green, 1965). A high frequency raster (1 megaHz triangular wave) was produced on the Y-axis covering a rectangular area 8 cm high and 12 cm wide. A wave-form generator connected to the Z-axis modulated the display sinusoidally with frequencies between 400 and 30,000 Hz, producing vertical gratings of spatial frequencies between 0.25 and 15 cycles/cm on the screen. An attenuator was used to vary the modulation voltage and hence the grating contrast. Gratings were stabilised temporally by connecting the wave-form generator to the external trigger of the oscilloscope. Precise luminance measurements were not possible owing to lack of equipment, so contrasts

were quantified in decibels of attenuation. Mean luminance, measured with an SEI spot photometer, was 0.4 foot-lamberts (= 1.4 cd/m ). The relationship between attenuation and contrast appeared to be constant for gratings of less than 5 cycles/cm. Finer gratings could not be produced at high contrast, probably because of the limitations of the oscilloscope and its phosphor. A timer was included in the circuit, in order to present brief grating displays of 10 msecs. Brief displays appeared from a field of equal mean luminance.

Design and Procedure

One emmetropic subject was tested. Two contrast sensitivity functions were obtained from each eye. Each function was composed of contrast thresholds at spatial frequencies ranging from 0.5 to 20 cycles/deg. Two different modes of presentation were used: Continuous and brief. In both modes one eye was tested at all spatial frequencies, then the other eye was tested at all spatial frequencies. In both modes spatial frequency was presented as an ascending series. For the continuous mode a method of limits was used, each contrast threshold being determined as a descending limit first and then as an ascending limit. The experimental procedure was: spatial frequency was set; contrast was adjusted to maximum (0 dB); then contrast was slowly and smoothly reduced by the experimenter until the subject reported the disappearance of the grating. Then contrast was reduced to an absolute minimum (100 dB), and slowly increased until the subject reported the grating's reappearance. For the brief presentation mode a forced-choice staircase was used: the subject was given a single 10 msec presentation of the grating at each contrast level and was required to respond 'yes' or 'no' to signify whether he had detected the grating or not. Contrast was adjusted in $2\frac{1}{2}$ dB steps. A descending threshold was defined as the contrast eliciting

the first 'no' in a sequence of decreasing contrasts, and
an ascending threshold was defined as the first 'yes' in
a sequence of increasing contrasts.

Testing was carried out in a darkened room (approx. 0.01
ft-lamberts) and the subject spent about 15 mins adapting to
this level of illumination.  He was seated 115 cm from the
oscilloscope screen so that each grating subtended an area
4 degrees high and 6 degrees wide.  He was not physically
restrained but was asked to sit perfectly still throughout
the testing sequence, and to fixate the central area of the
screen.  A soft occluder was used to cover the eye which
was not being tested.  Before the sequence proper began
he was shown two sample gratings, chosen randomly, to
illustrate the task.  All thresholds were recorded in dB
of attenuation, and these were plotted against spatial
frequency by means of a standard computer package program.

Attempts to plot functions for two amblyopic subjects failed
because they found gratings in the brief presentation mode
impossible to detect.

Results

The contrast sensitivity functions plotted by two different
presentation modes are shown in figs. 4.1 and 4.2.  For this
subject the labels 'good eye' and 'bad eye' are post hoc
classifications; his Snellen acuities were equal (6/4 in
each eye) but in order to keep most of the symbols for
'sensitivity difference' above the abscissa the right eye
was designated the 'bad eye'.  'Sensitivity difference' was
calculated as the difference between the mean contrast
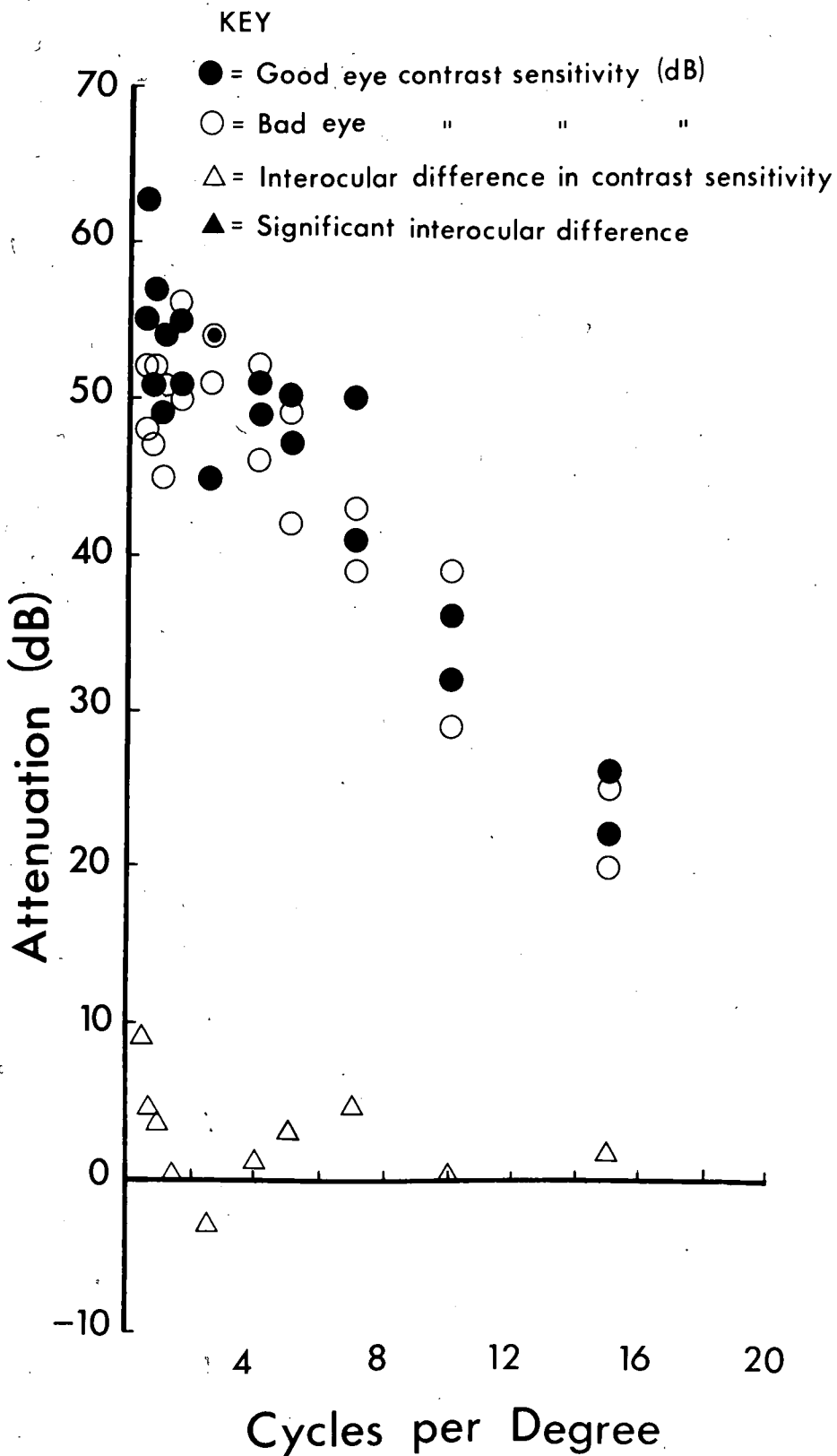thresholds of the two eyes:  good eye mean - bad eye mean.

Figure 4.1.

Contrast sensitivity functions of both eyes of an emmetropic subject (NA), and interocular difference in contrast sensitivity. Thresholds were obtained with continuous presentation of gratings, and the so-called 'good eye' was tested first.
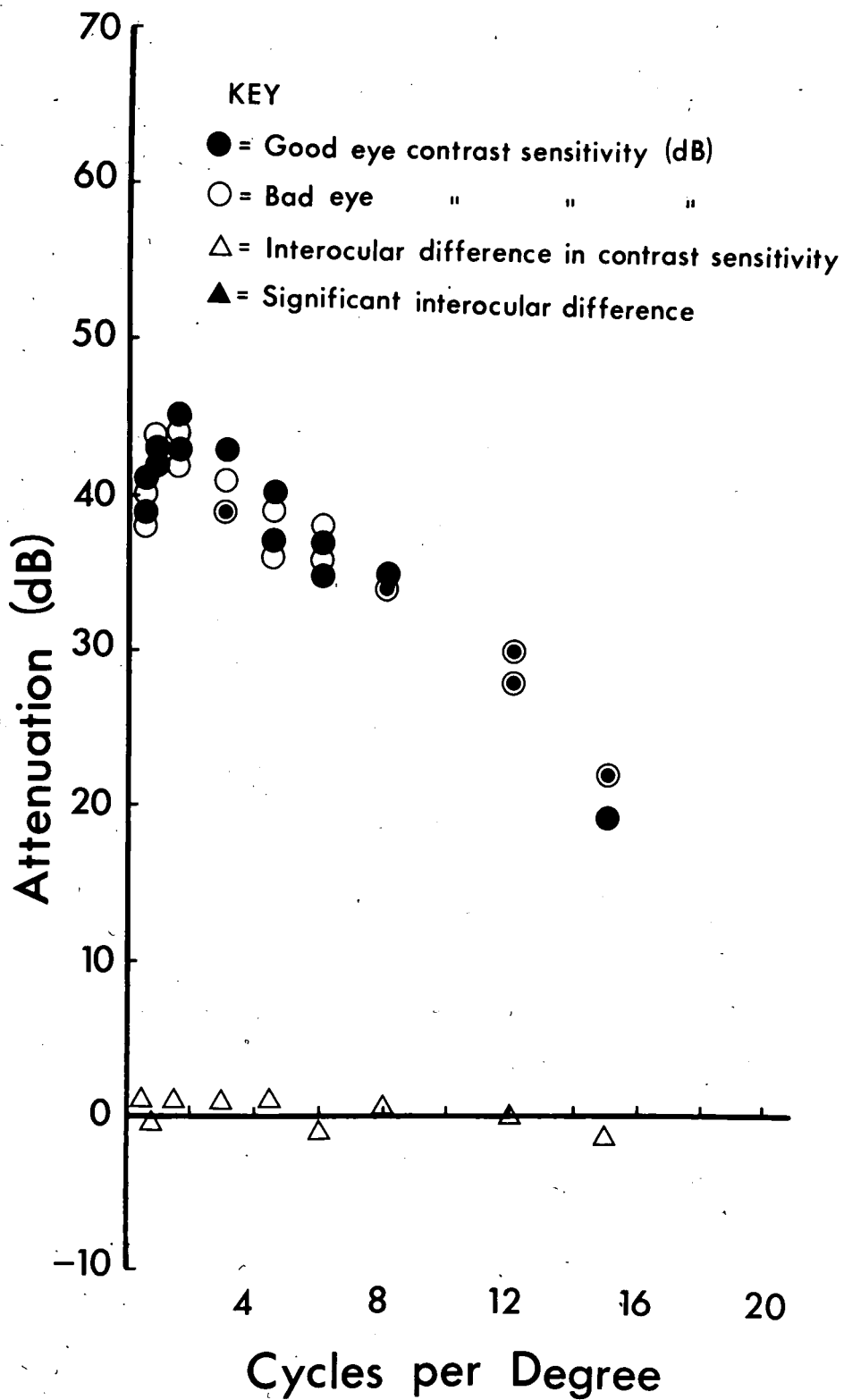
Figure 4.2.

Contrast sensitivity functions of emmetrope NA obtained with brief (10 msec) presentation of gratings. The 'good eye' was tested first.

Both figures show normal contrast sensitivity functions, with approximately linear declines with increasing spatial frequency. There is also some indication of a reduction in contrast sensitivity at lower spatial frequencies, but this might be influenced by the small numbers of cycles presented in the low spatial frequency displays; at 1 cycle/deg there were only 6 cycles, and at 0.5 cycle/deg there were only 2.7 cycles.

The significances of interocular differences in contrast sensitivity were assessed by obtaining a t value making no equivariance assumptions (Ostle, 1954); for all spatial frequencies except one, $p > 10\%$ (one-tailed).

Peak contrast sensitivity is around 40 dB in fig.4.2 compared with about 55 dB in fig.4.1. The functions obtained from brief presentations in a forced choice design are significantly worse than those obtained from continuous presentations with a method of limits. Comparison of the means of thresholds indicate that, overall, functions in fig.4.2 are significantly lower than those in fig.4.1 ($t = 6.8$, $df = 17$, $p < 0.05\%$, one tailed).

Conclusions

The figures show that the brief presentation mode with forced-choice procedure produced less variability between contrast threshold estimates than the continuous presentation mode with staircase procedure. The former mode required 15 minutes total testing time while the latter required 30 minutes.

These two findings both favour usage of the former method for contrast sensitivity testing. However, amblyopes were unable to detect any brief grating displays shorter than about one second, and this increased display time would negate one

advantage (shorter testing time) of the former method. Nonetheless the advantage of reduced variability might remain, and with these two conflicting considerations in view both methods have been used in the experiments on amblyopes to be described later (see Chapter 5).

### 4.3.3. Pilot Study 4.2: to investigate the effects of the interaction of testing distance and stimulus field size upon contrast sensitivity to high spatial frequency gratings.

## Introduction

In Pilot Study 4.1 difficulties were encountered when presenting gratings above 5 cycles/cm at high contrast. In order to cover a full high spatial frequency range without using displays beyond this apparent limit it would be necessary to increase testing distance and consequently reduce stimulus field size.

Campbell and Robson (1968) isolated these two variables and demonstrated that when stimulus field size was constant, changes in testing distance did not affect contrast sensitivity at low spatial frequencies. -Similarly, when testing distance was held constant, an increase in stimulus field size increased contrast sensitivity at low spatial frequencies. Despite having mentioned that gratings consisting of less than four cycles depressed contrast sensitivity, they did not emphasize that their five-fold increase in stimulus field size raised three of their low spatial frequency gratings above this critical number. They attributed the improvement in contrast sensitivity to increased field size rather than increased number of cycles. Hoekstra et al (1974) demonstrated that the critical number of cycles for grating displays with mean luminances between 165 and 600 $cd/m^2$ was around 7. If this figure is used instead of Campbell and Robson's estimate of 4, all their data points showing substantial improvement with increased stimulus field size can be interpreted as improvements due to increases in number of cycles from below the critical level to above it. They used gratings with mean luminance constant at 500 $cd/m^2$, so the application of Hoekstra et al's

critical number is valid. Campbell and Robson did not present comparative data for spatial frequencies above 9 cycles/deg, where small numbers of cycles would not have confounded their conclusions.

Schober and Hilz (1965) showed the combined effects of increased testing distance and reduced stimulus field size at different mean luminance levels. At 110 cd/m$^2$ contrast sensitivity to gratings above 5 cycles/deg increased as testing distance was increased from 1m to 3m to 7m. At 1.4 cd/m$^2$ this direct relationship was only found above 24 cycles /deg. Between 4 and 24 cycles/deg,maximum contrast sensitivity was obtained at the intermediate testing distance of 3m. This indication that the effects of testing distance and stimulus field size are also luminance-dependent necessitated the following investigation. The mean luminance of the display had not been precisely quantified at this stage so assumptions based on Schober and Hilz's data were not possible.

## Design and Procedure

The appaatus used in Pilot Study 4.1 was used again, with the exception of the timer. Three different testing distances were used: 57cm, 115 cm and 230 cm. The stimulus field sizes were about 8 degrees high by 12 degrees wide for the first distance, 4 by 6 degrees for the second, and 2 by 3 degrees for the third. The continuous presentation mode was used in this study, with the method of limits, as described in Pilot Study 4.1. All other testing conditions were the same as in the previous study except that the right and left eyes were tested alternately at each spatial frequency instead of each eye being tested at all spatial frequencies consecutively.

## Results

As before the significances of interocular differences were assessed without making equivariance assumptions. There were no significant differences at any of the testing distances ( p > 5%, one tailed). Fig. 4.3 shows the data for 115 cm testing distance. Only four spatial frequencies were tested at the other two distances, and since interocular differences were insignificant, the means of the four thresholds obtained at each spatial frequency have been plotted in fig.4.4 for simplicity. (The data points shown in fig. 4.3 are reproduced in full in fig. 4.4).

Comparison of thresholds obtained at different distances yielded only 2 differences significant at 5% level. At 10 cycles/deg contrast sensitivity was lower at 57 cm than at 115 cm (t = 2.8, df = 4, p = 2.5%, one tailed); and at 15 cycles/deg contrast sensitivity was lower at 115 cm than at 230 cm (t = 4.0, df = 3, 2.5 > p > 1%, one tailed).

## Discussion and Conclusions

High spatial frequency gratings obtained by increasing testing distance seem to be more easily detectable than gratings of identical spatial frequency obtained by increasing modulation frequency.

The smallest number of cycles used in any display in this experiment was 36, so this cannot have been a contributory factor. Intuitively there might be some functional value in a visual system with maximal contrast sensitivity for small distant objects, but this would require some mechanism for separate processing of visual information according to its absolute size, rather than its angular subtense. A more parsimonious explanation of these results (and those of Schober and Hilz, 1965) rests in the previous observation
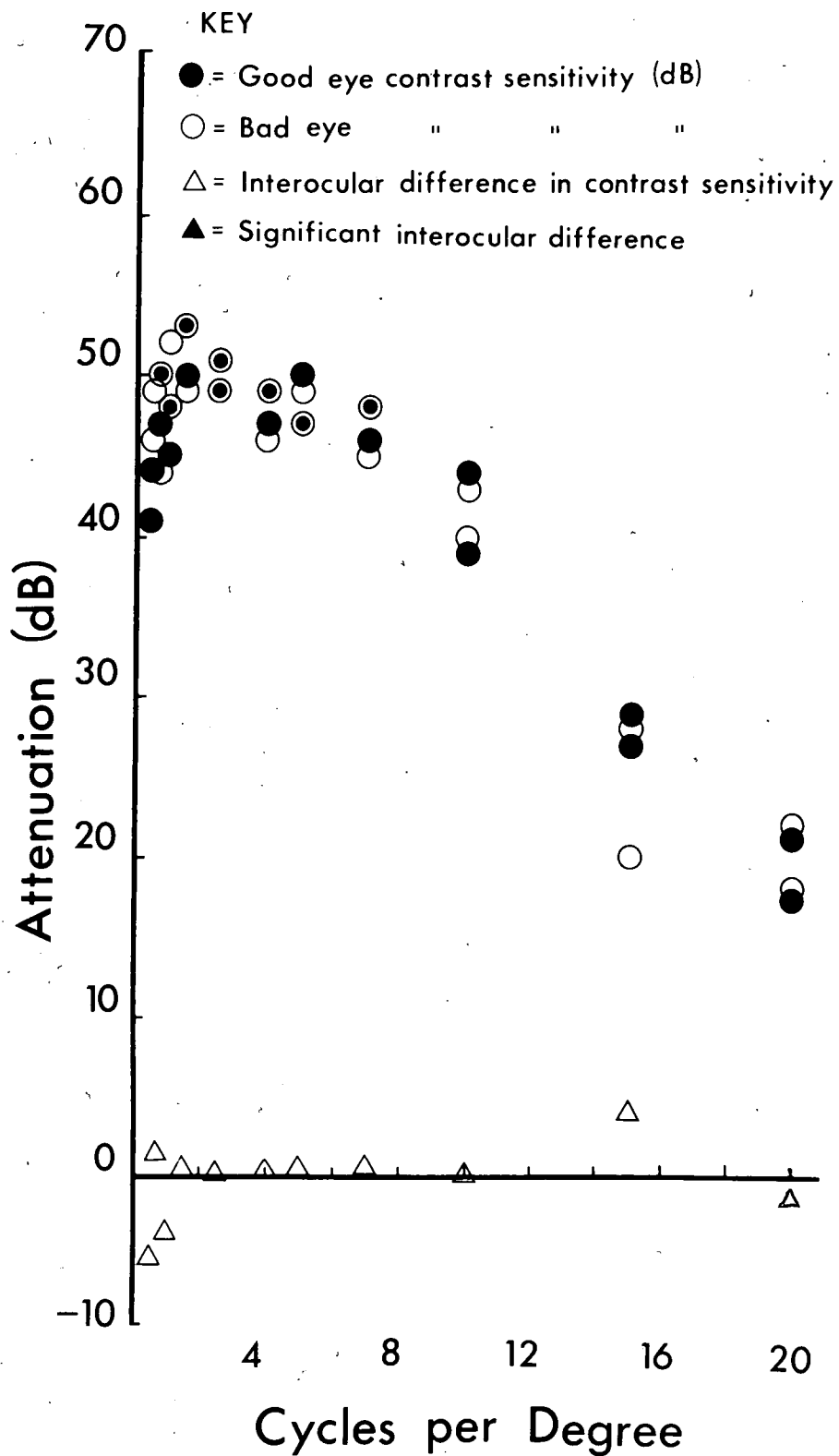
Figure 4.3.

Contrast sensitivity functions of emmetrope NA obtained
with continuous presentation of gratings, and with right
and left eyes tested alternately at each spatial
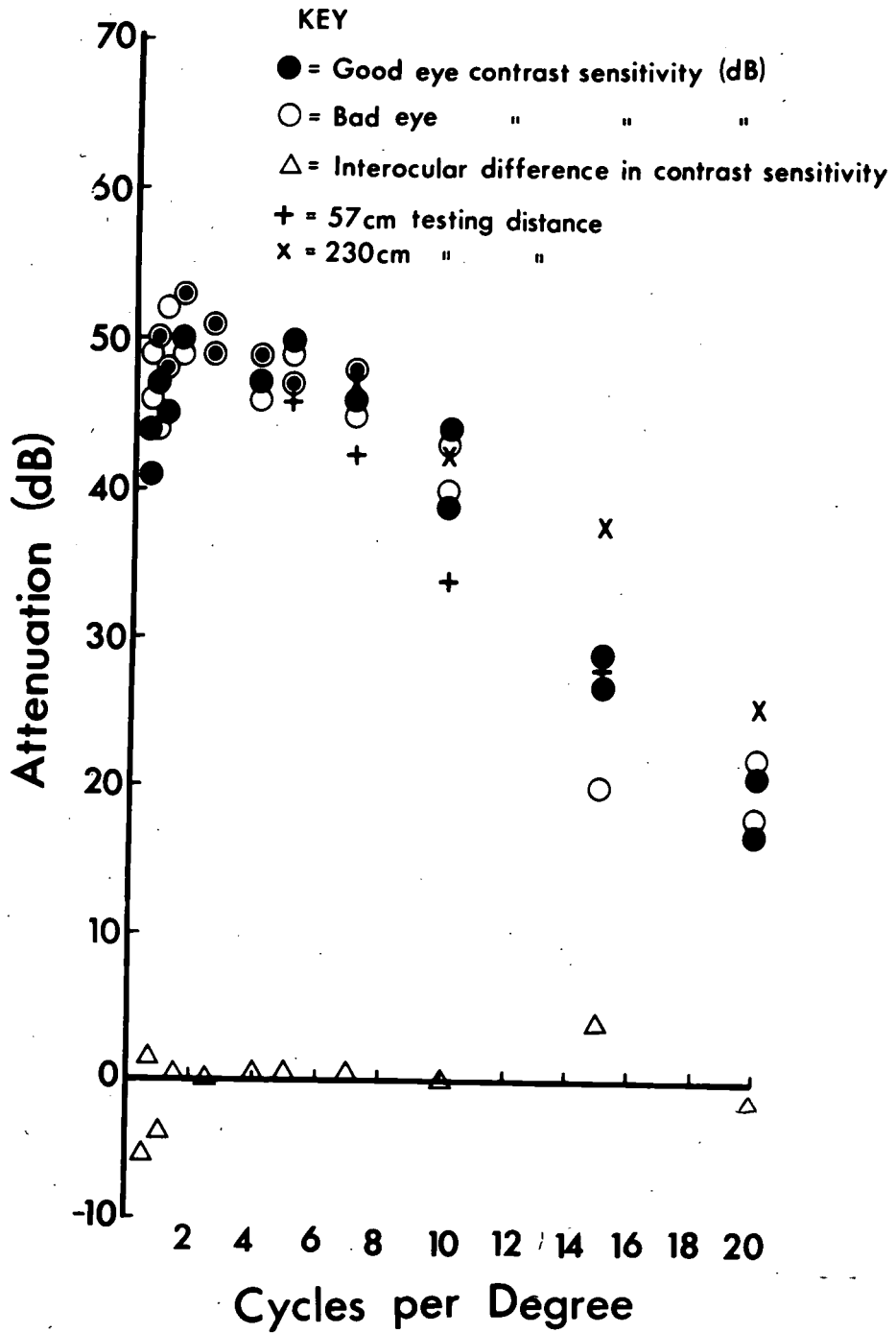frequency in an ascending series. Testing distance =
115 cm.

Figure 4.4.

Contrast sensitivity functions as shown in Fig. 4.3.,
with additional thresholds obtained by testing at
57 cm and 230 cms.

that the contrast of gratings produced with high modulation frequencies (> 5 cycles/cm) is degraded by the oscilloscope. High spatial frequency gratings obtained by increasing testing distance instead of modulation frequency do not suffer contrast degradation and therefore appear to raise contrast sensitivity.

In conclusion, there appears to be some advantage in testing contrast sensitivity to high spatial frequency gratings at greater distances in order to avoid using high modulation frequencies, but for the purposes of interocular comparison, and with due regard for expediency, a single testing distance would seem to be adequate.

### 4.3.4. Pilot Study 4.3: to investigate the effect of order of testing on interocular differences in contrast sensitivity.

This investigation simply required the comparison of data from the continuous presentation mode in Pilot Study 4.1 where eyes were tested consecutively (fig. 4.1) with data from Pilot Study 4.2, testing distance 115cm, (fig. 4.3) where eyes were tested alternately.

The effect of order of testing on the magnitude of interocular differences was evaluated without making equivariance assumptions, and was found to be insignificant ($p > 5\%$). Hence the more convenient order of testing can be chosen. The consecutive testing procedure was more quickly administered because the occluder did not require moving from one eye to the other between trials.

## 4.4 CONTRAST SENSITIVITY IN NORMAL EMMETROPIC SUBJECTS

### 4.4.1 Pilot Study 4.4: to investigate random variability in contrast sensitivity.

The three foregoing pilot studies led to the selection of a basic procedure for measuring contrast sensitivity, and this was used to test three more emmetropic subjects. The main purpose of this pilot study was to determine the levels of interocular difference in contrast sensitivity which might occur due to random variability between testing the two eyes, and between pairs of normal eyes. All three subjects had equally perfect eyes.

Procedure

The continuous presentation mode was used with a staircase procedure and consecutive testing of the right and then left eye of each subject. Methodological details are given in the preceding studies.

Results

As before contrast thresholds were plotted against spatial frequency, and the functions obtained were essentially the same as those shown in fig.4.1. No significant interocular differences in contrast sensitivity were found at any spatial frequency.

In order to evaluate the functions more fully several other features were compared. For each eye the following data values were noted: 1) spatial frequency at which peak contrast sensitivity occurred, 2) the slope of the least-squares regression line fitted to data points to the right of the peak, 3) the spatial frequency at which the regression line cut the abscissa. These parameters have been mentioned by previous workers (see Chapter 5). The three values, referred to as peak, slope and cut-off, are

given in Table 4.1 with interocular differences for each
measure, and data for the subject used in Pilot Studies
4.1 - 3 is also included. All least squares regression
lines attained linear correlations between 0.92 and 0.99.

Table 4.1.  Contrast sensitivity data for emmetropic subjects

| name | good eye peak (c/deg) | bad eye peak (c/deg) | peak diff | good eye slope | bad eye slope | slope diff. | good eye cut-off (c/deg) | bad eye cut-off (c/deg) | cut-off diff. |
|---|---|---|---|---|---|---|---|---|---|
| NA | 0.5 | 1.5 | 1.0 | -1.6 | -1.4 | +0.2 | 28.9 | 31.2 | +2.3 |
| DB | 2.0 | 2.0 | 0.0 | -1.8 | -1.8 | 0.0 | 30.2 | 28.3 | -1.9 |
| CJ | 1.5 | 1.5 | 0.0 | -1.3 | -1.3 | 0.0 | 31.0 | 33.1 | +2.1 |
| CS | 1.5 | 1.5 | 0.0 | -2.6 | -3.3 | -0.9 | 20.7 | 16.5 | -4.2 |

## Discussion

Assuming that these four emmetropic subjects had perfectly
identical eyes, the tabulated interocular differences must
be considered negligible and due to random variability or
the non-reliability of the apparatus and procedure. This
assumption will provide a baseline for the evaluation of
interocular differences in the various measures with non-
emmetropic subjects, which are described in later experiments.
Thus the following criterion levels will be used to distinguish
'significant' interocular differences in peaks, slopes and
cut-offs: peak shift > 1.0, slope difference > 1.0, cut-off
difference > 5.0 cycles/deg.

## Results and Discussion

Averaged evoked responses to the twelve stimuli are shown in Figs.4.5, 4.6 and 4.7.  Fig.4.5 shows responses to the 0.5 cycles/deg gratings which were presented with impedances of 10,30,40 and 50 dB.  As before, contrasts are specified in decibels since luminances could not be precisely measured.  Vertex recordings show prominent $N_1$ and $P_2$ peaks at all but the lowest contrast, at which the record is indistinguishable from random noise.  Peak-to-peak amplitude appears to decrease with decreasing contrast, and there also seems to be a slight increase in latency, $N_1$ occurring about 25 msecs later at 40 dB than at 10 dB.  A latency effect is also evident in the occipital recordings, although the amplitude-contrast relationship is less apparent.

Fig.4.6 shows recordings from 0.9 cycles/deg gratings.  Once again $N_1$ and $P_2$ are more prominent in vertex recordings than in the occipital ones.  Whereas the peaks had disappeared at 50 dB for the 0.5 cycle/deg grating, here they are still apparent.  Records at 70 dB resemble random noise.  Again there is some suggestion of a latency effect.  Fig.4.7 shows data for gratings of 5 cycles/deg which are essentially similar to those in figs.4.5 and 4.6.

Precise threshold values at which $N_1$ and $P_2$ amplitudes become negligible were not measured, since this entire procedure was extremely time-consuming.  The general trend of the results is in keeping with the psychophysical data obtained from the same subject in Pilot Study 4.1.  The psychophysical contrast thresholds at these three spatial frequencies with briefly presented stimuli were 40, 43 and 38 dB in ascending order of spatial frequency.

The duration and technical complexity of this method makes it unsuitable for use in plotting detailed contrast
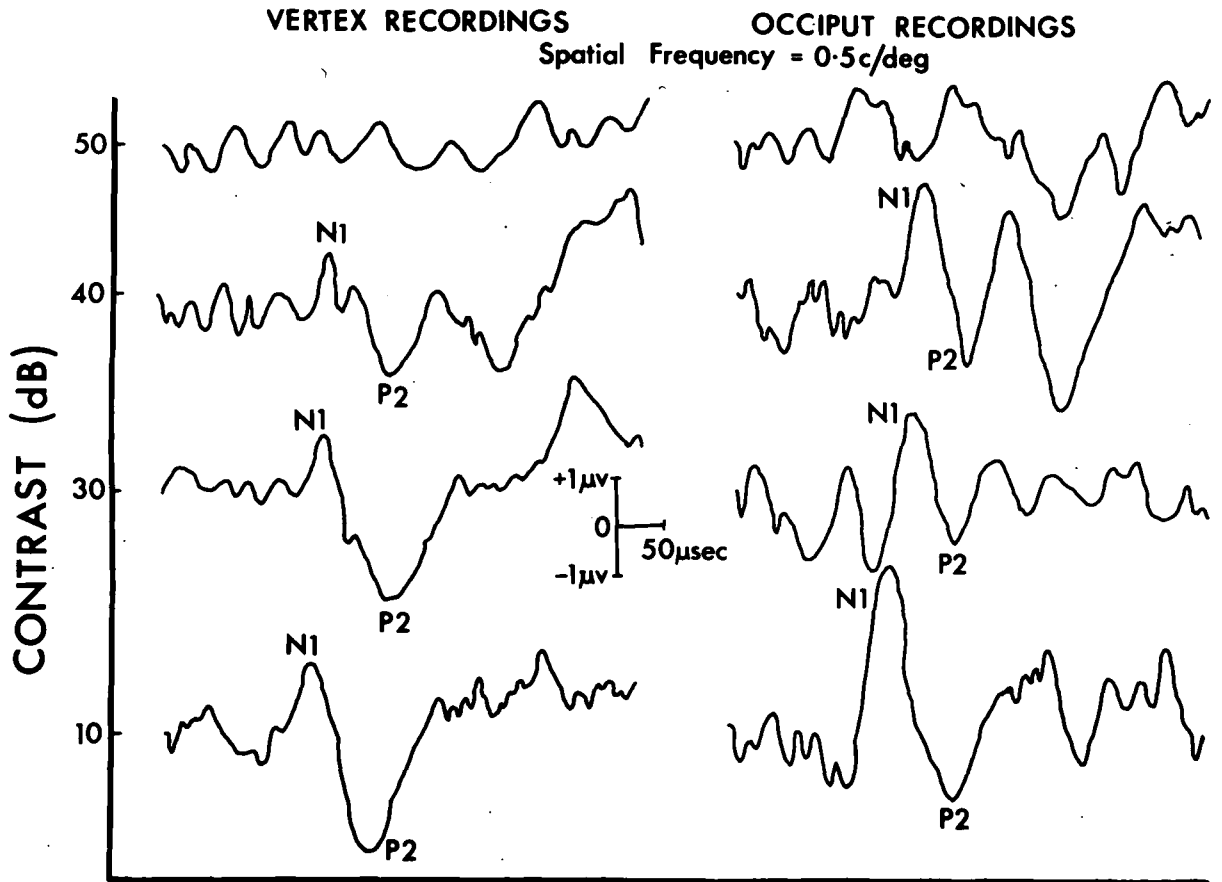
Figure 4.5.

Visually evoked cortical potentials recorded from emmetrope NA. Scalp recordings were taken from the vertex and the occiput. The subject viewed briefly presented (10 msec.) gratings of spatial frequency 0.5 cycles per degree. See text for further details.
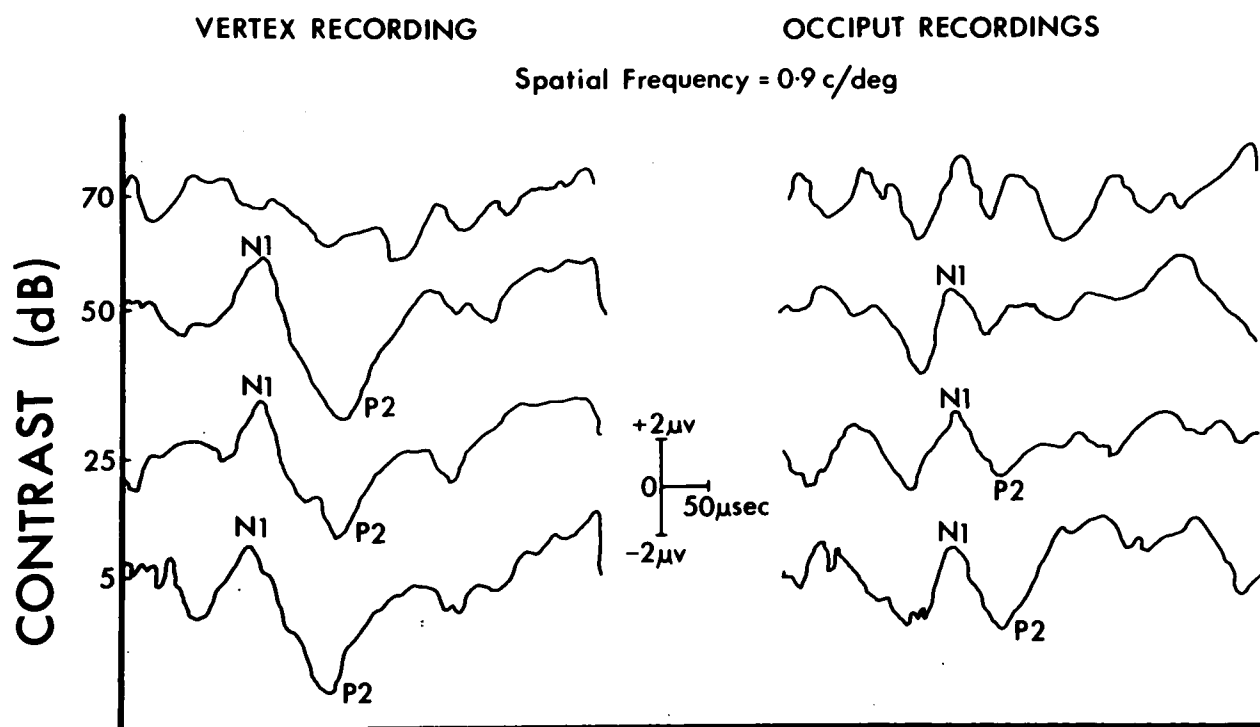
Figure 4.6.

As fig. 4.5; recordings obtained while subject viewed gratings
of 0.9 cycles per degree.
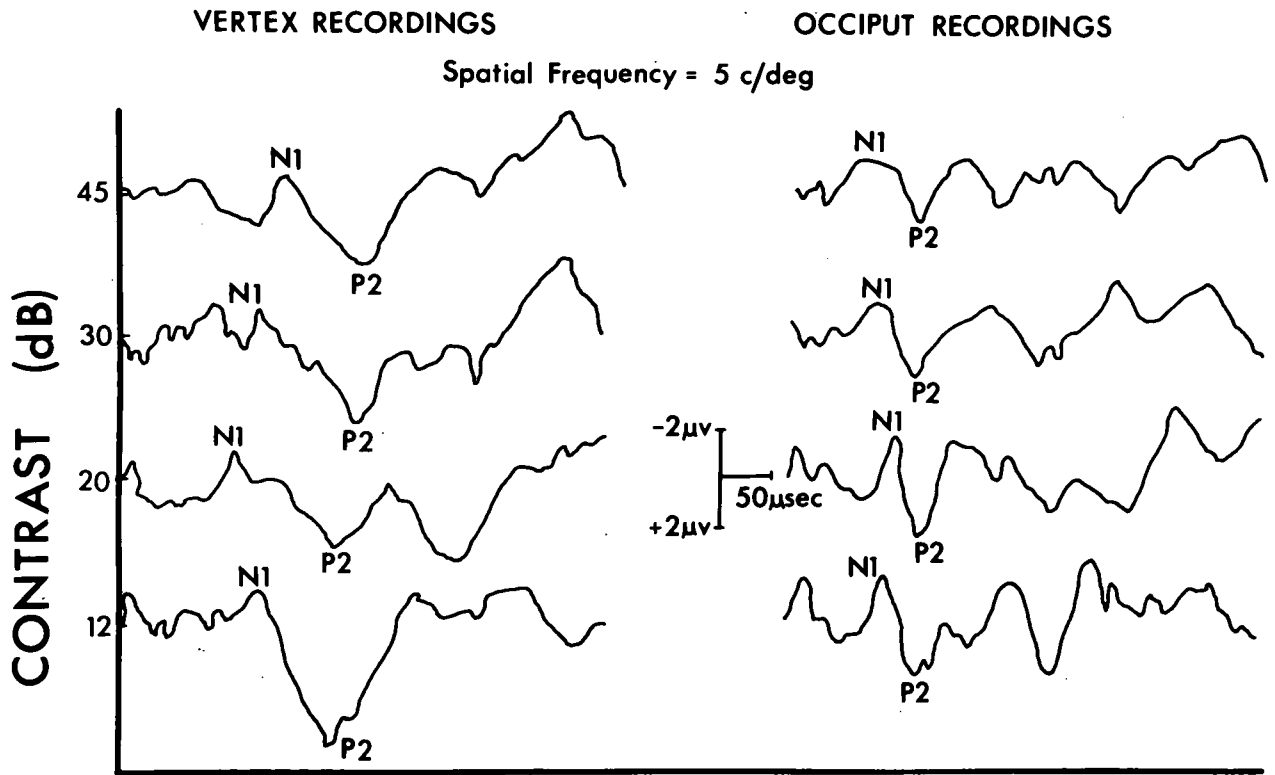
Figure 4.7.

As fig. 4.5; recordings obtained while subject viewed gratings
of 5.0 cycles per degree.

sensitivity functions, the preceding psychophysical methods being much simpler and less tedious for the subject.

CHAPTER 5 :   CONTRAST SENSITIVITY IN HUMAN SUBJECTS
              WITH VISUAL ABNORMALITIES.

5.1.  Introduction

In Chapter 1 the advantages of using contrast sensitivity
data to describe visual function were indicated.   In
recognition of these advantages Bodis-Wollner (1972) studied
contrast sensitivity in 16 patients with clinically-diagnosed
lesions involving the visual pathway.   Most of them showed
reduced contrast sensitivity at high spatial frequencies
only, but one patient seemed to have a specific loss for
medium spatial frequencies (2 - 10 cycles/deg).   Bodis-
Wollner felt that this finding supported the channel model
of visual processing.   In a later report Bodis-Wollner (1976)
demonstrated that patients with cerebral lesions involving
visual areas of the brain had reduced contrast sensitivity
and reduced evoked potential amplitude for high spatial
frequency gratings.   During recovery these patients reported
improvements in visual acuity, and contrast sensitivity and
evoked potential amplitude increased concurrently.   Bodis-
Wollner suggested that the apparent specific vulnerability
of high spatial frequency channels to certain types of
cerebral lesions might support the existence of two types of
spatial precessors with different spatial frequency ranges
and different neuropharmacological requirements.
Sjostrand and Frisen (1977) demonstrated that the contrast
sensitivity  function was a better descriptive measure of
the visual handicap caused by macular disease than Snellen
acuity.   Their patients showed contrast sensitivity losses
at all spatial frequencies above 2 cycles/deg.   The clinical
value of contrast sensitivity measurements has been realised
by the ophthalmological world in the last two years, and

its acceptance is illustrated by the recent proliferation of papers reporting contrast sensitivity data with various ocular disorders, e.g. Arden (1978), Arden and Gucokoglu (1978), Arundale (1978), Minassian et al (1978). Some of these papers will be discussed in more detail in connection with a clinical contrast sensitivity test devised by the author.

Non-pathological visual abnormalities have also been found to affect contrast sensitivity. Freeman, Mitchell and Millodot (1972) found an orientation-specific contrast sensitivity deficit in subjects with high amounts of astigmatism, even when optical components were bypassed and gratings were imaged directly on the retina. Freeman and Thibos (1973) demonstrated the same phenomenon by recording visually evoked cortical potentials from astigmatic subjects. However, two of their highly astigmatic subjects did not show any orientation-specific differences: they had received optical corrections at the ages of 2 and 3 years respectively. None of the subjects described by Mitchell et al (1973) were corrected before the age of 6 years and all appeared to be 'meridional amblyopes' i.e. amblyopic for certain grating orientations only. Further evidence of meridional amblyopia has been presented by Mitchell and Wilkinson (1974), Freeman and Thibos (1975), and Freeman (1975), all of whom found contrast sensitivity reductions at all spatial frequencies when gratings were presented at the 'amblyopic' orientation.

These findings seem to suggest that abnormal early visual experience affects future visual capacities very specifically. Types of stimuli not encountered in early infancy (because of optical blurring in this case) remain undetectable throughout life. Since Freeman, Mitchell and Millodot (1972)

have eliminated the possibility that optical factors cause
meridional amblyopia, neural plasticity must be responsible
for this apparent encoding of early visual experience.  The
various mechanistic explanations which have been proposed
to locate the site of plasticity in the visual system have
already been discussed (Chapter 2).

When the experiments to be described were started (March
1976) there was only one published report of contrast
sensitivity in normal (i.e. not meridional) amblyopia.
Gstalder and Green (1971) found reductions in contrast
sensitivity at high spatial frequencies (> 6 cycles/deg) in
two amblyopic subjects.  During the last three years several
papers on this subject have appeared in the literature, and
these will be briefly reviewed here.

Fiorentini and Maffei (1976) described reduced contrast
sensitivity at all spatial frequencies in myopic amblyopes.
The shape of their contrast sensitivity functions was not
affected and the spatial frequency at which peak contrast
sensitivity occurred was not different from that of normal
subjects.

Levi and Harwerth (1977) found that anisometropic and
strabismic amblyopes had reduced contrast sensitivity
at all spatial frequencies, with a shift in peak contrast
sensitivity from 4 cycles/deg to 2 cycles/deg. They also
noted a flatter gradient at the low spatial frequency end
of the function, and a lower cut-off spatial frequency for
the amblyopic eye of each subject.  They looked at the effects
of duration of stimulus, optical blurring, eccentric fixation,
and neutral density filtration.  Their findings in these
studies will be discussed later.  They considered their
findings in the light of channel theories of visual processing
and suggested that amblyopes had defective sustained channels

for one eye, while its transient channels were normal.

Hess and Howell (1977) found two types of contrast detection
defect in strabismic amblyopes: one caused losses at high
spatial frequencies only, while the other caused losses at
all spatial frequencies.  They postulated the existence of
two different types of strabismic amblyopia and the
dichotomy could not be explained by any known characteristics
of their subjects.

Hilz, Rentschler and Brettel (1977) briefly reported that
myopic amblyopes had reduced pattern sensitivity while
strabismic amblyopes had reduced pattern and movement
sensitivity.  Optical blurring caused pattern and movement
sensitivity losses at high spatial frequencies only.

Thomas (1978) compared contrast sensitivities of central and
peripheral retinal areas for normal and strabismic amblyopic
eyes.  He found interactions between severity of acuity
reduction and the range of spatial frequencies over which
contrast sensitivity was reduced.  Severity of amblyopia
also influenced the extent of peripheral retina with
reduced contrast sensitivity.

More detailed discussion of these papers will be found later
in this chapter where my own experimental data are evaluated.

## 5.2. Experiment 5.1: Measurement of contrast sensitivity in amblyopes.

<u>Subjects</u>

The procedure for obtaining amblyopes has already been described (Expt 3.1 in Chapter 3) . At the time of this experiment 7 amblyopes were available. Their clinical conditions are summarised in Table 5.1, in alphabetical order.

<u>Design and Procedure</u>

The apparatus used to present sinusoidal gratings of different spatial frequencies and contrasts has been described in Pilot Study 4.1. The procedure in this experiment was similar to the continuous presentation conditio n in that study. The right eye of each subject was tested before the left, through an ascending series of spatial frequencies ranging from 0.1 to 20 cycles/ deg. At each spatial frequency descending and ascending thresholds were obtained as previously described. The grating display was continuously visible to the subject throughout the testing sequence. Threshold data was stored on magnetic disk and a Fortran program was written by the author to generate mean thresholds for each eye, and calculate interocular differences. The program also calculated significance levels for the differences, using a t test formula (Ostle, 1954) which did not require equivariance assumptions. Functions were plotted via a standard package program on N.U.M.A.C.

<u>Results</u>

In figs. 5.1 to 5.7 contrast thresholds in dB are plotted against spatial frequency in cycles per degree. The key refers to contrast sensitivity upon the assumption that the attenuation in decibels was inversely

Table 5.1 : Clinical data

| Name | Eye | Uncorrected acuity | Refractive error | Corrected acuity | Other clinical details |
|------|-----|-------------------|------------------|------------------|------------------------|
| MB | R | 0.7 | +1.00DS | 0.7 | Neonatal conjunctivitis; measles at 2 yrs; occlusion and orthoptics |
|  | L | 3.0 | +3.50/-2.50 x 90 | 3.0 | at 5-9 yrs, and 12 yrs. Glasses at 14 yrs. ANISOMETROPIC AMBLYOPIA. |
| SC | R | 1.5 | -0.25/-0.75 x 180 | 1.2 | Divergent strabismus first detected at 11 yrs; surgery, orthoptics and |
|  | L | 6.0 | +0.25/-2.50 x 180 | 0.8 | later glasses. STRABISMIC AMBLYOPIA. |
| BC | R | Not known because wearing contact lenses. No improvement in | | 1.5 | Glasses at 9 yrs because RE myopic and LE hypermetropic. Occlusion of |
|  | L | corrected acuity with pinhole. | | 2.0 | RE later. ANISOMETROPIC AMBLYOPIA. |
| ME | R | 1.7 | -0.75DS | 1.7 | Glasses at 14 yrs. ANISOMETROPIC |
|  | L | 1.0 | nil | 1.0 | AMBLYOPIA. |
| HE | R | Not known because wearing contact lenses. No improvement in | | 0.7 | Convergent strabismus since infancy. Glasses at 2½ yrs, then occlusion |
|  | L | corrected acuity with pinhole. | | 1.5 | and orthoptics. Surgery at 8 and 9 yrs. Cosmetic surgery at 39 yrs, but still has manifest convergent strabismus. STRABISMIC AMBLYOPIA. |
| AM | R | >10.0 | -5.00/-1.00 x 90 | 0.8 | Convergent strabismus corrected by |
|  | L | >10.0 | -5.00/-1.00 x 90 | 1.5 | occlusion at 6 yrs. STRABISMIC AMBLYOPIA. |
| PS | R | 0.8 | nil | 0.8 | Measles at 6 yrs, believed to be cause of reduction of L acuity. No treatment |
|  | L | 2.0 | nil | 2.0 | given. No strabismus. ORGANIC AMBLYOPIA. |

(Acuities are given as reciprocals of the Snellen fractions).
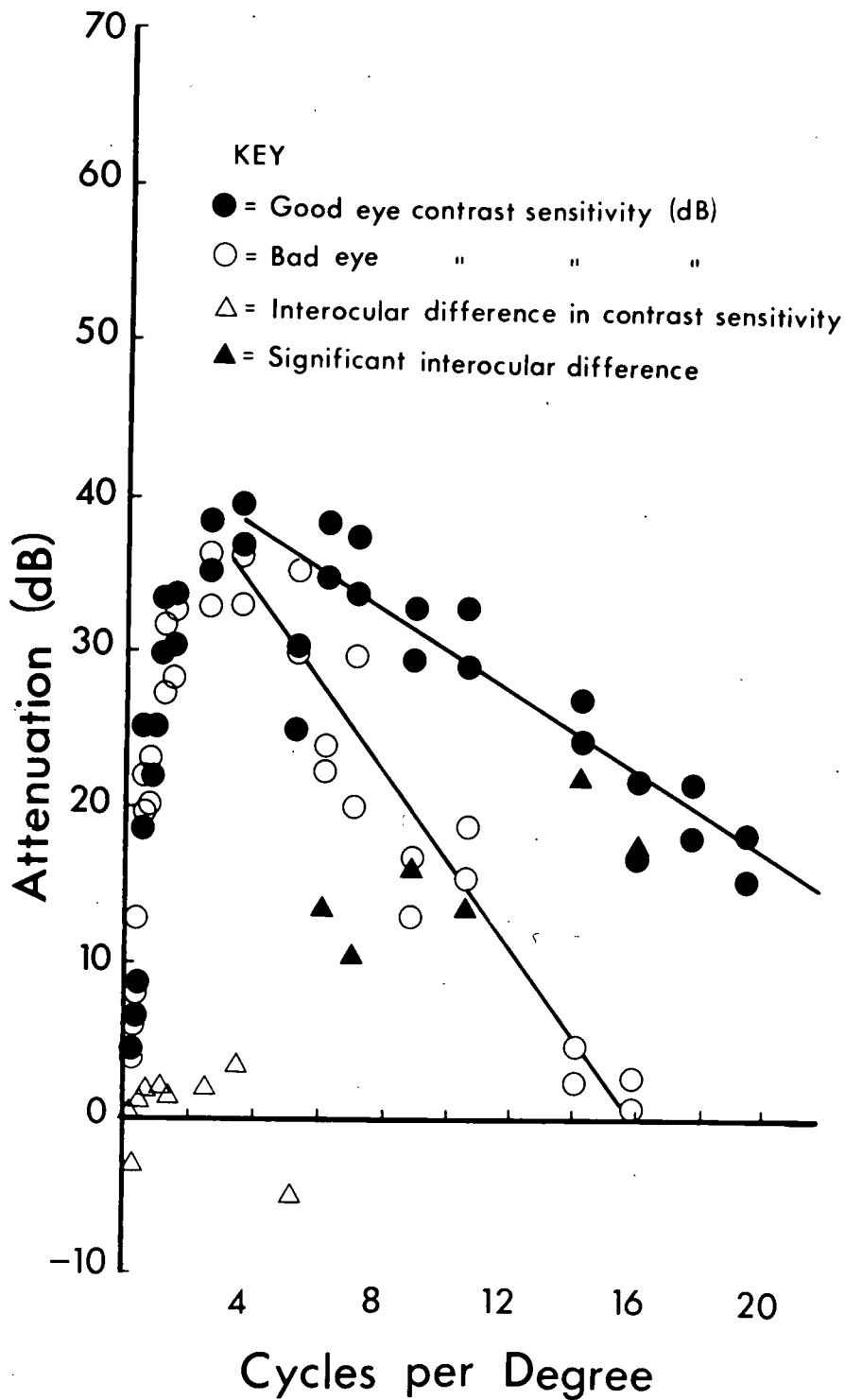
Figure 5.1.

Contrast sensitivity functions of both eyes of anisometropic amblyope MB, and interocular difference in contrast sensitivity. Least-squares regression lines have been fitted to data points to the right of the peak of each function.
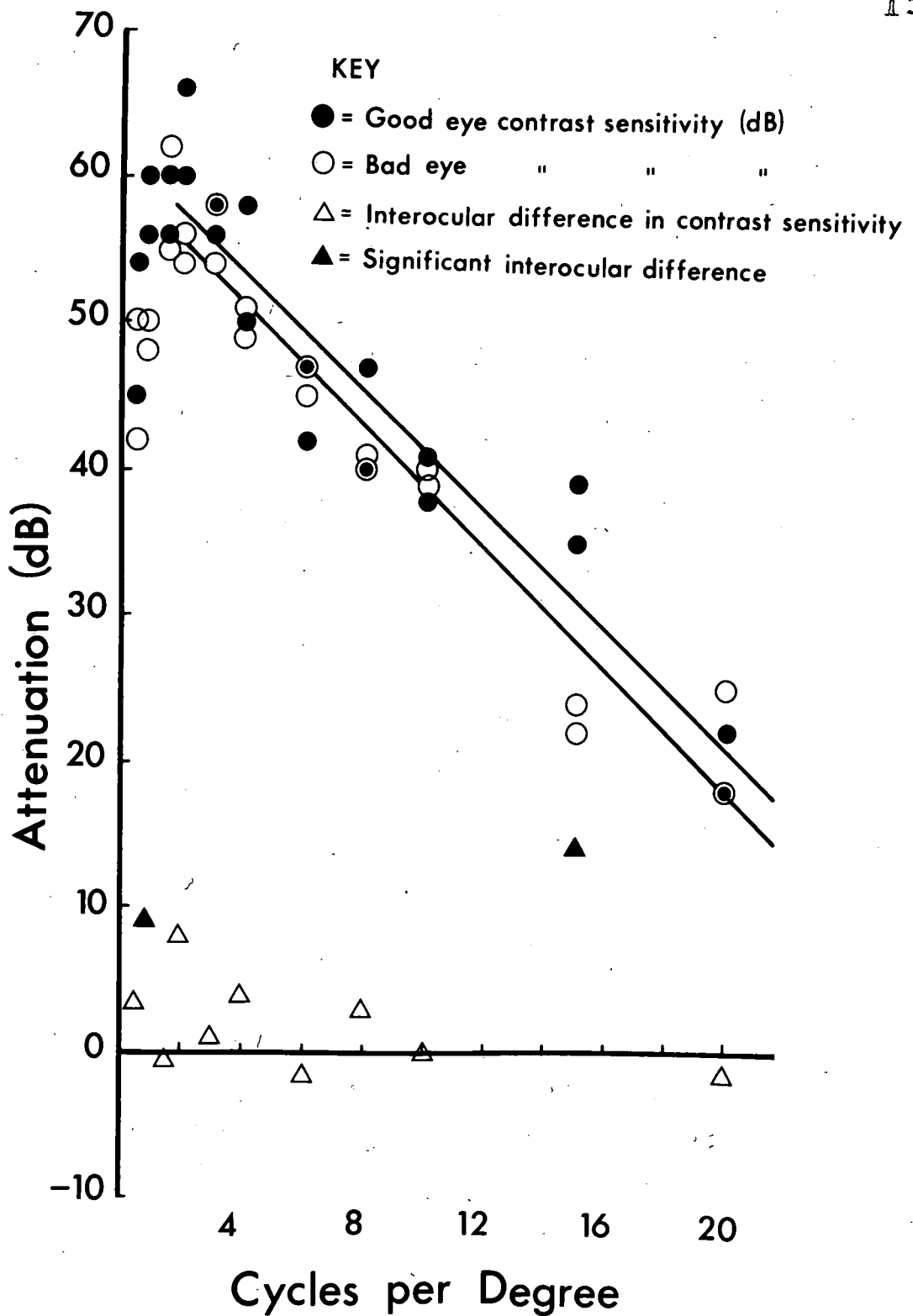
Figure 5.2.

Contrast sensitivity functions of both eyes of strabismic amblyope SC, with interocular differences and least-squares regression lines as in figure 5.1.

KEY

● = Good eye contrast sensitivity (dB)
○ = Bad eye    "    "    "
△ = Interocular difference in contrast sensitivity
▲ = Significant interocular difference
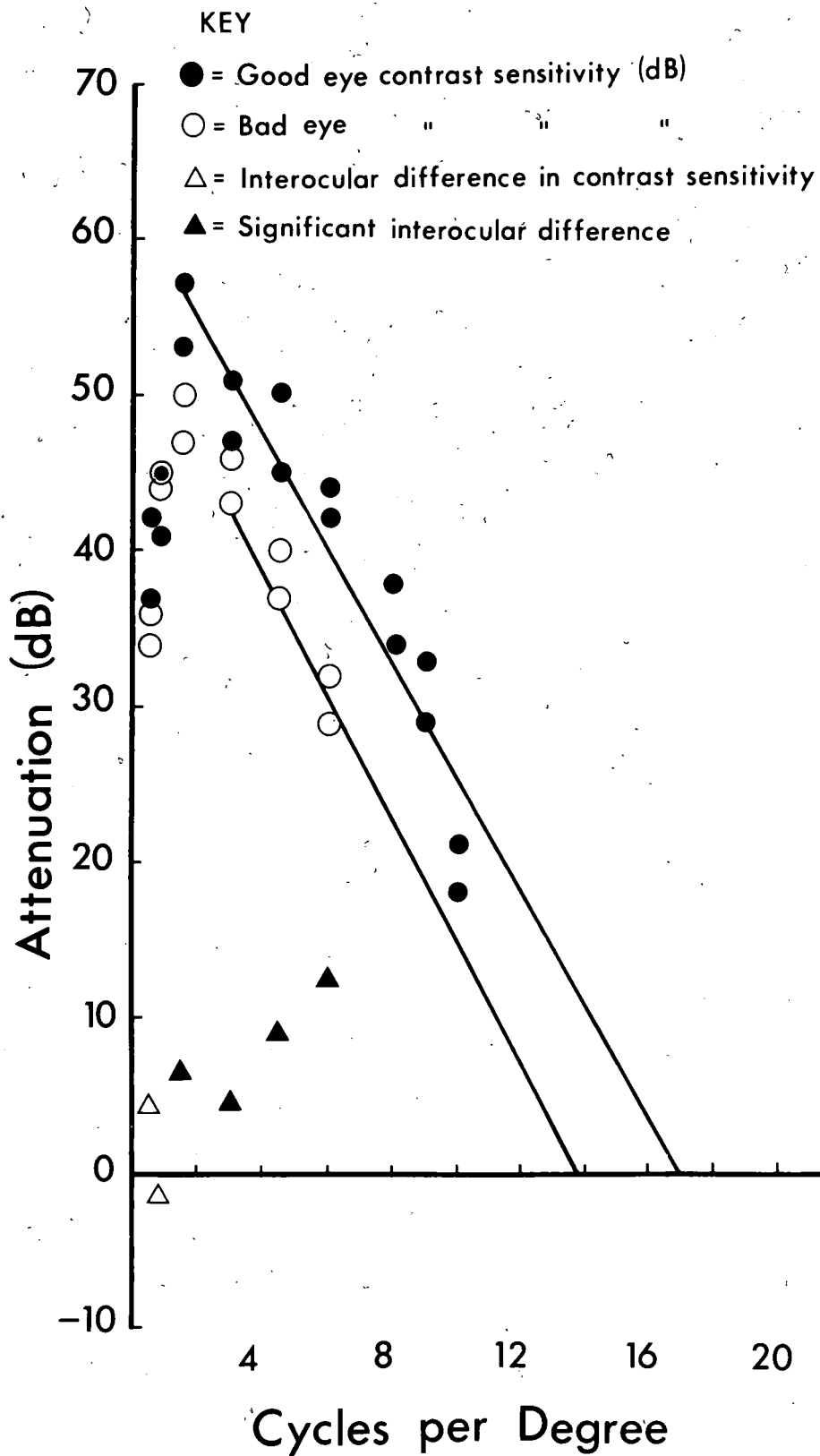
Figure 5.3.

Contrast sensitivity functions of anisometropic amblyope BC.
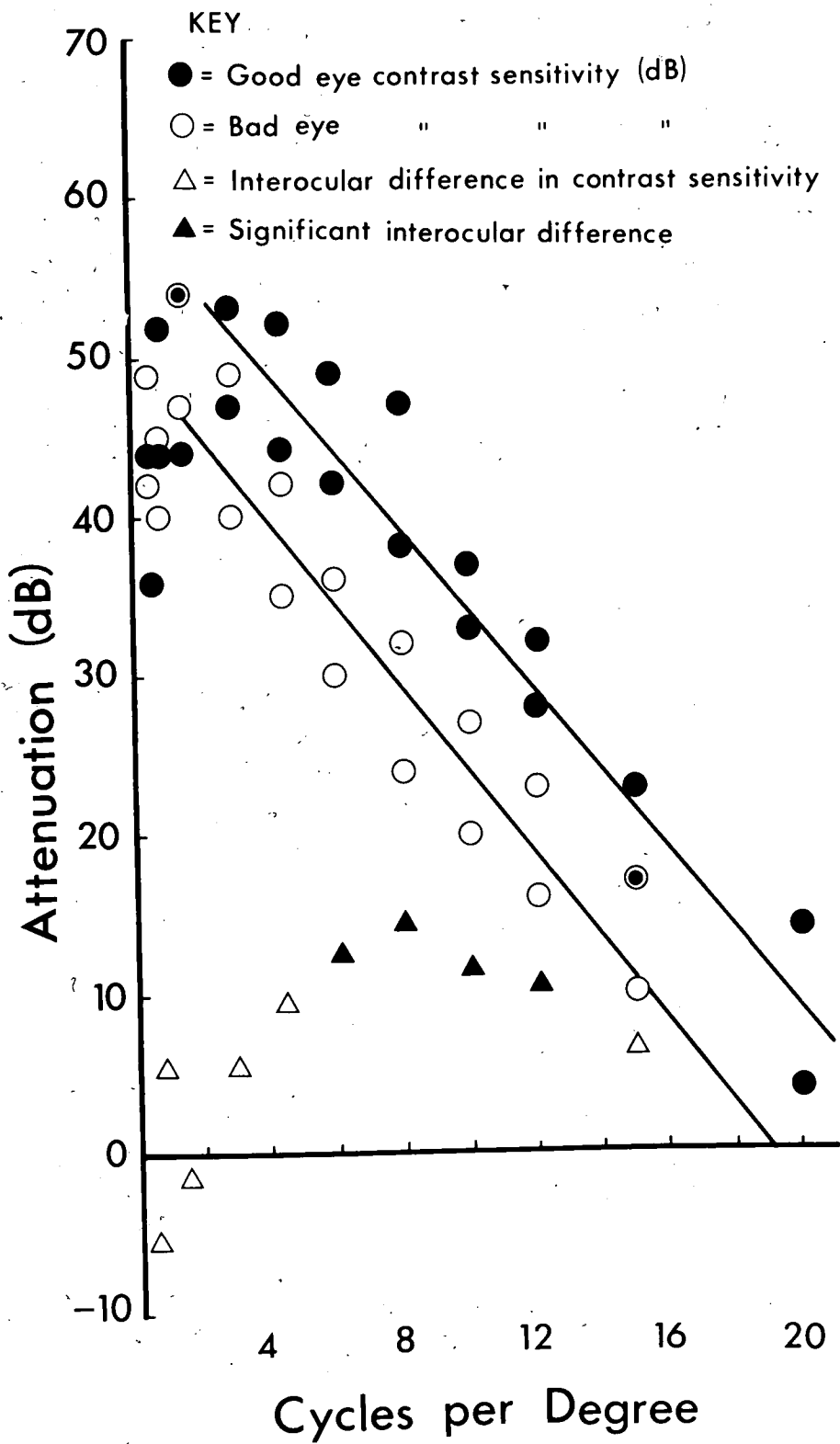
Figure 5.4.

Contrast sensitivity functions of anisometropic amblyope ME.
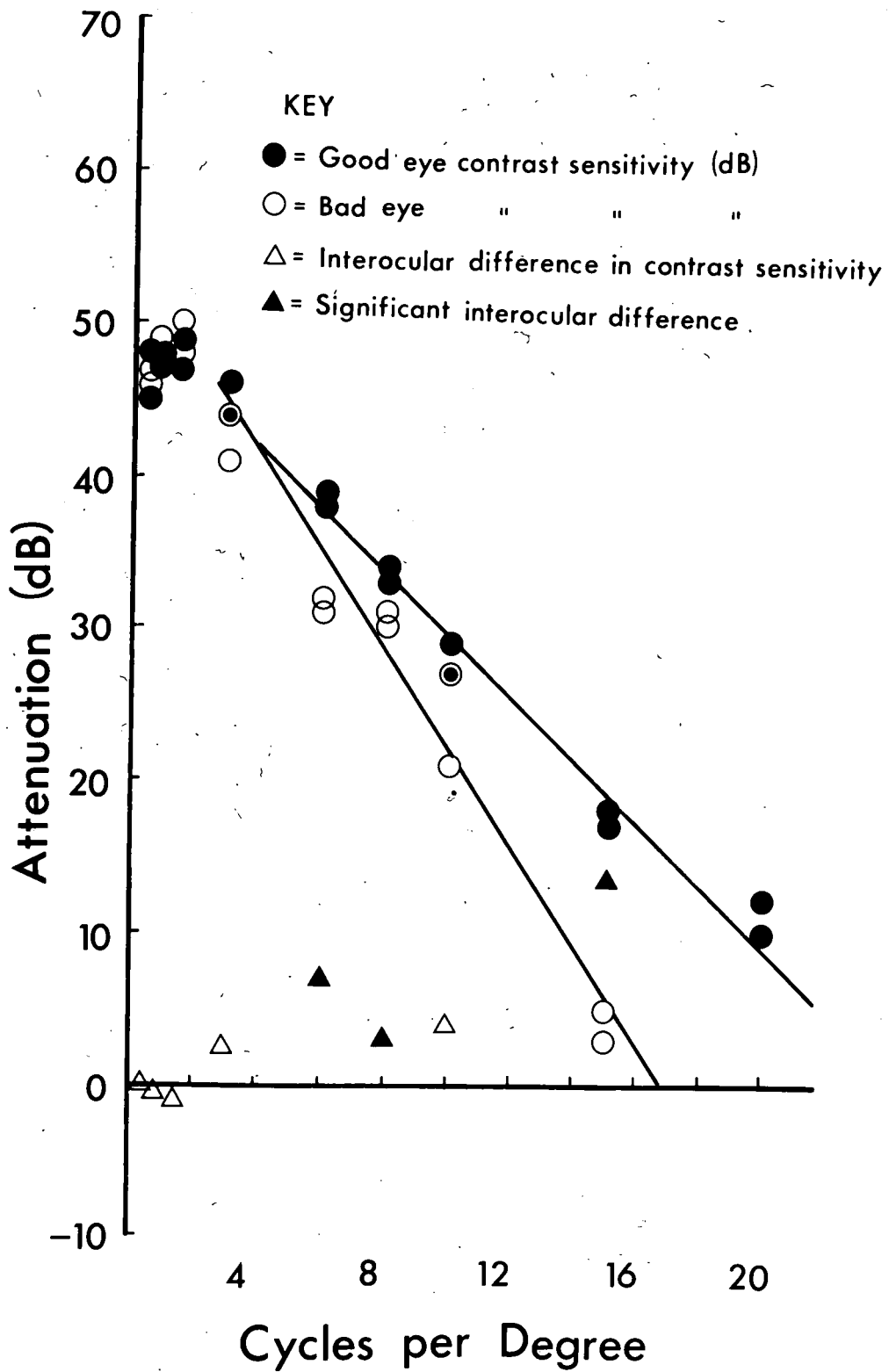
Figure 5.5.

Contrast sensitivity functions of strabismic amblyope HE.
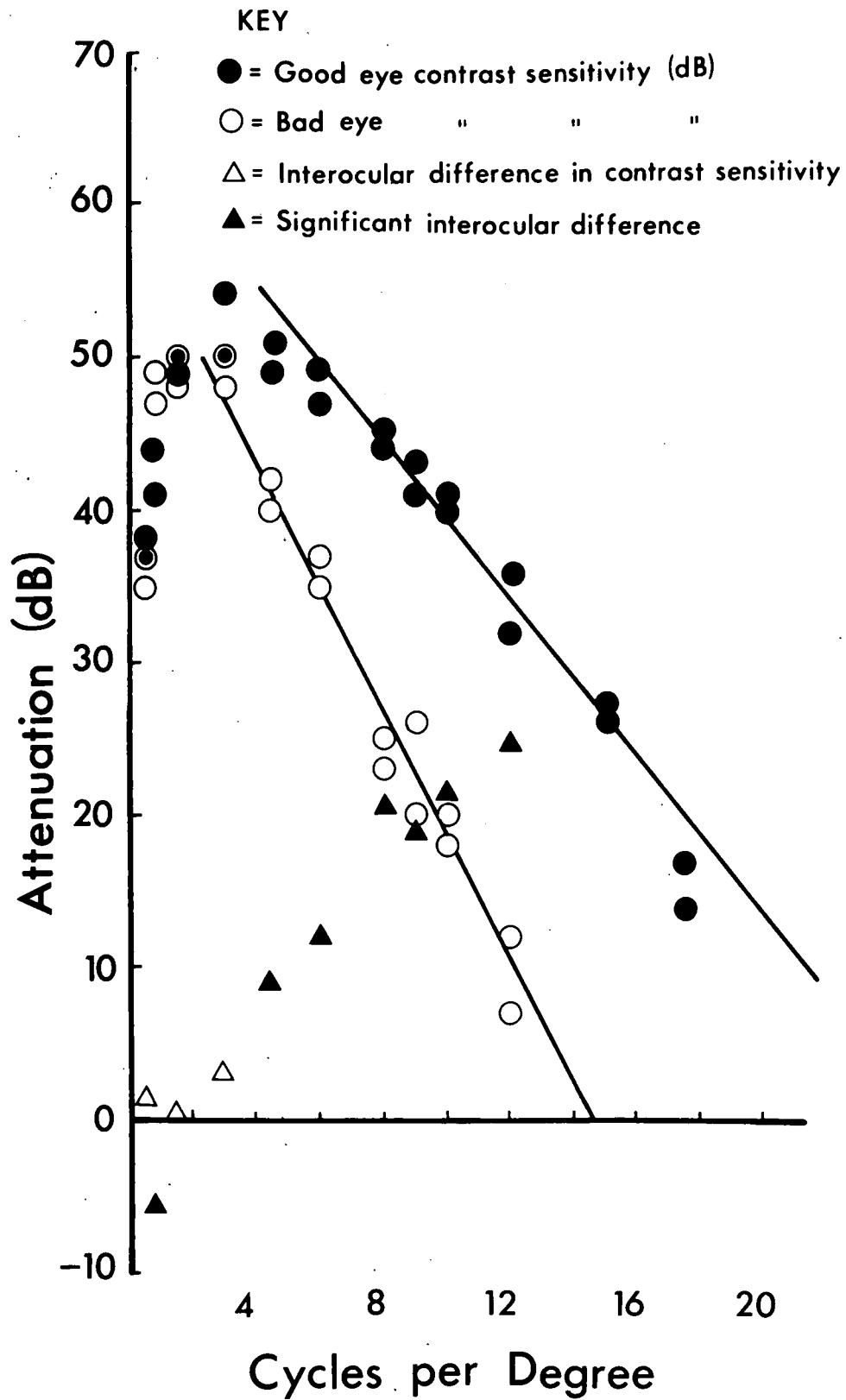
Figure 5.6.

Contrast sensitivity functions of strabismic amblyope AM.
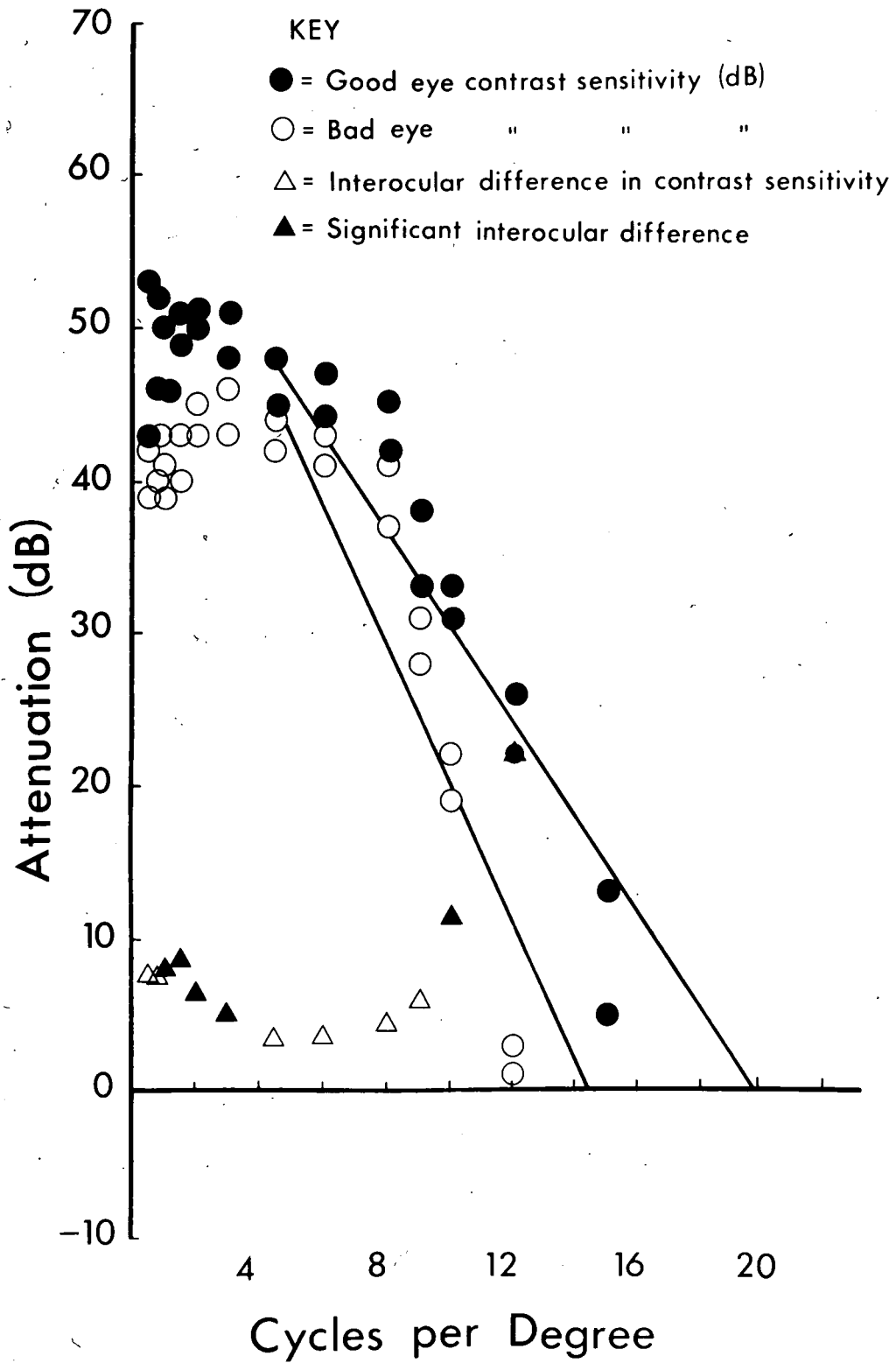
Figure 5.7.

Contrast sensitivity functions of organic amblyope PS.

proportional to log contrast. The figures show both thresholds obtained at each spatial frequency. The 'good eye' referred to in the key is the eye with higher Snellen acuity, and the bad eye is the amblyopic eye. Interocular difference in contrast sensitivity was calculated as the difference between the 'good eye mean threshold' and the 'bad eye mean threshold'. As in Pilot Study 4.1, the spatial frequency at which each eye reached its peak contrast sensitivity was noted, and least squares regression lines were fitted to all mean contrast thresholds at spatial frequencies to the right of the peak. Correlation coefficients for all eyes' regression lines were between 0.90 and 0.99. The slopes of the regression lines were calculated, and the lines were extrapolated to the abscissa to give a cut-off spatial frequency for each eye, i.e. the spatial frequency at which a grating of 100% contrast would be just detectable.

Table 5.2 shows the spatial frequency at which peak contrast sensitivity was found for each eye and the interocular peak shift for each subject. Only ME shows a peak shift greater than that found with the emmetropic subjects (see Table 4.1).

### Table 5.2.

| Name | Good eye peak (cycles/deg) | Bad eye peak (cycles/deg) | Peak shift |
|------|------|------|------|
| MB | 3.5 | 3.0 | -0.5 |
| SC | 2.0 | 1.5 | -0.5 |
| BC | 1.5 | 1.5 | 0.0 |
| ME | 3.0 | 1.5 | -1.5 |
| HE | 1.5 | 1.5 | 0.0 |
| AM | 3.0 | 2.0 | -1.0 |
| PS | 2.0 | 3.0 | +1.0 |

Table 5.3 shows the slope of the regression line for
each eye and the interocular slope difference for each
subject. Four subjects show slope differences greater
than the emmetropic subjects in Table 4.1.

### Table 5.3

| Name | Good eye slope | Bad eye slope | Slope difference |
|------|----------------|---------------|------------------|
| MB   | -1.3           | -2.7          | -1.4             |
| SC   | -2.1           | -2.1          | 0.0              |
| BC   | -3.7           | -4.0          | -0.3             |
| ME   | -2.5           | -2.7          | -0.2             |
| HE   | -2.1           | -3.2          | -1.1             |
| AM   | -2.5           | -4.0          | -1.5             |
| PS   | -3.1           | -4.4          | -1.3             |

Table 5.4 shows the cut-off spatial frequency for each
eye and the interocular difference for each subject. 5
subjects show greater interocular differences than the
emmetropes in Table 4.1.

### Table 5.4

| Name | Good eye cut-off spatial frequency (cycles/deg) | Bad eye cut-off spatial frequency (cycles/deg) | Interocular difference (cycles/deg) |
|------|-------------------------------------------------|------------------------------------------------|-------------------------------------|
| MB   | 33.4  | 15.9 | -17.5 |
| SC   | 30.2  | 28.2 | - 2.0 |
| BC   | 16.9  | 13.9 | - 3.0 |
| ME   | 23.6  | 19.1 | - 4.5 |
| HE   | 24.3  | 16.8 | - 7.5 |
| AM   | 25.4  | 14.7 | -10.7 |
| PS   | 19.8  | 14.6 | - 5.2 |

The significances of interocular differences in contrast
sensitivity at each of the tested spatial frequencies
were calculated without making any assumptions of equivariance.
Table 5.5 lists the spatial frequencies at which interocular
differences were significant at the 5% level of probability

(one-tailed), and the triangle symbols representing these differences are filled in figs 5.1 - 5.7.

### Table 5.5

| Name | Significant interocular differences |
|------|-------------------------------------|
| MB | 6 c/deg and above |
| SC | 0.8 c/deg and 15 c/deg |
| BC | 1.5 c/deg and above |
| ME | 6 c/deg and above (excluding 15 c/deg) |
| HE | 6 c/deg and above (excluding 10 c/deg) |
| AM | 4.5 c/deg and above |
| PS | 1 - 3 c/deg (inclusive) and 10 c/deg and above. |

## Discussion

All 7 subjects show some decline in contrast sensitivity at low spatial frequencies ($<1.5$ cycles/deg). It must be remembered that at 1 cycle/deg there were only 6 cycles in the display and for lower spatial frequencies there were proportionally fewer cycles. The effect of small numbers of cycles in a grating upon contrast sensitivity has already been discussed (Chapter 4), and this might be at least partially responsible for the low spatial frequency declines shown in the functions. However, assuming that the effect operates equally for both eyes, one might expect any interocular differences to remain evident. One subject (AM, fig. 5.6) has a significant negative interocular difference (amblyopic eye better). Two subjects show significant positive interocular differences to the left of the peak:(SC fig. 5.2 and PS fig. 5.7), and two subjects have significant positive interocular differences at their peak spatial frequency (BC fig 5.3, and PS fig 5.7). The remaining 4 subjects only have significant positive interocular differences at spatial frequencies to the right of their peaks.

4 subjects have clearly diverging con‿trast sensitivity functions at high spatial frequencies, indicating increasing interocular difference with increasing spatial frequency (MB, HE, AM, PS, figs. 5.1, 5.5, 5.6, 5.7). 2 subjects have approximately parallel functions (BC fig 5.3 and ME fig. 5.4) and one subject (SC, fig. 5.2) shows hardly any difference. His ocular condition is rather interesting. He was surgically treated for a right eye divergent strabismus at 11 years of age, and as expected the RE has the lower acuity. However the LE has the greater refractive error: (R = -0.25/-0.75 x 180; L = +0.25/-2.50 x 180) and in dissociation tests the RE is dominant. The left eye's astigmatism has its most deleterious effect for vertical gratings and one possible explanation for the closeness of his two functions might be that the LE has some meridional amblyopia which has lowered the function of the good eye to the level of that of the amblyopic eye. This explanation does not help to account for the RE dominance in dissociation tasks. Two possible reasons for this are i) extensive pre- and post-operative orthoptic training of the RE; ii) frequent non-use of his glasses resulting in the LE being the more blurred eye most of the time.

The two subjects with parallel functions are both anisometropic amblyopes, but the third anisometropic amblyope (MB) has diverging functions.

Despite the high correlation coefficients obtained for all least-squares regression lines some subjects' functions do appear to have non-linearities in them. BC's good eye function (fig. 5.3) looks paraboloid, with a cut-off spatial frequency in the region of 11 cycles/deg. There are not enough points in the bad eye function to be sure of a

similar curvature. There is some suggestion of a down-turn at the high spatial frequency end of AM's good eye function (fig. 5.6), while PS's functions (fig. 5.7) both appear to change gradient considerably after 8 cycles/deg.

Non-linearities confined to the high spatial frequency ends of functions might be caused by poorer stimulus quality for gratings generated at frequencies greater than 5 cycles/cm on the oscilloscope face, i.e. 10 cycles/deg at the testing distance used. However, both BC and PS seem to show non-linearities at lower spatial frequencies than this.

Early studies of non-amblyopic contrast sensitivity functions demonstrated that a linear relationship existed between spatial frequency in cycles/deg and the logarithm of contrast sensitivity (e.g. Campbell and Green, 1965). Most authors describing amblyopic contrast sensitivity functions have plotted both contrast sensitivity and spatial frequency on logarithmic scales, so that their functions are exponential curves. The exception is Freeman (1975) who used a linear spatial frequency scale, and fitted straight lines to his data points for spatial frequencies greater than that at which peak contrast sensitivity occurred. His subjects, who were meridional amblyopes, do not appear to show any interocular differences in the slopes of their functions. Obviously authors presenting their data as exponential curves do not discuss it in terms of interocular differences in slope, although some do mention changes in the shape of the function. Examination of their figures suggests that some of them (Hess and Howell, 1977, and Thomas, 1978) did find gradient changes in some of their subjects while others (Gstalder and Green, 1971; Fiorentini and Maffei,

1976; Hilz et al, 1977; Levi and Harwerth, 1977) did not.

Interocular differences between the spatial frequencies
at which peak contrast sensitivity was found were reported
(or illustrated) by Gstalder and Green (1971), Levi and
Harwerth (1977) and Thomas (1978), all of whom found that
some amblyopic eyes had peak contrast sensitivity at
lower spatial frequencies than their normal fellow eyes.
Freeman (1975), Fiorentini and Maffei (1976), Hess and
Howell (1977), and Hilz et al (1977) did not find any
peak shifts.

Interocular differences in cut-off spatial frequency are
mentioned by Freeman (1975) and Levi and Harwerth (1977)
and are also illustrated by all other authors who have
published data on amblyopic contrast sensitivity.
Gstalder and Green (1971) reported interocular differences
in contrast sensitivity at high spatial frequencies only,
whereas deficits at all spatial frequencies were found
by Freeman (1975), Fiorentini and Maffei (1976), and Levi
and Harwerth (1977). Some authors found both high spatial
frequency and broad spectrum contrast sensitivity reductions
in their samples of amblyopes (Hess and Howell, 1977 and
Thomas, 1977).

The evidence in the recent literature seems to have confirmed
the results of the experiment described above in showing
that amblyopic contrast sensitivity functions do not differ
from those of normal eyes in a simple predictable fashion.
Several types of difference can be found, and to date,
there have been no explanations to account for the existence
of these various types of contrast sensitivity deficit.

In order to determine whether some of the amblyopes'

contrast sensitivity deficits were simply a consequence of interocular acuity difference the following experiment was done, in which different degrees of interocular acuity difference were produced in an emmetropic subject with convex lenses. Thus the effects of optical blurring on contrast sensitivity were investigated and compared with the effects of amblyopia.

5.3 Experiment 5.2:    Contrast sensitivity in artificial
                        monocular myopia.

## Design and Procedure

Three different degrees of artificial myopia were produced
by placing convex lenses in front of one eye of an
emmetropic subject, in a clinical trial frame.  The lenses
used were +1.50 DS, + 3.00 DS, and +4.50 DS.

All procedural details were identical to those in Experiment
5.1 (see Pilot Study 4.1), except that the unfogged (right)
eye was tested first, and then the left eye was tested
with each of the convex lenses, beginning with the weakest
one.

## Results

The unfogged eye's function is reproduced on all three
figures (5.8, 5.9 and 5.10)
for the purposes of comparison.  As before data on peaks,
slopes and cut-offs is tabulated (Table 5.6).  All
regression lines have correlations greater than 0.99.

### Table 5.6

| | | | |
|---|---|---|---|
| Unfogged acuity (RE) | 0.7 | 0.7 | 0.7 |
| Fogged acuity (LE) | 3.0 | 6.0 | 25.0 |
| Fogging lens (DS) | +1.50 | +3.0 | +4.5 |
| RE peak (c/deg) | 1.5 | 1.5 | 1.5 |
| LE peak (c/deg) | 0.8 | 0.5 | 0.5 |
| Peak shift | -0.7 | -1.0 | -1.0 |
| RE slope | -1.4 | -1.4 | -1.4 |
| LE slope | -2.2 | -9.3 | -24.3 |
| Slope diff. | -0.8 | -7.9 | -22.9 |
| RE cut-off (c/deg) | 31.1 | 31.1 | 31.1 |
| LE cut-off (c/deg) | 18.5 | 4.6 | 1.9 |
| Cut-off diff. | -12.6 | -26.5 | -29.2 |

Figures 5.9 and 5.10 show interocular differences in
slope and all three figures show interocular differences
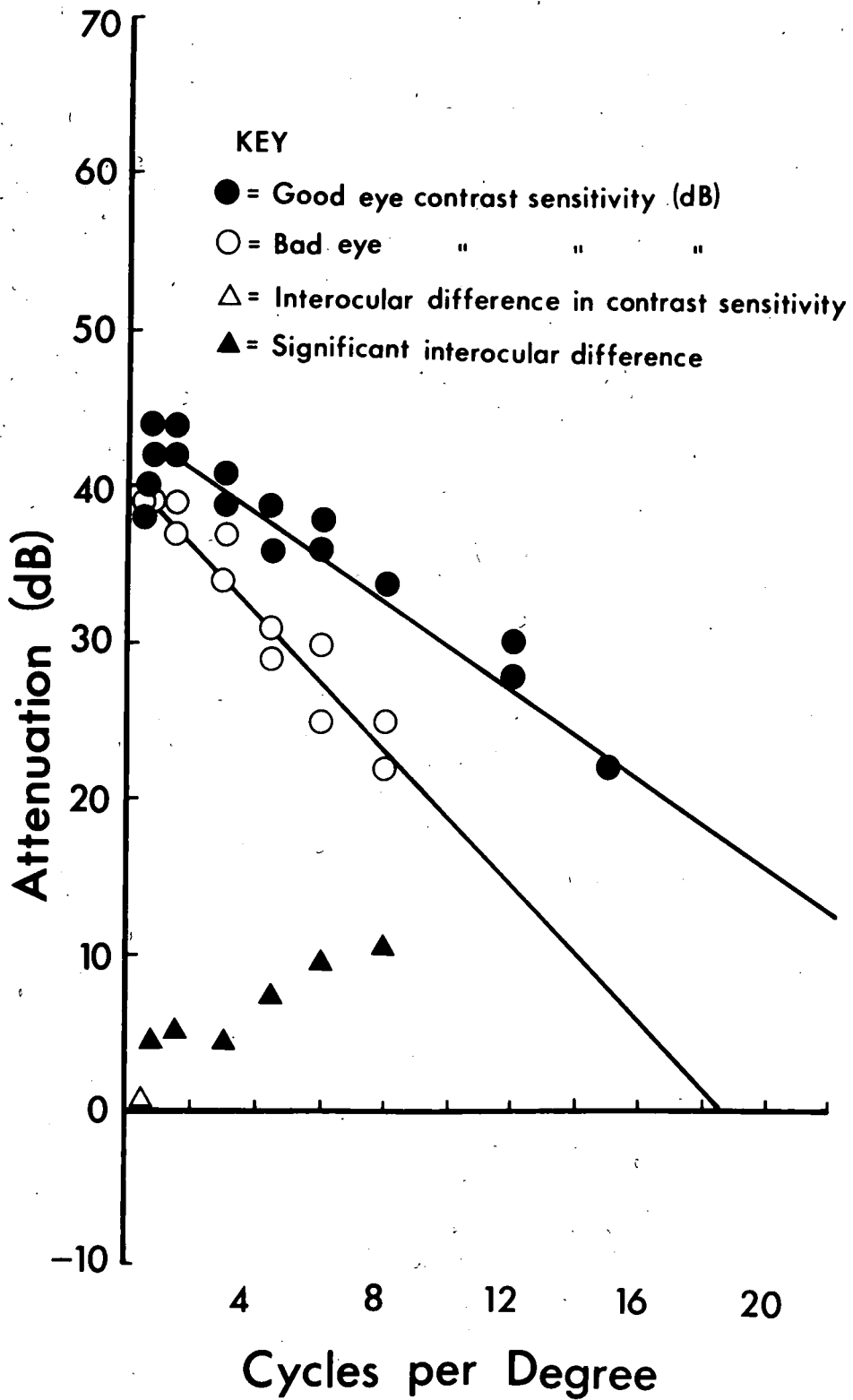in cut-off spatial frequency greater than those found in

Figure 5.8.

Contrast sensitivity functions of emmetrope NA with left ('bad') eye fogged by a +1.50 DS lens.
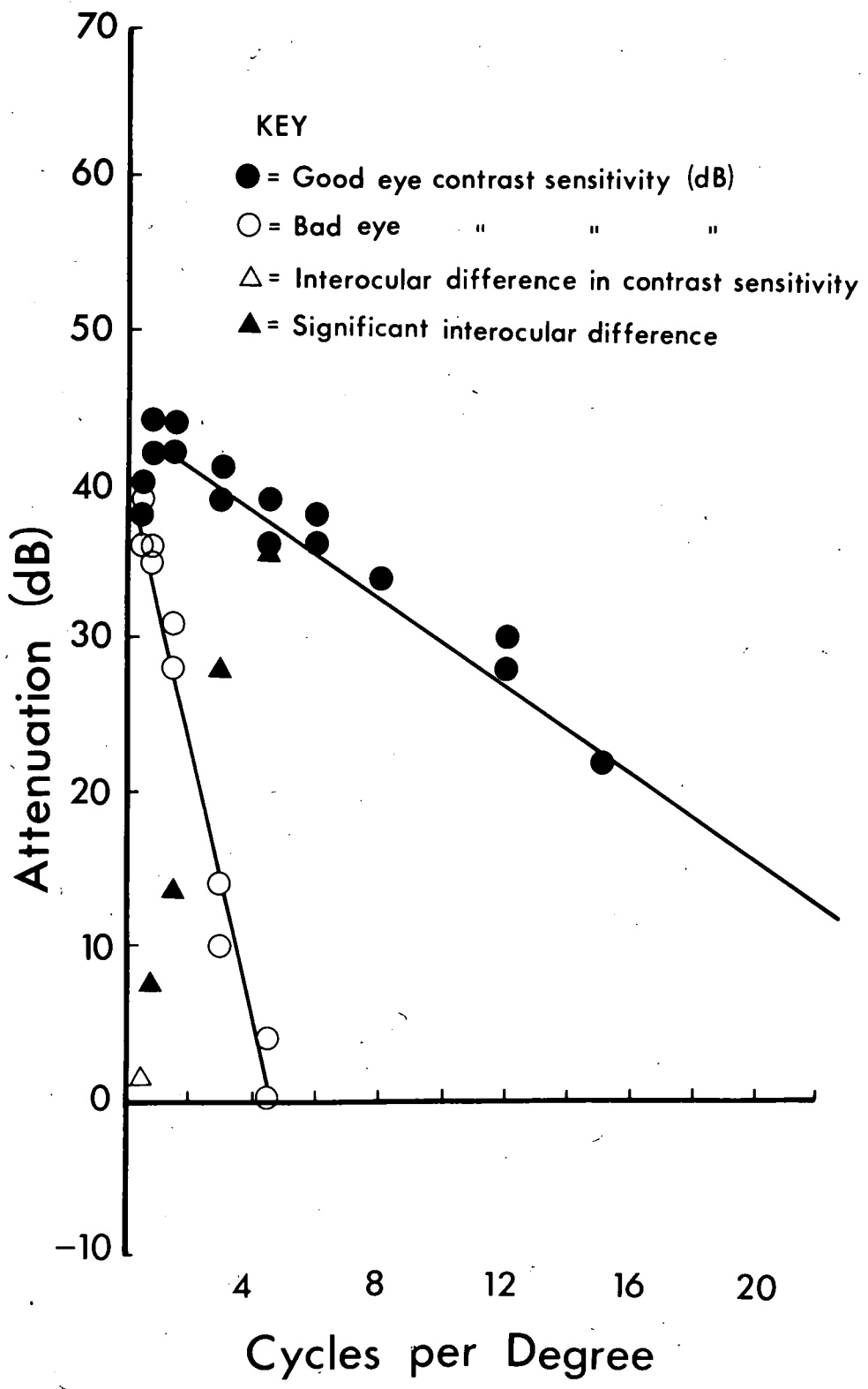
Figure 5.9.

Contrast sensitivity functions of NA with left eye fogged by a +3.00 DS lens.
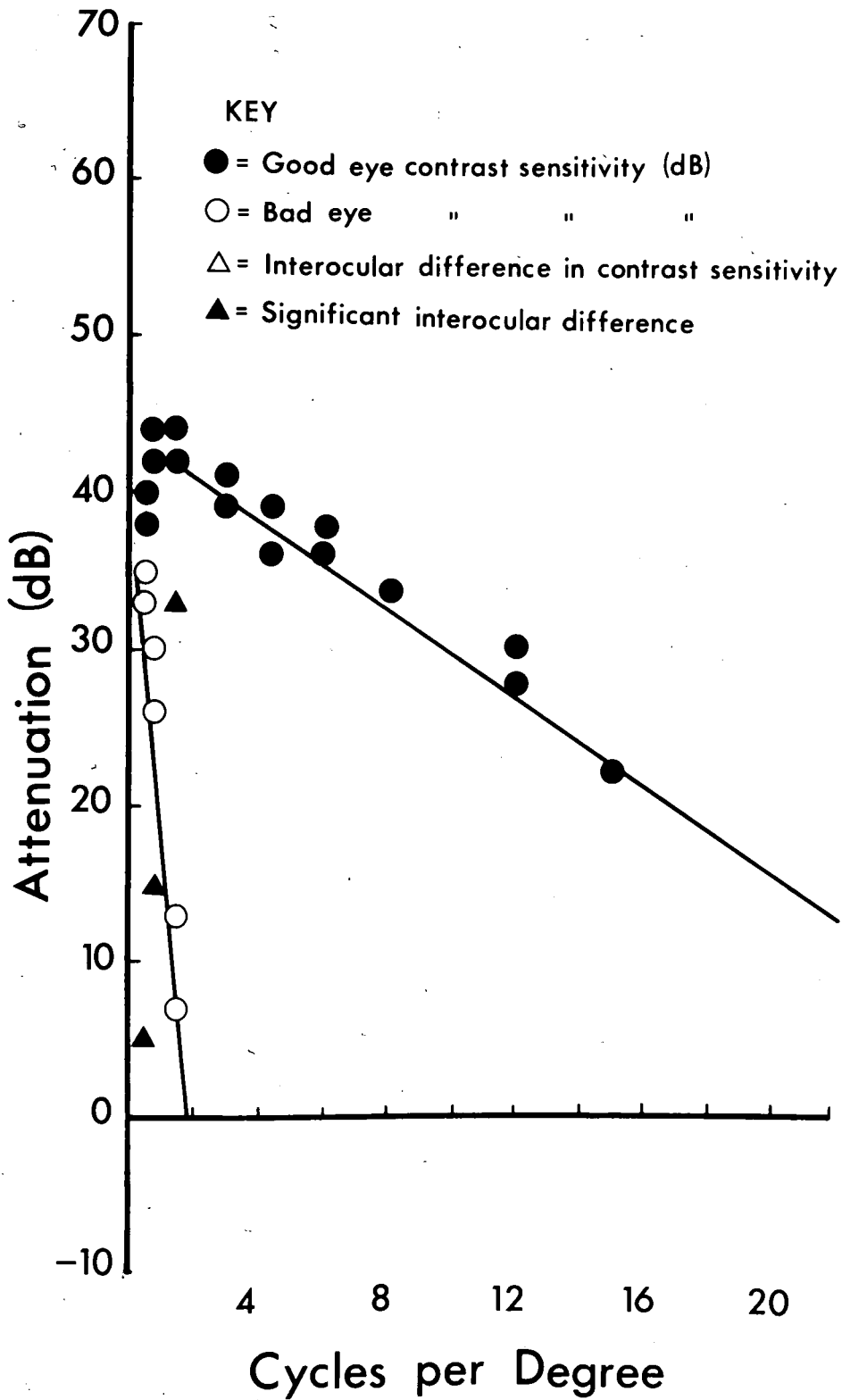
Figure 5.10.

Contrast sensitivity functions of NA with left eye fogged by a +4.50 DS lens.

the emmetropic group of subjects (Table 4.1). Significant interocular differences in contrast sensitivity occur at all but the lowest spatial frequency (0.5 cycles/deg) in figs. 5.8 and 5.9, and at all spatial frequencies in fig. 5.10. Peak differences are small. In fig. 5.8 there is some suggestion of a shift from 1.5 to 0.5 cycles/deg; in figs. 5.9 and 5.10 this shift is slightly more apparent but the lack of low spatial frequency data (< 0.5 cycles/deg) prevents any firm conclusions about peak shifts.

## Discussion

Fiorentini and Maffei (1976) illustrated the contrast sensitivity function of an emmetropic subject made monocularly myopic with a +1.00DS lens. They noted a distinct peak shift towards a lower spatial frequency and their figure does not show a noticeable gradient change. On the other hand, Levi and Harwerth (1977) found optical blurring lenses acted as high spatial frequency filters. Their figure shows increasing peak shifts and gradient changes with increasing (+1.00 DS, +2.00 DS, and +3.00 DS) degrees of blur. The results of the present experiment are comparable with those of Levi and Harwerth (1977) in that they show a dramatic change in gradient with myopic blurring.

The acuities obtained in this experiment, with the fogging lenses, were far worse than those of the amblyopic eyes tested in the previous experiment, as witnessed by comparison of tables 5.1 and 5.6. The subject was not given any time to adapt to his acuity deficit, whereas the amblyopic group had suffered their acuity deficits for several years. Therefore, in order to investigate the acuity deficit of amblyopia more precisely the following experiment was done, in which the subjects were

true monocular myopes who habitually did <u>not</u> wear their

refractive corrections.

5.4.Experiment 5.3:   Contrast sensitivity in monocular
myopia.

## Subjects, design and procedure

Four subjects were found to fulfil the two criteria of
monocular myopia and non-use of refractive correction.
Their clinical data are summarised in Table 5.7 in
alphabetical order.  The experimental procedure was
exactly as for Experiment 5.1 (see Pilot Study 4.1),
except that subjects were tested without refractive
corrections.

### Table 5.7

| Name | Eye | Uncorrected acuity | Refractive error | Corrected acuity |
|------|-----|------|------|------|
| JP | R | 2.0 | -0.50 DS | 0.7 |
|    | L | 0.7 | nil | 0.7 |
| GR | R | 3.5 | -0.75 DS | 0.7 |
|    | L | 0.7 | nil | 0.7 |
| MR | R | 0.8 | nil | 0.8 |
|    | L | 1.0 | -0.25 DS | 0.8 |
| MS | R | 20.0 | -3.50/-0.50 x 15 | 0.7 |
|    | L | 1.5 | +0.25/-0.25 x 105 | 0.7 |

## Results

Figs. 5.11, 5.12, 5.13, and 5.14 show the contrast
sensitivity functions of the four monocular myopes.
Table 5.8 gives peak, slope and cut-off data.

### Table 5.8 (continued overleaf)

| Name | Good eye peak | Bad eye peak | Peak diff | Good eye slope | Bad eye slope | Slope diff |
|------|------|------|------|------|------|------|
| | (cycles / degree) | | | | | |
| JP | 1.0 | 3.0 | +2.0 | -1.6 | -3.0 | -1.4 |
| GR | 3.0 | 1.5 | -1.5 | -1.3 | -2.2 | -0.8 |
| MR | 3.0 | 4.5 | +1.5 | -1.8 | -2.0 | -0.2 |
| MS | 1.5 | 0.5 | -1.0 | -2.3 | -3.6 | -1.5 |

**KEY**

● = Good eye contrast sensitivity (dB)
○ = Bad eye " " "
△ = Interocular difference in contrast sensitivity
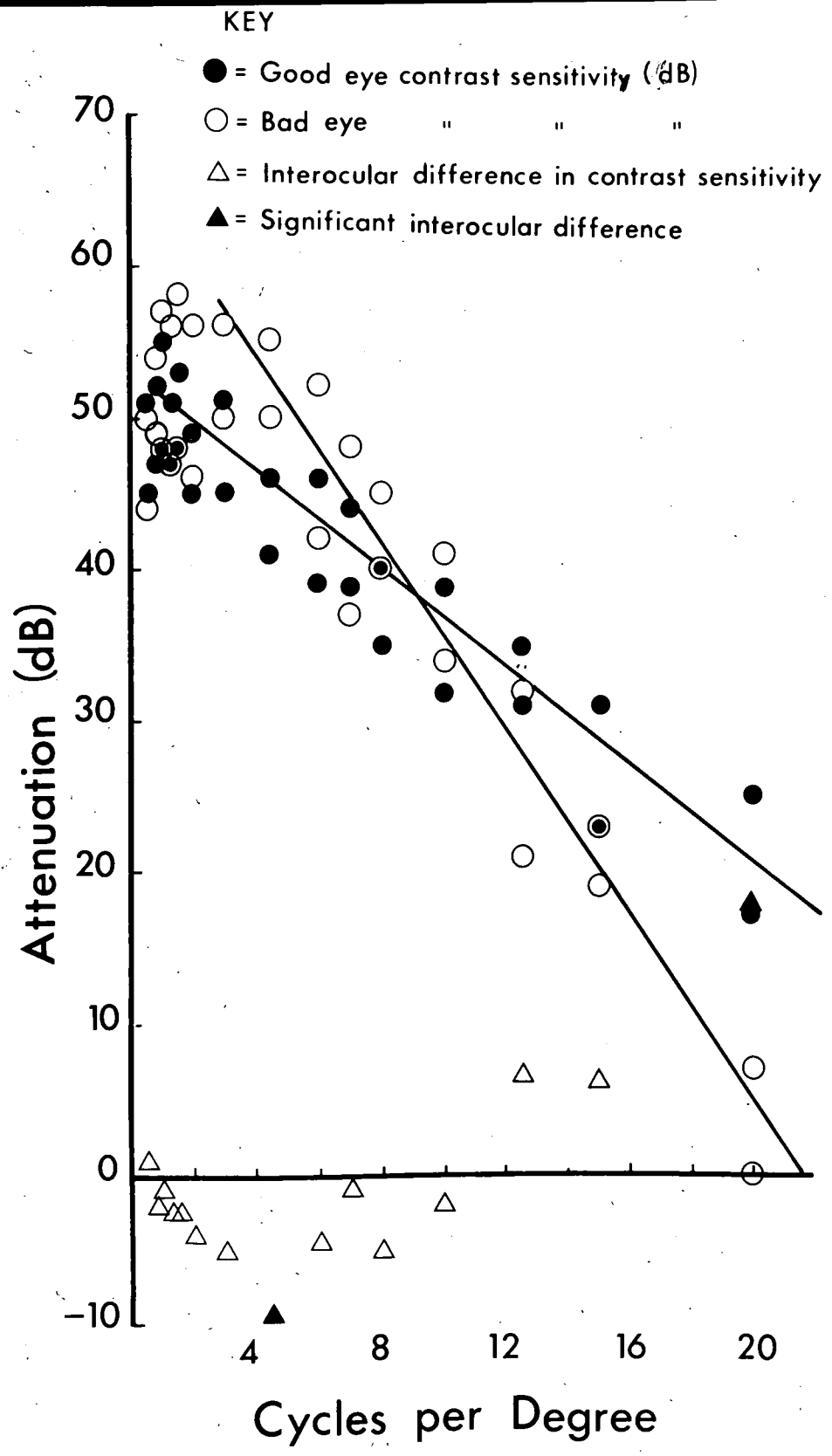▲ = Significant interocular difference

Figure 5.11.

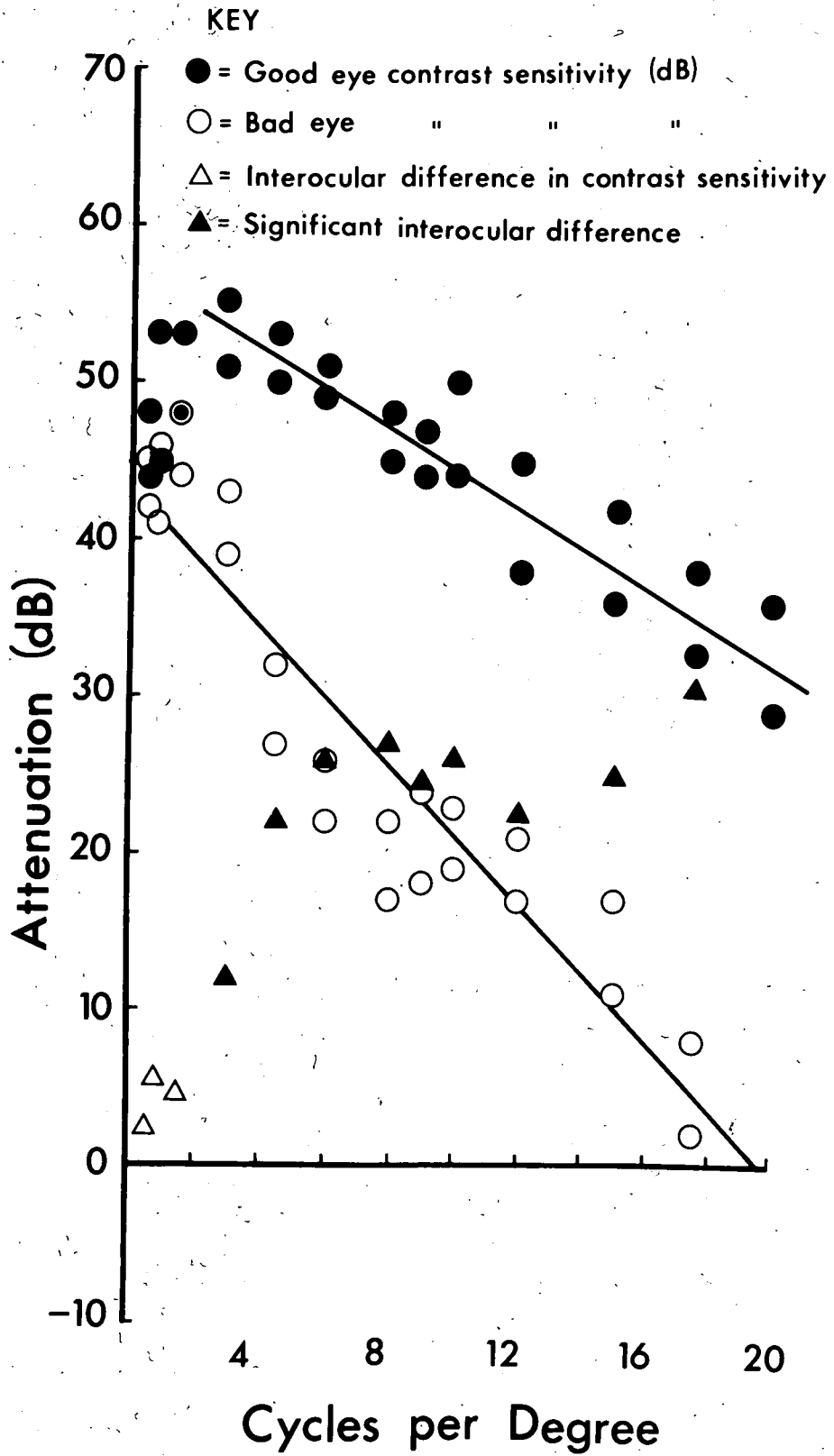Contrast sensitivity functions of monocular myope JP.

Figure 5.12.

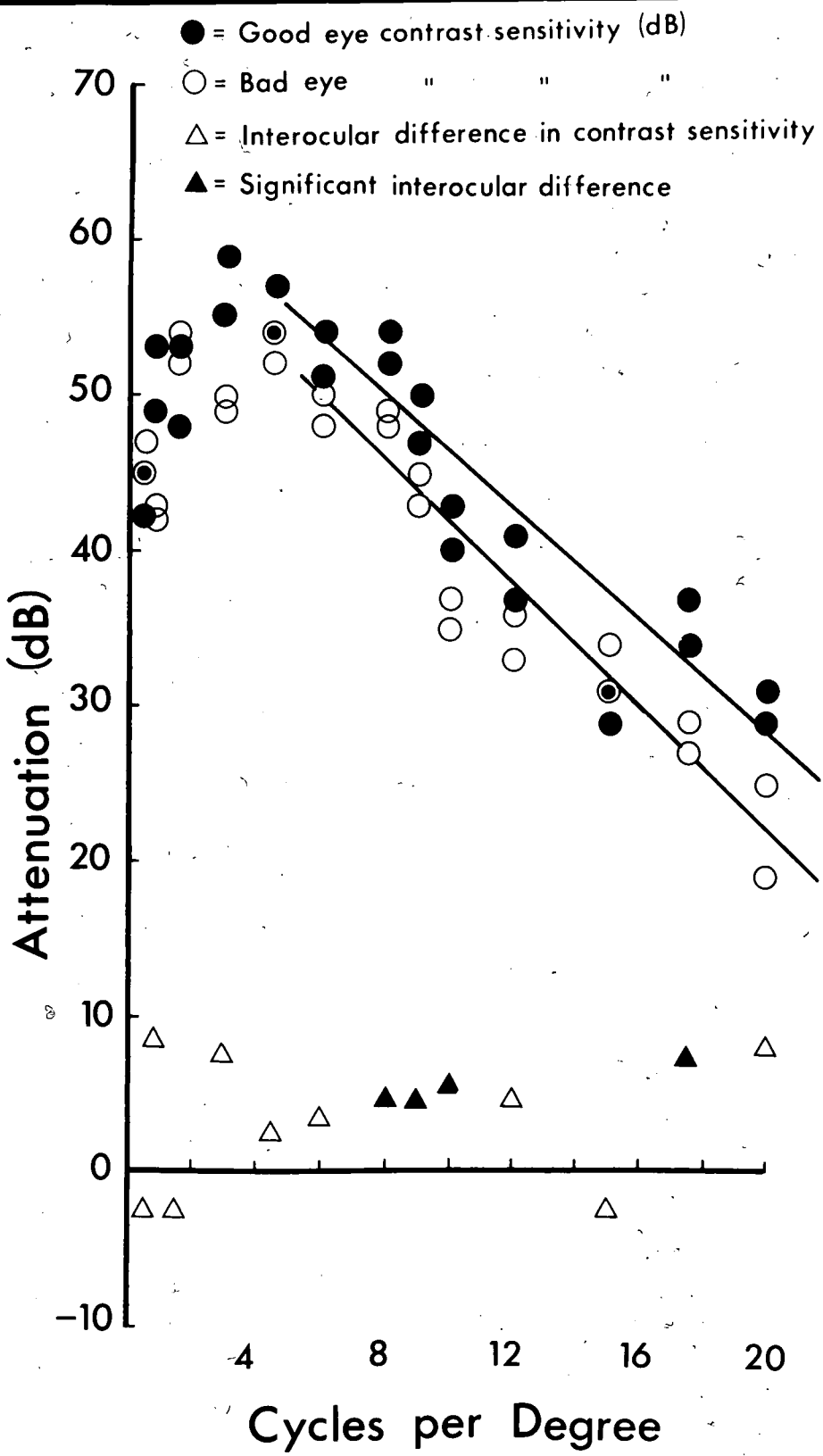Contrast sensitivity functions of monocular myope GR.

Figure 5.13.
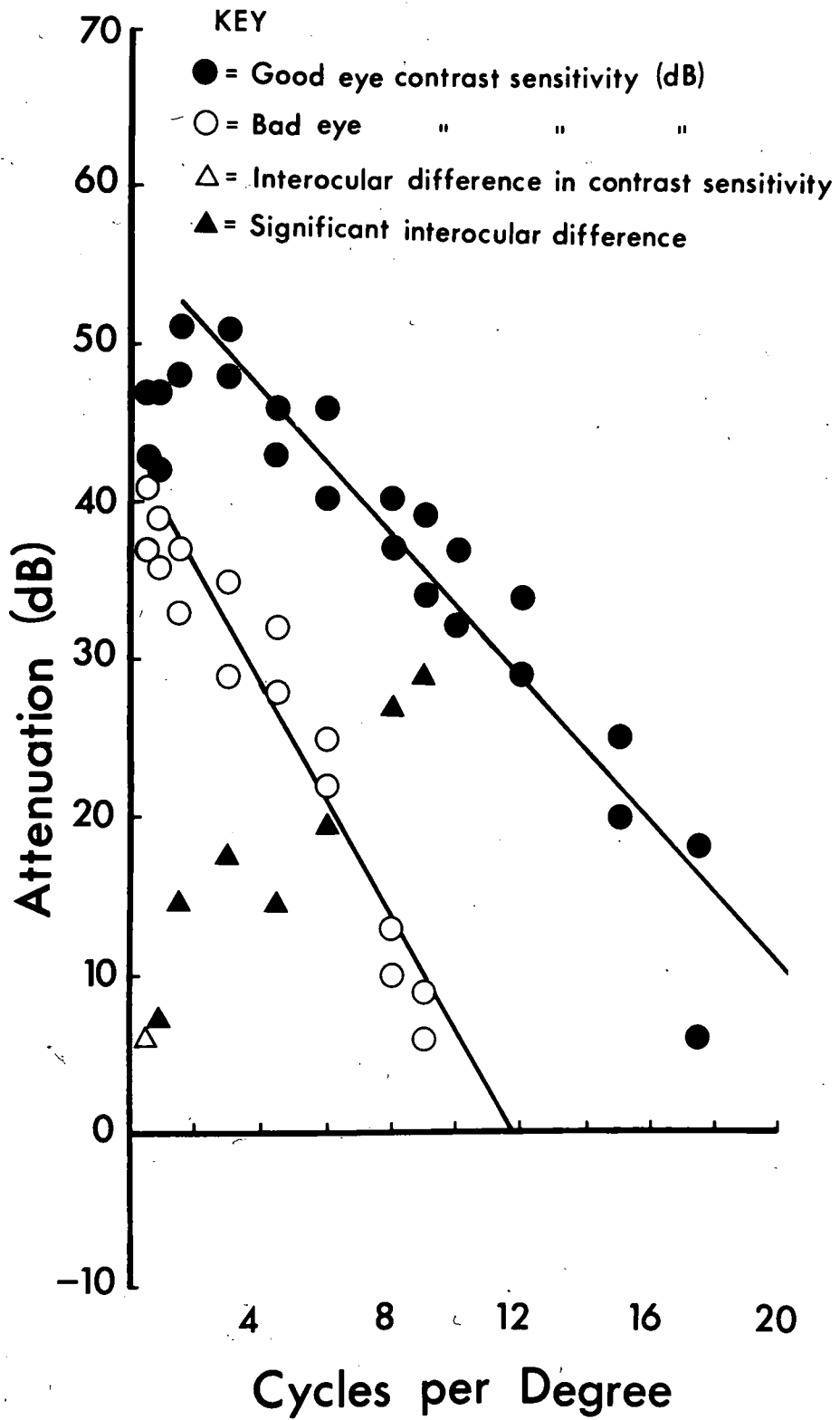
Contrast sensitivity functions of monocular myope MR.

Figure 5.14.

Contrast sensitivity functions of monocular myope MS.

Table 5.8 (continued)

| Name | Good eye cut-off | Bad eye cut-off | Cut-off diff |
|------|-----------------|-----------------|--------------|
|      | (cycles / degree) |               |              |
| JP   | 32.8            | 21.7            | -11.1        |
| GR   | 44.7            | 19.6            | -25.1        |
| MR   | 35.7            | 31.1            | - 4.6        |
| MS   | 24.6            | 11.8            | -12.8        |

Regression lines all achieved correlations between 0.93 and 0.99. Distinct negative peak shifts are shown in figs. 5.12 and 5.14 (GR and MS), while slope differences are found in figs. 5.11 and 5.14 (JP and MS). Three subjects show significant differences in cut-off spatial frequency, the exception being MR (fig. 5.13). As in previous figures, significant interocular differences in contrast sensitivity at specific spatial frequencies are represented by filled triangles. Two subjects (GR fig. 5.12 and MS fig. 5.14) have significant differences at all but the lowest spatial frequencies; one subject (JP fig. 5.11) has only a high spatial frequency loss, and one appears to have a mid-spatial frequency loss (MR fig. 5.13).

## Discussion

JP's functions (fig. 5.11) are interesting in that they cross over: the bad eye has higher contrast sensitivity at low spatial frequencies (< 10 cycles/deg) than the good eye, though only one negative difference is significant at the 5% level. His only positive significant difference is at 20 cycles/deg. Theoretically 0.50 DS of myopia should not interfere with resolution at distances less than 2 metres, so this single positive significant point must be viewed cautiously, and perhaps attributed to the difficulties of presenting high spatial frequencies with the present apparatus.

MR's two functions (fig. 5.13) appear to be essentially identical, and this is not surprising in view of her minimal myopia (-0.25 DS), which should not interfere with resolution at distances less than 4 metres. The significant differences found at 8-10 cycles/deg cannot be attributed to excessive variability in her data, which are actually less variable than that of some other subjects. Another interesting feature in this figure is the apparent depression of both eye's functions between 10 and 15 cycles/deg.

The two highest myopes both show clearly divergent functions with significant interocular differences at all but the lowest spatial frequencies. GR's bad eye function (fig. 5.12) has a depression between 4 and 8 cycles/deg, whereas his good eye function has no non-linearities. MS's functions (fig. 5.14) do not show any remarkable irregularities. It is interesting to compare his functions with those in fig 5.10 which an emmetropic subject was given +4.50 DS of monocular myopia. The artificial myope seems to have suffered much more dramatic contrast sensitivity reduction than the true myope. Even 3.00 DS of artificial myopia (fig 5.9) has degraded contrast sensitivity more than 4.00 DS of true myopia (fig 5.14).

The myopic eye acuity of JP is identical to the amblyopic eye acuities of BC and PS, but there is no apparent similarity between his bad eye function and either of their's (cf. fig. 5.11 with figs. 5.3 and 5.7). MR (myope) and SC (amblyope) are closely matched on acuity and their functions do seem alike (figs. 5.13 and 5.2). The other two myopes have lower worse eye acuities than any of the amblyopes so such comparisons cannot be made with their functions.

These experiments have not succedded in extracting a component of contrast sensitivity decrement which is attributable to simple acuity differences between the eyes, as caused by myopia. The types of functions described in Experiments 5.2 and 5.3 are as varied as those described in Experiment 5.1.

Some of the difficulties of interpreting the data arise from its variability; most other experimenters have used more than two estimates to determine each contrast threshold and this might be an important shortcoming of the three experiments described above.

In view of this point (and other, to be discussed later) this experimental protocol was abandoned for the next experiment, in favour of a more time-consuming forced-choice procedure with randomised presentation of spatial frequencies.

5.5. Experiment 5.4:  Contrast sensitivity functions
                      obtained by a forced-choice procedure

## Introduction

The results of Pilot Study 4.1 indicated that variability

in contrast sensitivity measurements was lower with a

forced-choice testing procedure than with a staircase

procedure (confirming Kelly and Savoie, 1973, and Furchner

et al, 1977).  In order to present a large number of

gratings of different spatial frequencies and contrasts

in a forced-choice design within a reasonable period of

time it was necessary to display each grating for only

10msec.  Such brief stimulus presentations were not

detected by amblyopic subjects, and so the alternative

staircase method with prolonged stimulus presentation

was used in  later pilot studies       and Experiments

5.1, 5.2, and 5.3.

However, the variability of the data obtained was found

to be a serious hindrance to analysis of the nature of

contrast sensitivity losses in amblyopic subjects, and

this was the primary factor which led to re-consideration

of a forced-choice procedure.  Re-designing the procedure

provided opportunities for reducing other undesirable

factors such as experimenter bias, practice effects, and

after-image interference.  These will be discussed in

more detail in the description of the new experimental

procedure.

## Subjects

The procedure for obtaining subjects has been described

previously.  This experiment was done over a period of

about 2 years, so that 12 amblyopic subjects were available.

Five non-amblyopic subjects were also tested.  Relevant

clinical data are given in Table 5.9 in alphabetical order.

Table 5.9 : Clinical data                    AMBLYOPES

| Name | Eye | Uncorrected acuity | Refractive error | Corrected acuity | Other clinical details |
|---|---|---|---|---|---|
| BC$_i$ | R | 50.0 | +5.50/-2.00 x 30 | 20.0 | Convergent strabismus. Never treated. Does not tolerate glasses, so tested without. STRABISMIC AMBLYOPE. |
| | L | 1.5 | +5.75/-0.75 x 15 | 1.0 | |
| BC$_{ii}$ | R | Not known because wearing contact lenses. No improvement in corrected acuity with pinhole. | | 1.5 | Glasses at 9 years because RE myopic and LE hypermetropic. Occlusion of RE later. ANISOMETROPIC AMBLYOPE. |
| | L | | | 2.0 | |
| BD | R | 0.8 | +0.25 DS | 0.7 | Refractive error first corrected at 10 years. ANISOMETROPIC AMBLYOPE. |
| | L | 4.0 | +2.75/-0.50 x 115 | 1.0 | |
| KD | R | 0.8 | +0.50/-0.25 x 15 | 0.8 | Refractive error first corrected at 5 years. Glasses and occlusion till 12 years. ANISOMETROPIC AMBLYOPE. |
| | L | 1.5 | +1.00/-0.75 x 175 | 1.5 | |
| HE | R | Not known because wearing contact lenses. No improvement in corrected acuity with pinhole. | | 0.7 | Convergent strabismus since infancy. Glasses at 2½ years, then occlusion and orthoptics. Surgery at 8 and 9 years. Cosmetic surgery at 39 years, but still has manifest convergent strabismus. STRABISMIC AMBLYOPE. |
| | L | | | 1.5 | |
| SI | R | 1.0 | +0.25 DS | 1.0 | Refractive error discovered at 14 years. Does not tolerate glasses, so tested without. ANISOMETROPIC AMBLYOPE. |
| | L | 10.0 | +2.75/-2.75 x 145 | 1.5 | |

Table 5.9 : Clinical data                    AMBLYOPES

| Name | Eye | Uncorrected acuity | Refractive error | Corrected acuity | Other clinical details |
|------|-----|--------------------|------------------|------------------|------------------------|
| LJ | R | 1.5 | +2.25/-0.25 x 80 | 1.0 | Refractive error first corrected at 31 years. |
|    | L | 10.0 | +3.50/-2.00 x 15 | 10.0 | ANISOMETROPIC AMBLYOPE. |
| SL | R | 0.8 | nil | 0.8 | Refractive error first corrected at 12 years. |
|    | L | 3.0 | +3.00/-1.50 x 30 | 1.1 | ANISOMETROPIC AMBLYOPE. |
| ML | R | 1.0 | +0.75/-0.75 x 180 | 0.8 | Measles in infancy, lazy eye detected at 8 |
|    | L | 1.6 | +0.75/-0.75 x 180 | 1.4 | years. No treatment, until glasses at 23 years.   ORGANIC AMBLYOPE. |
| AM | R | 30.0 | -5.00/-1.00 x 90 | 0.8 | Convergent strabismus corrected by occlusion |
|    | L | 30.0 | -5.00/-1.00 x 90 | 1.5 | at 6 years.   STRABISMIC AMBLYOPE. |
| PS | R | 0.8 | nil | 0.8 | Measles at 6 years believed to be cause of |
|    | L | 2.0 | nil | 2.0 | reduction of L acuity.  No treatment. No strabismus.   ORGANIC AMBLYOPE. |
| LS | R | 0.8 | nil | 0.8 | Measles at 4 years believed to be cause of |
|    | L | 1.0 | nil | 1.0 | reduction of L acuity.  Occlusion at 6-7 years gave some improvement. No strabismus. ORGANIC AMBLYOPE. |

## Table 5.9 : Clinical data NON-AMBLYOPES

| Name | Eye | Uncorrected acuity | Refractive error | Corrected acuity | Other clinical details |
|------|-----|--------------------|------------------|------------------|------------------------|
| AC | R | 30.0 | -5.00/-0.75 x 180 | 0.7 | With present glasses L acuity = 1.5 |
|    | L | 30.0 | -5.50/-2.75 x 180 | 0.8 | because 0.50 DC too weak. |
| JC | R | 0.7 | nil | 0.7 | With present glasses L acuity = 1.0 |
|    | L | 4.0 | -4.50 DS | 0.7 | because 0.50 DS too weak. |
| GD | R | 1.0 | nil | 1.0 | Never had glasses. |
|    | L | 1.5 | -1.00 DC x 180 | 1.0 | |
| SD | R | 30.0 | -2.25/-3.50 x 5 | 0.8 | Fully corrected with present glasses. |
|    | L | 30.0 | -3.50/-4.00 x 175 | 0.8 | |
| GR | R | 3.5 | -0.75 DS | 0.7 | Never had glasses. |
|    | L | 0.7 | nil | 0.7 | |

## Apparatus

Sine wave gratings were generated on a Tektronix 602
display oscillocope with a P31 phosphor. A function
generator connected to the Y-axis produced a high
frequency raster (1 megaHz) across the full area of the
oscilloscope screen (8.5cm high x 10cm wide). Mean
screen luminance as measured by an SEI photometer was
about $6cd/m^2$, and this level was standardised between
experimental sessions (and occasionally checked during
sessions) by adjusting the oscilloscope brightness control
to obtain a constant potential difference of 50 volts
between a reference socket and the oscilloscope case.
An equiluminant mask (40 cm x 40 cm) surrounded the
oscilloscope face; this was constructed from green perspex
and tungsten tubes.

Grating spatial frequency and contrast were controlled
by an IBM 1130 computer. The mean luminances of gratings
produced remained constant and equal to the luminance of
the blank screen for a wide range of spatial frequencies
and contrasts. The computer also recorded and printed
subject's responses. (Programming details will be
described later). Subjects viewed the oscilloscope
screen from 1 m. in a darkened room while wearing an
eyepatch over one eye. All but two amblyopes were
tested with full optical corrections and myopes were
tested either with or without refractive corrections
depending on personal habit (see Table 5.9). They made
their responses by pressing buttons on a response box
which was connected to the 1130 computer.

## Design and Procedure

The program controlling grating presentation required

input of four parameters: spatial frequency, contrast of the initial display, duration of the display, and number of trials.

Each display trial comprised i) a visual warning signal which was a 2cm wide vertical band slightly brighter than the blank screen. It was displayed centrally on the oscilloscope screen for 1 sec.; ii) a vertical grating display then appeared across one lateral half of the oscilloscope screen (i.e. an area 8.5cm high and 5 cm wide). The other half of the screen remained uniformly illuminated during the grating display and the two halves remained equiluminant. The half-field grating display duration was determined by the third input parameter, and throughout this experiment was 1 second. The second parameter (initial contrast) was set at about 50%, and contrast for second and subsequent grating displays was adjusted by the computer according to the subject's responses.

The subject was required to press one of two buttons to indicate whether the brief grating display had appeared on the right or left half of the oscilloscope face. Each correct response triggered a reduction in contrast. The first incorrect response triggered entry into a sequence of display trials at near-threshold contrasts. Full details of the design of this near-threshold testing sequence are given in Findlay, (1978). Briefly, after the first wrong response, contrast was held constant for several trials (up to a maximum of 12). According to the percentage of correct responses in this block of repeated trials, a second block of repeated trials was presented at either a higher or lower contrast. The

magnitude of the contrast change was also governed by the number of trials in the previous block. A series of blocks of repeated contrast displays was presented until either the fourth input parameter (i.e. the total number of trials in the near-threshold testing sequence) was exceeded, or two blocks were obtained: one with percentage of correct responses between 50 and 75%, and one with percentage of correct responses between 75 and 100%. 50% correct was assumed to be the chance level of performance for a forced-choice task with two alternatives, so 75% was selected as the level of performance likely to indicate contrast threshold.

8 to 10 spatial frequencies (between 0.9 and 16 cycles/deg) were used in this experiment, and the fourth input parameter (maximum number of trials in the near-threshold testing sequence) was 30 throughout. Total testing time for both eyes varied from 1½ hours to 2½ hours, amblyopic subjects being much slower than others because of their reluctance to make responses based on their amblyopic vision. The major disadvantage consequent upon this increased testing time was that subjects found the experiment extremely tedious; one even fell asleep, and several refused to take part in any further such experiments. Amblyopes found the task particularly tiring when using their amblyopic eyes, and some emerged at the end of the testing session with slight conjunctival inflammation.

The advantages of this procedure over that described in previous experiments were numerous. The new oscilloscope was more easily calibrated to a constant brightness level to control mean luminance between subjects. At high spatial frequencies high contrast gratings did not appear

to be as degraded as they were with the previous oscilloscope. Subjects could be left alone to press response buttons, thus removing the visual and audible distractions of the experimenter's presence. The oscilloscope was situated in a different room from the computer, so the subject had no feedback on the beginnings and endings of blocks of trials. Threshold determinations were not biased by experimenter expectations. Random ordering of the spatial frequencies used reduced the possibility that practice and learning might improve contrast sensitivity systematically. In the previous experiments spatial frequencies were presented as an ascending series, and this might have contributed to the gradient of the low spatial frequency end of the derived functions. Brief presentations of gratings reduced the possibility of after-images interfering with successive displays.

The value of these advantages against the disadvantages mentioned above can only be assessed in the light of the data obtained, its variability being the most important factor for consideration.

## Results

A sample of the printed output from the computer is shown in Table 5.10. The author wrote a subprogram which summed data for blocks at the same contrast, and re-arranged the data for each spatial frequency in order of increasing contrast, as shown in Table 5.10. The subprogram also converted the computer's spatial frequency notation into cycles/deg for a given testing distance. The relationship between these two scales was exponential between spatial frequencies of 8 and 130 in computer notation, corresponding to 16 and 0.9

```
SPATIAL FREQUENCY   98  CONTRAST   3.12  11  TRIALS   6  CORRECT
SPATIAL FREQUENCY   98  CONTRAST   4.05  12  TRIALS   8  CORRECT
SPATIAL FREQUENCY   98  CONTRAST   4.55   8  TRIALS   7  CORRECT

1.22  CYCLES PER DEGREE
  6  OUT OF  11  AT CONTRAST OF   3.12
  8  OUT OF  12  AT CONTRAST OF   4.05
  7  OUT OF   8  AT CONTRAST OF   4.55
```

Table 5.10.

Sample output from computer in Experiment 5.4.

cycles/deg respectively for a testing distance of 1
metre. The oscilloscope was not able to present higher
spatial frequencies, and at lower spatial frequencies,
the half-field display consisted of less than $2\frac{1}{2}$ cycles,
since at 0.9 cycles/deg there were 2.6 cycles displayed.
As in previous experiments, precise luminance measurements
were not possible due to lack of photometric equipment,
so it was necessary to assume that the oscilloscope
responded linearly within the range of contrasts and
spatial frequencies used. Computer contrast units
were transformed to log contrast sensitivity units for
plotting.

J.M.Findlay and C. Thompson wrote a subprogram which
attempted to fit the data values for each spatial
frequency, expressed as percentage of correct responses
at each contrast level, to an ogive function with
asymptotes at 50% and 100%, which was transformed by
probit analysis (see Finney, 1947) to a straight line.
The subprogram was designed to estimate the contrast
level at which the subject would have been correct for
75% of trials, and the standard error of this estimate.
Unfortunately the amount of data obtained from a
maximum of 30 near-threshold trials was insufficient
for the subprogram to operate in most cases. A
satisfactory ogive function was obtained from an experienced
observer (the author) after 75 trials. Instead of
increasing the number of trials, and hence testing time,
by a factor of $2\frac{1}{2}$, least squares regression lines were
computed for each batch of data (as in Table 3.10)
ommitting blocks where performance was $\leqslant$ 50% or equal
to 100%. This procedure was grounded on the assumption

that the central portion of the ogive psychophysical
function was approximately linear.  Batches of data
with less than three useable blocks were discarded.
From the derived linear regression equations (Edwards,
1976), the program estimated the contrast at which
the subject's performance would have been 75% for each
spatial frequency used (i.e. equivalent to threshold
contrast, as explained above), and it calculated the
standard error of the estimate from the following
formula:

$$SE = \frac{\sum_{i=1}^{n}(C_i - C_{75})}{n-2}\sqrt{1 + \frac{1}{n}\frac{(75 - \overline{P})^2}{\sum_{i=1}^{n}(P_i - \overline{P})^2}}$$

where SE = standard error of the estimate, C = contrast,
P = performance level (percentage), and n = number of
blocks used in deriving the regression equation;(Dixon
and Massey, 1969).  The significance of interocular
differences in $\log_e$contrast sensitivity were tested
at each spatial frequency, making no equivariance
assumptions.  The following formulae (from Hays, 1969)
were used:

$$t = \frac{\overline{C}_1 - \overline{C}_2}{\sqrt{SE_1^2 + SE_2^2}} \quad \text{and} \quad N = \frac{SE_1^2 + SE_2^2}{\frac{SE_1^4}{n_1+1} + \frac{SE_2^4}{n_2+1}} - 2$$

where t = one-tailed t-statistic, N= number of degrees
of freedom, subscripts 1 and 2 refer to good and bad eyes
respectively.  A standard package program was used to
obtain probabilities from the derived statistics.

Contrast sensitivity functions were plotted as before
(figs. 5.15 to 5.26) via a standard package program.
The ordinate labelling in this set of figures is slightly
different from that of preceding figures.  From the
assumption that the computer attenuated contrast
linearly, it was possible to plot $\log_e$ contrast
sensitivity.  The interocular difference between $\log_e$
contrast sensitivities equals $\log_e$ of the interocular
sensitivity ratio.

The position of the peak of each function was noted(by
inspection of the data), and  regression lines were
fitted to the estimated thresholds to the right of each
peak.  Correlation coefficients for all the regression
lines fell between 0.83 and 0.99 (mean=0.95, SD = 0.04).
Table 5.11 gives the spatial frequency at which the
peak occurred for each eye of each subject, interocular
peak shifts, slopes of each regression line, and
interocular slope differences. Table 5.12 lists the
spatial frequencies at which each subject had significant
($p < 0.1$, one-tailed)interocular differences in $\log_e$
contrast sensitivity.  In both these tables subjects
are listed in order of increasing acuity deficit, and
amblyopes are listed seperately, and before, non-amblyopes.
The figures are similarly ordered, except that those of
BD,SL,SD, AC and GR have been omitted since they show
no interocular differences at all.

Discussion

By inspection of the data,peak contrast sensitivity for
the good eyes of all subjects occurred between 1.22
and 5.26  cycles/deg (mean = 2.85, SD = 1.17); for the
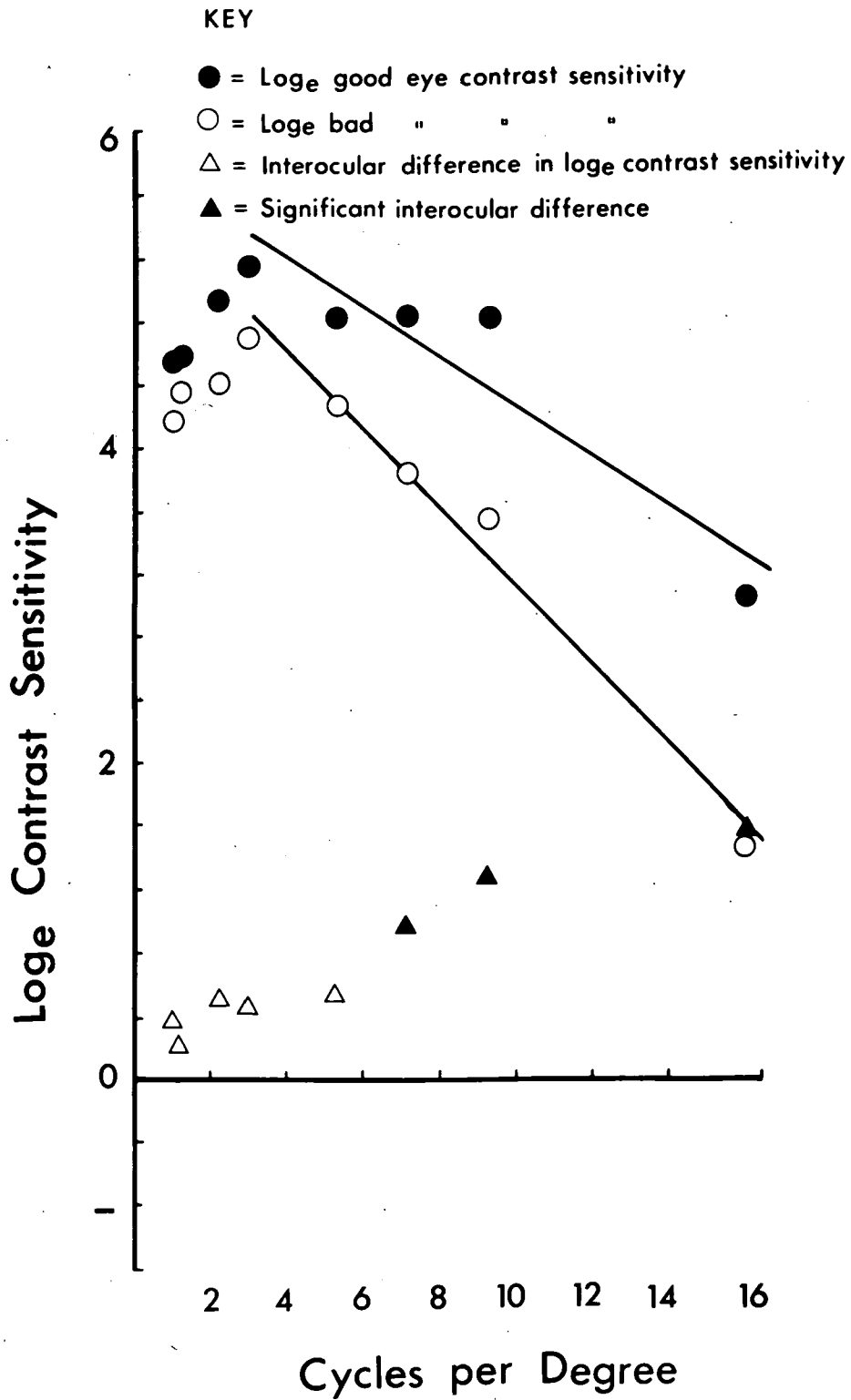bad eyes of amblyopic subjects the peak range was 0.90

Figure 5.15.
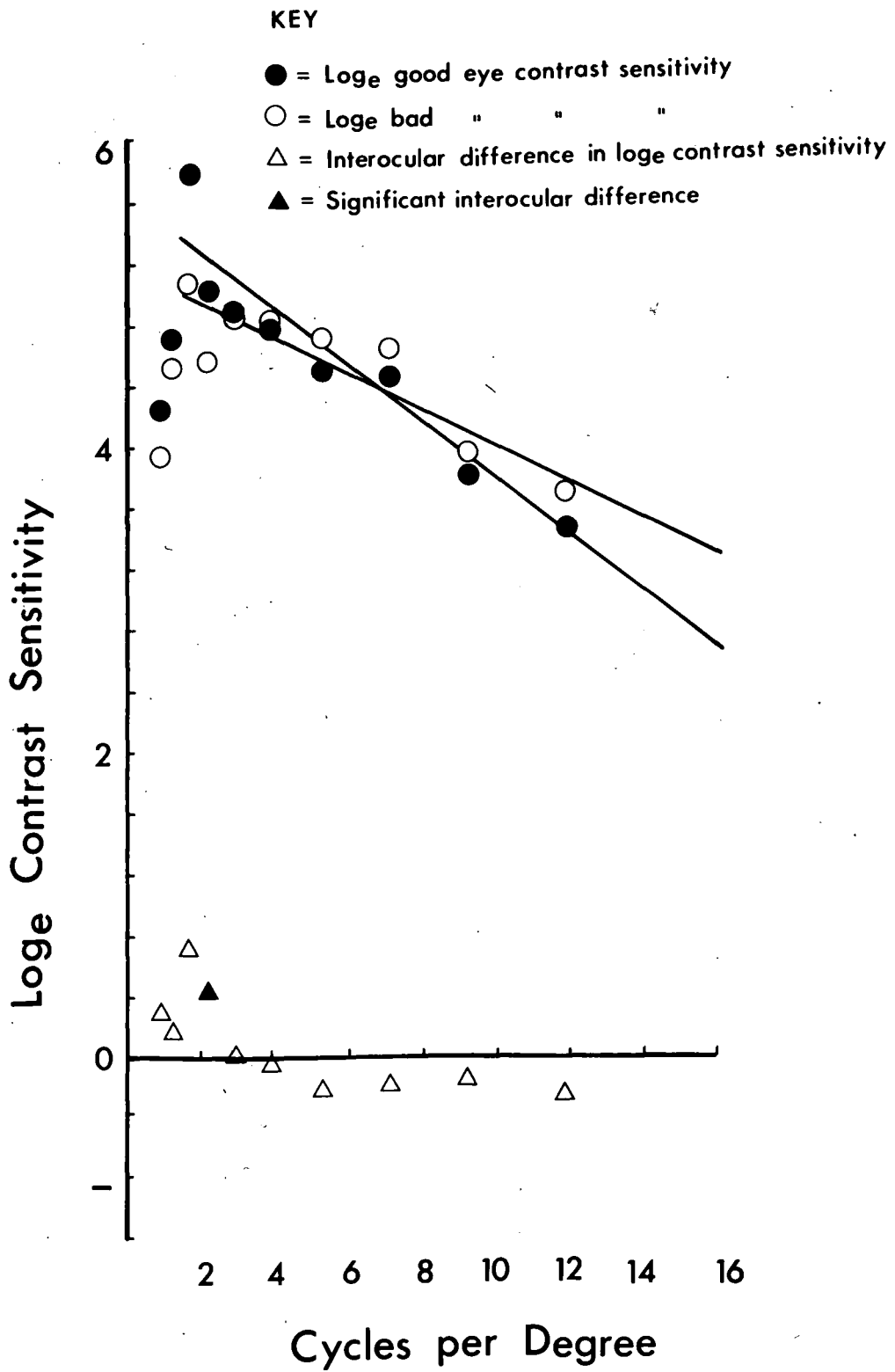
Contrast sensitivity functions of organic amblyope LS.

Figure 5.16.

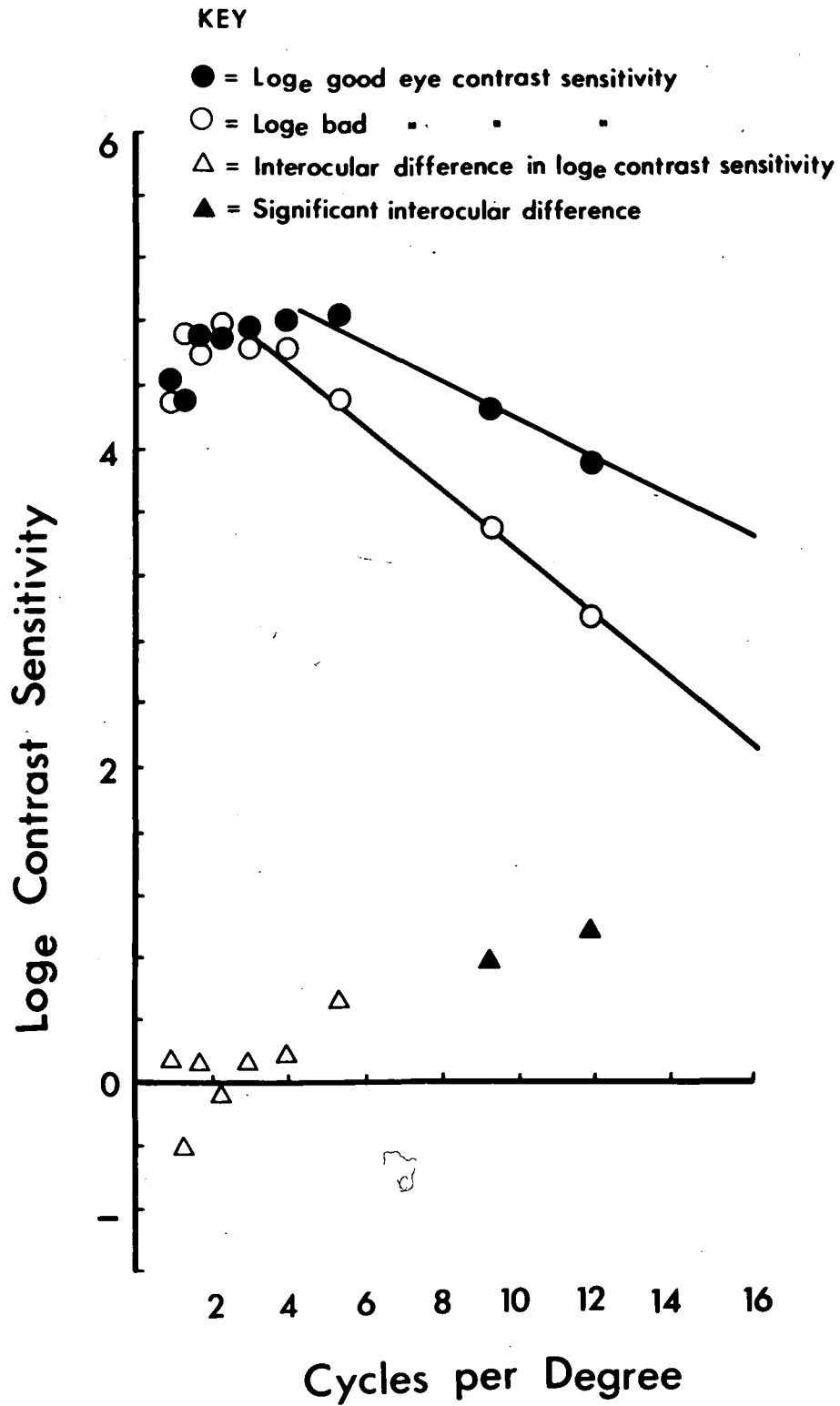Contrast sensitivity functions of organic amblyope ML.

Figure 5.17.

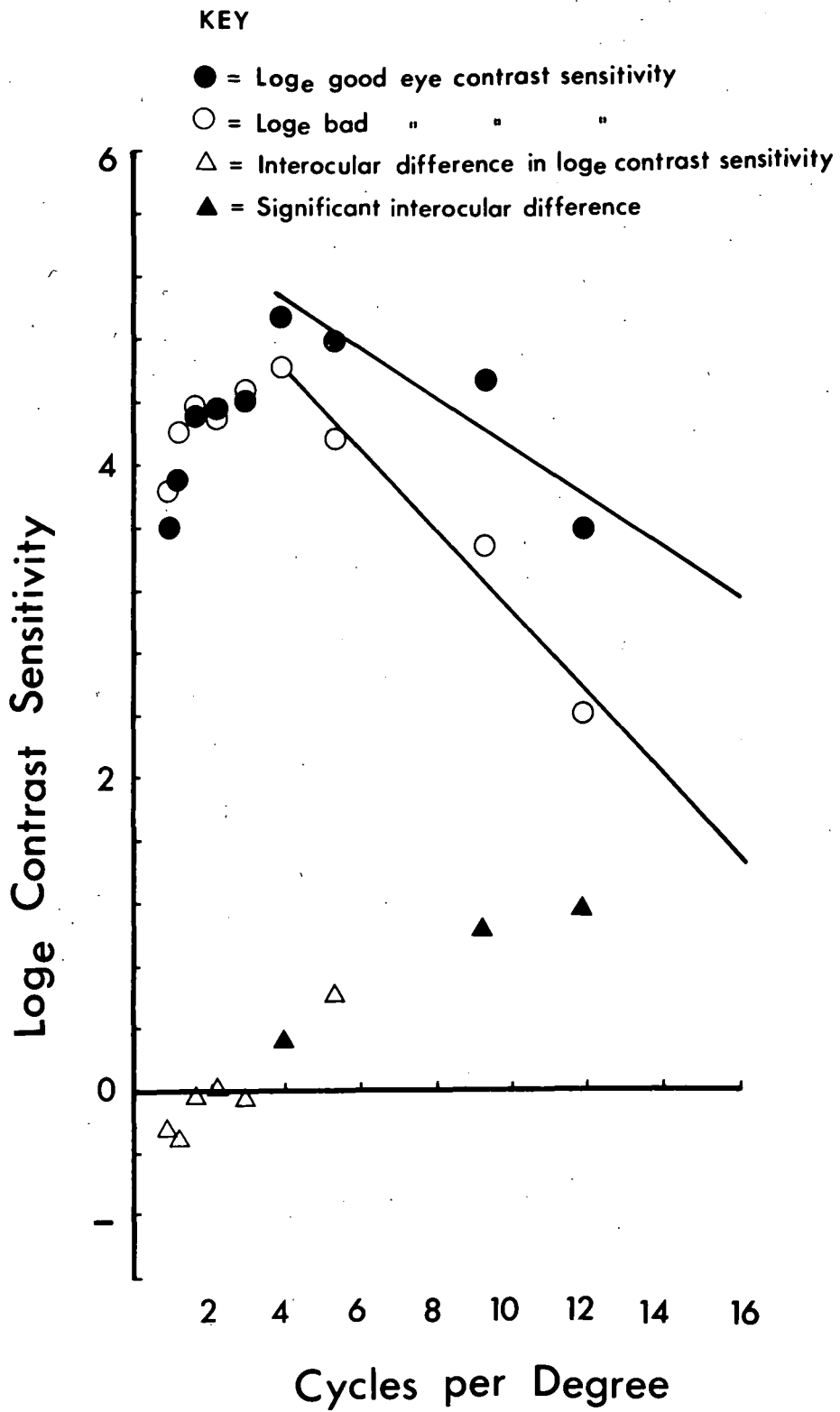Contrast sensitivity functions of strabismic amblyope AM.

**KEY**

● = $\log_e$ good eye contrast sensitivity
○ = $\log_e$ bad    "       "          "
△ = Interocular difference in $\log_e$ contrast sensitivity
▲ = Significant interocular difference

Figure 5.18.
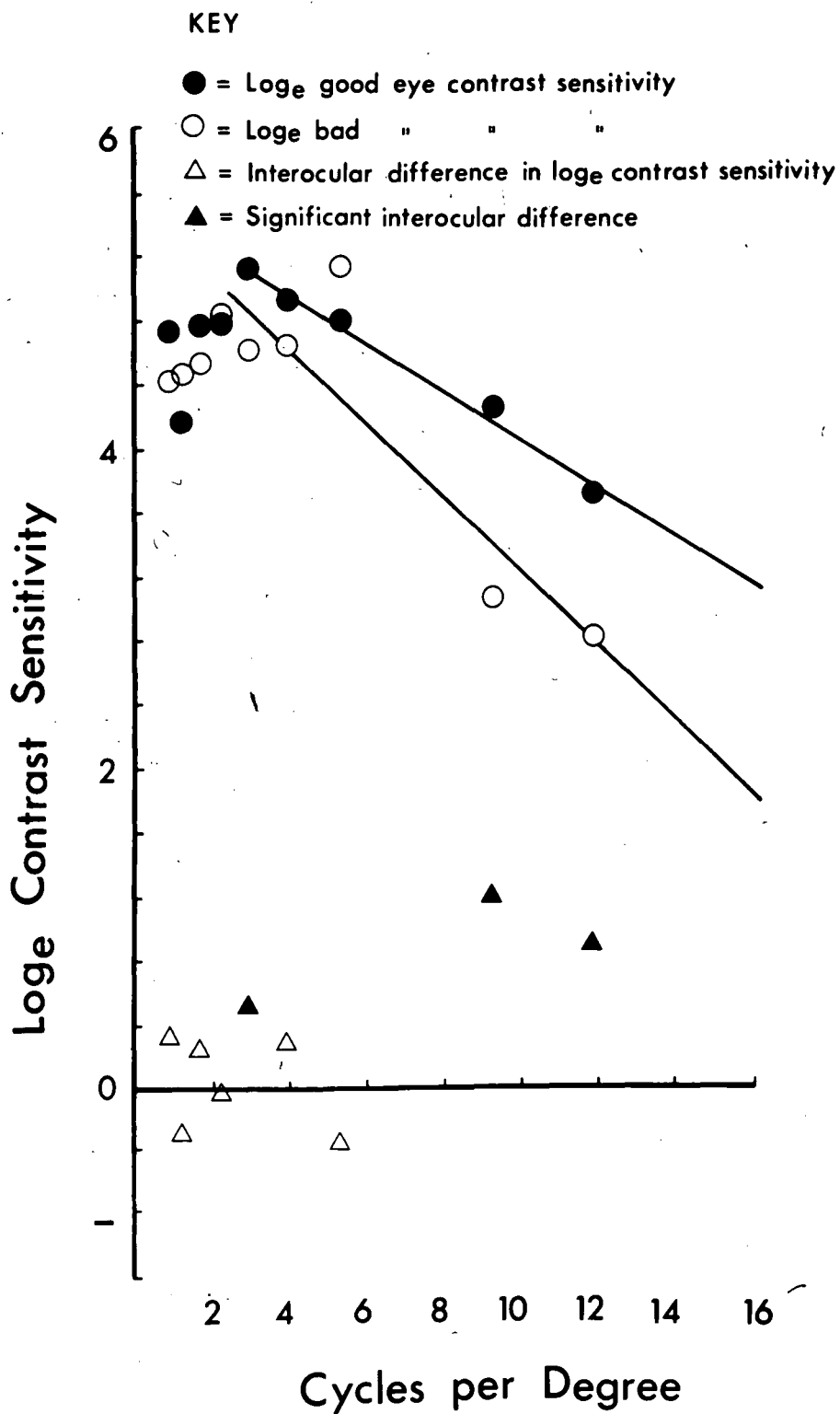
Contrast sensitivity functions of anisometropic amblyope KD.

Figure 5.19.
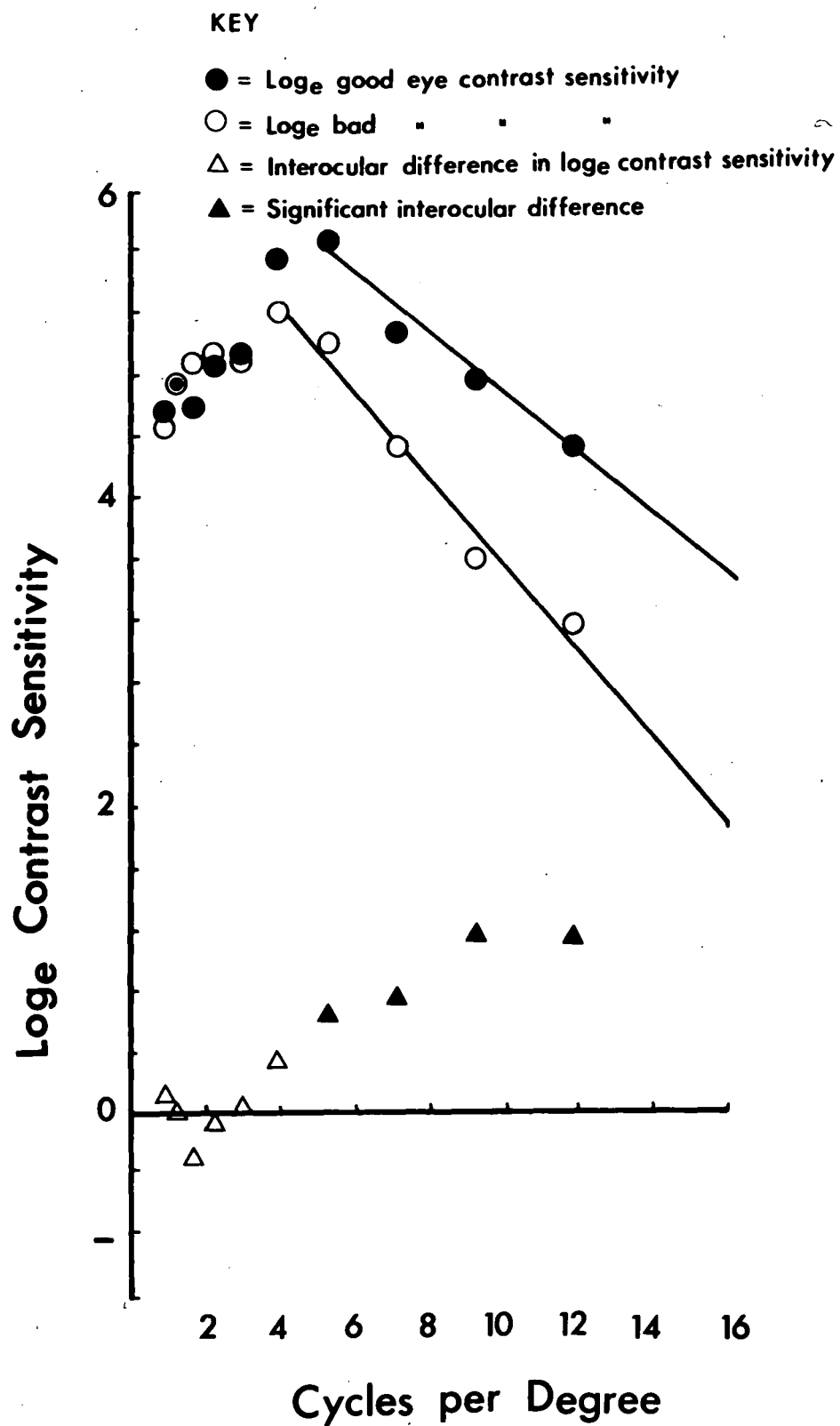
Contrast sensitivity functions of strabismic amblyope HE.

Figure 5.20.

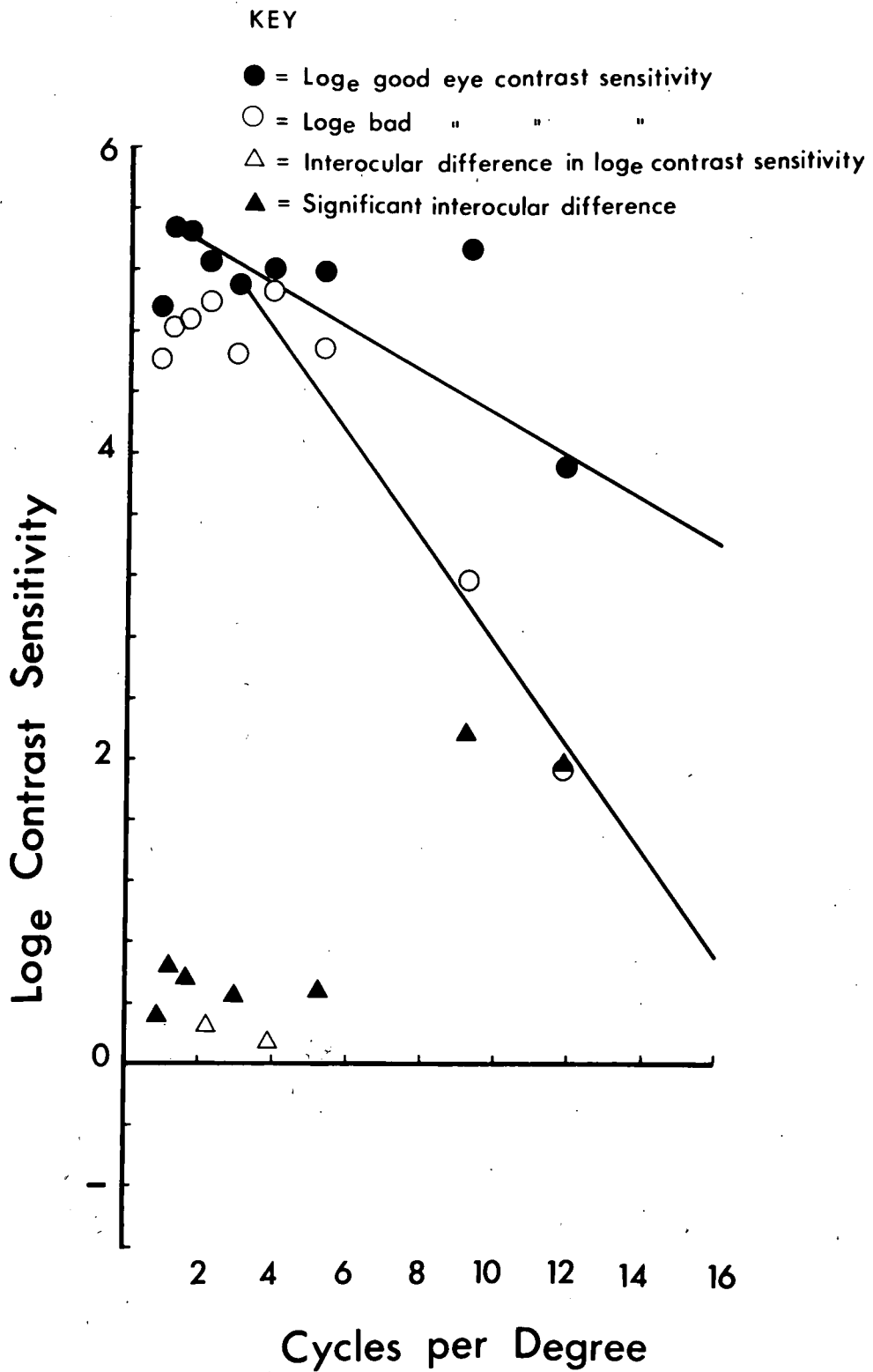Contrast sensitivity functions of organic amblyope PS.

KEY

● = Log$_e$ good eye contrast sensitivity
○ = Log$_e$ bad    "    "    "
△ = Interocular difference in log$_e$ contrast sensitivity
▲ = Significant interocular difference

Figure 5.21.

Contrast sensitivity functions of anisometropic amblyope BC$_{ii}$.

KEY

● = Log$_e$ good eye contrast sensitivity
○ = Log$_e$ bad      "        "         "
△ = Interocular difference in log$_e$ contrast sensitivity
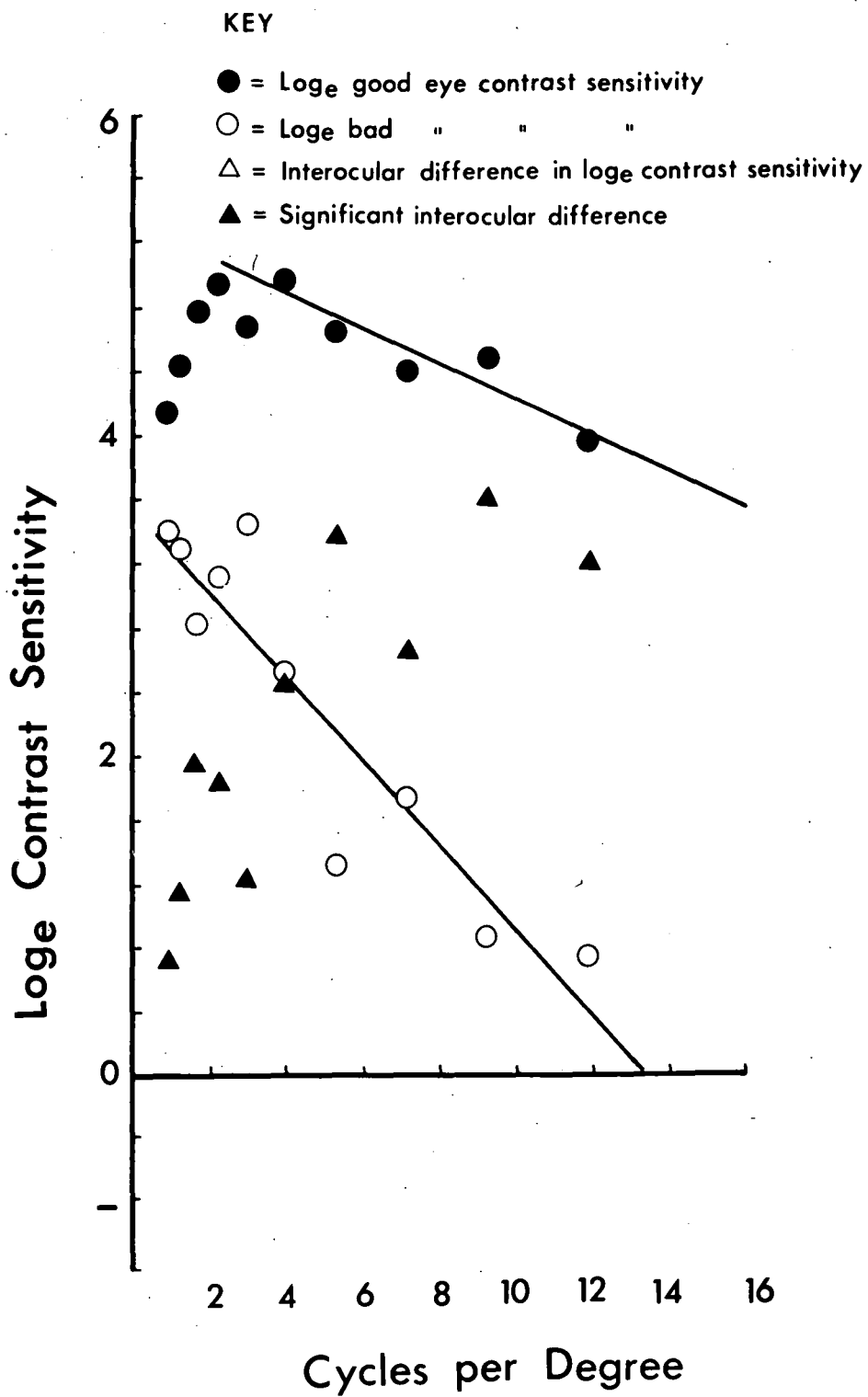▲ = Significant interocular difference

Figure 5.22.

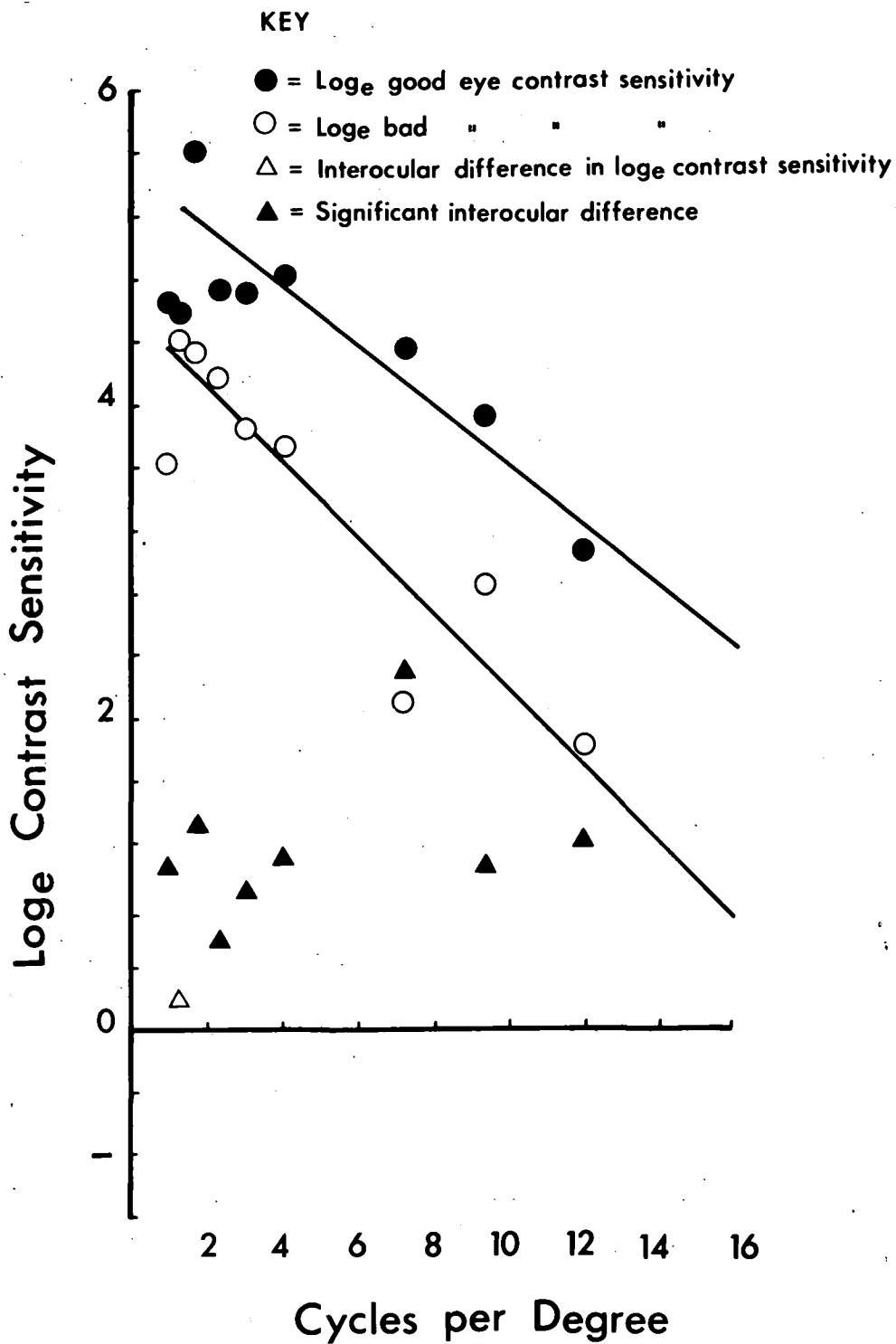Contrast sensitivity functions of anisometropic amblyope SI.

Figure 5.23.

Contrast sensitivity functions of anisometropic amblyope
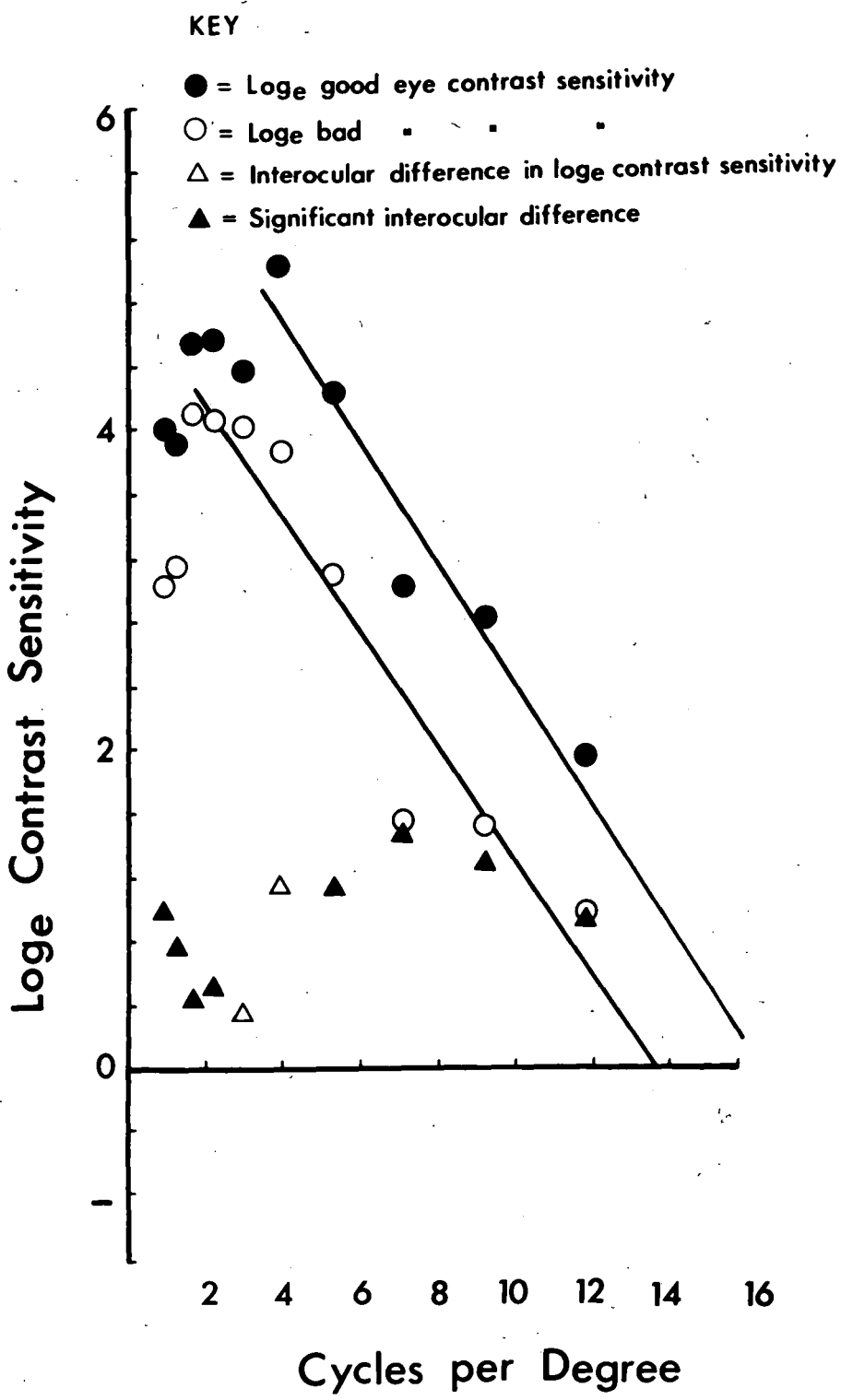LJ.

Figure 5.24.

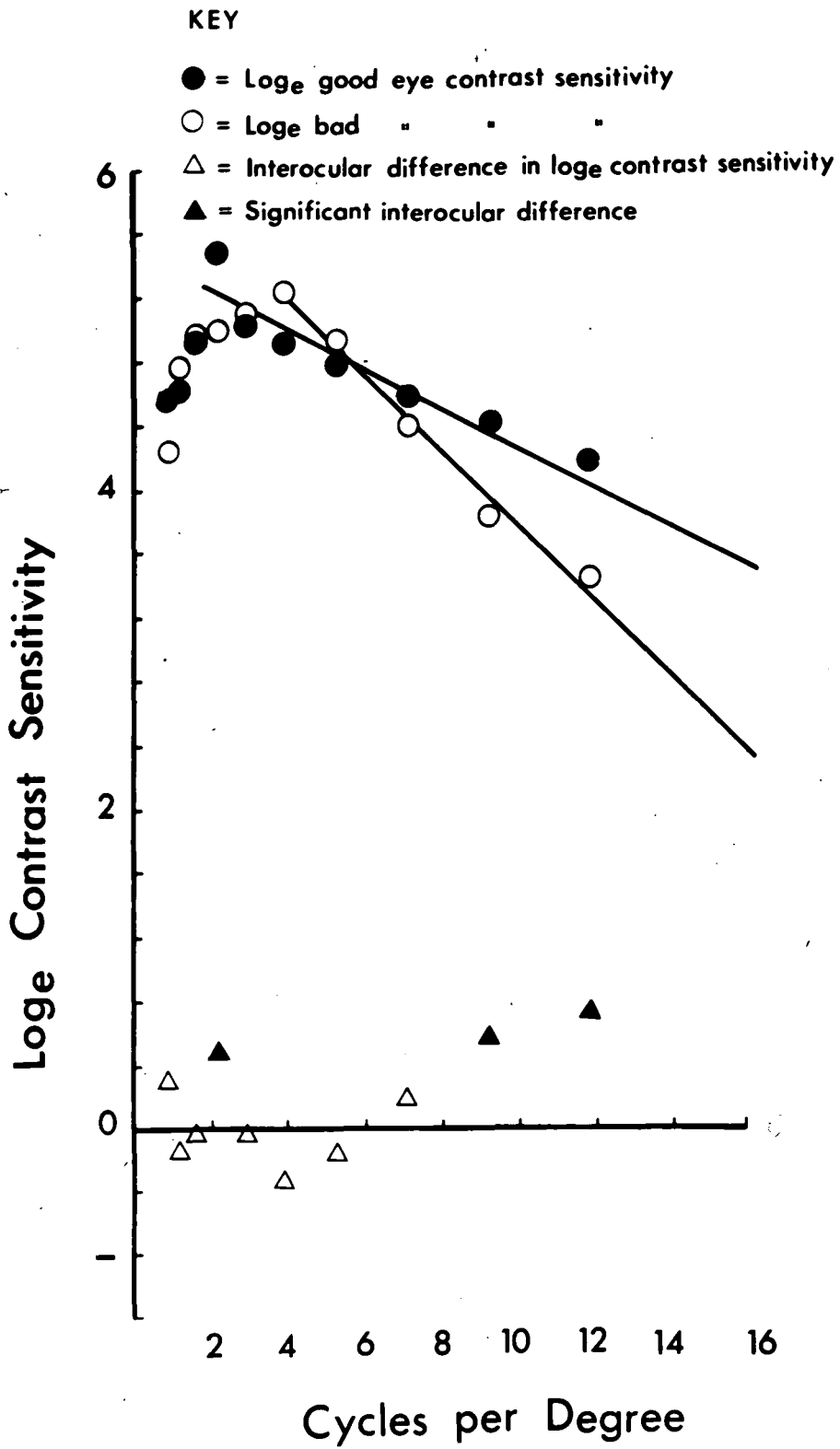Contrast sensitivity functions of strabismic amblyope $BC_i$.

Figure 5.25.

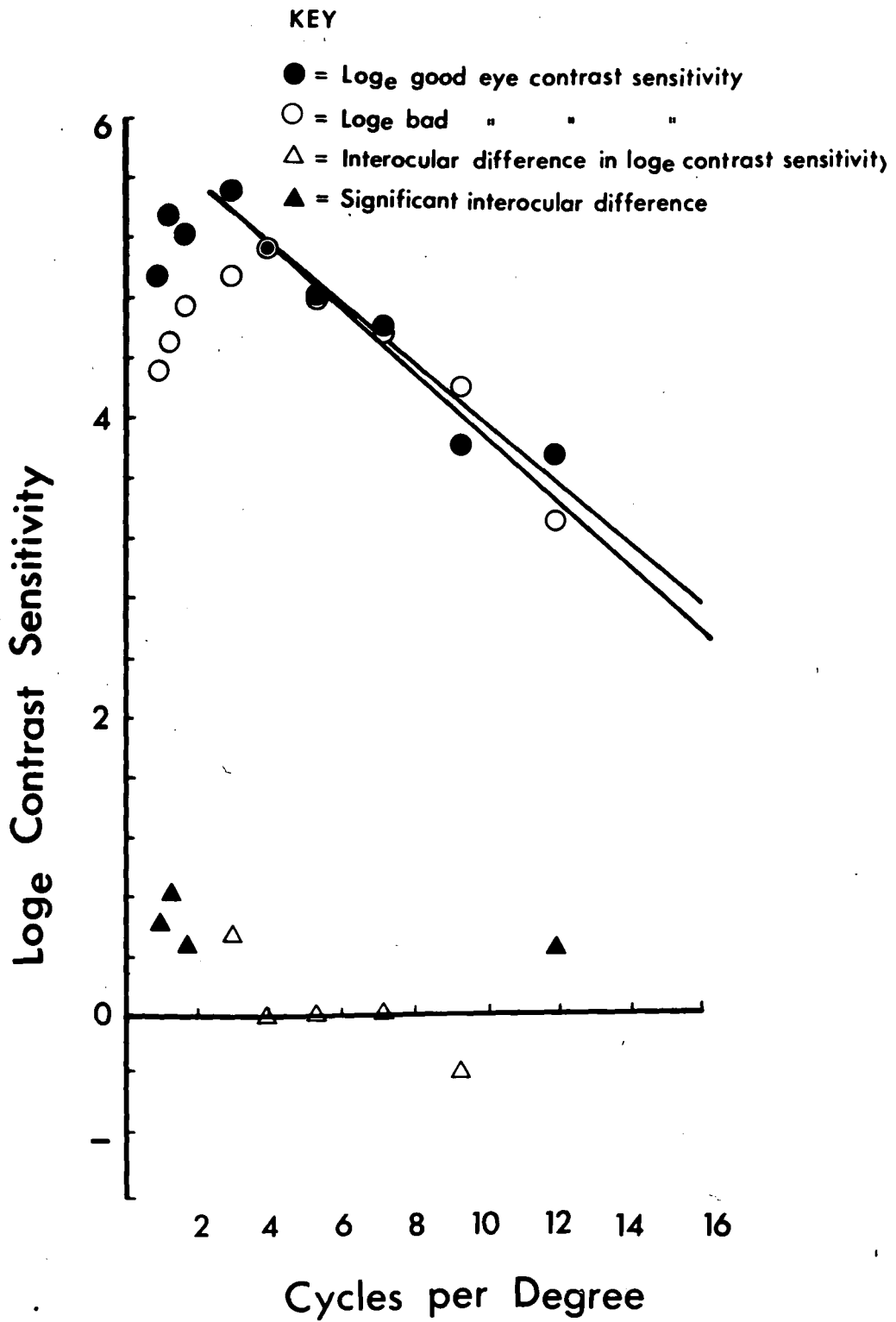Contrast sensitivity functions of undercorrected myope JC.

Figure 5.26.

Contrast sensitivity functions of uncorrected monocular myope GD.

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Table 5.11.  Peak and slope data of contrast
                 sensitivity functions

| Name | Good eye peak (cycles | Bad eye peak / degree) | Peak shift | Good eye slope | Bad eye slope | Slope diff. |
|------|------|------|------|------|------|------|
| **AMBLYOPES** | | | | | | |
| LS | 2.98 | 2.98 | 0.00 | −0.16 | −0.25 | +0.09 |
| BD | 3.90 | 3.90 | 0.00 | −0.29 | −0.27 | −0.02 |
| SL | 3.90 | 1.65 | +1.25 | −0.18 | −0.10 | −0.08 |
| ML | 1.65 | 1.65 | 0.00 | −0.19 | −0.12 | −0.07 |
| AM | 3.90 | 2.22 | +1.68 | −0.12 | −0.19 | +0.07 |
| KD | 3.90 | 3.90 | 0.00 | −0.16 | −0.26 | +0.10 |
| HE | 2.94 | 2.22 | +0.72 | −0.15 | −0.23 | +0.08 |
| PS | 5.26 | 3.90 | +1.36 | −0.19 | −0.27 | +0.08 |
| $BC_{ii}$ | 1.22 | 2.94 | −1.72 | −0.14 | −0.34 | +0.20 |
| SI | 3.90 | 0.90 | +3.00 | −0.11 | −0.27 | +0.16 |
| LJ | 1.65 | 1.22 | +0.43 | −0.19 | −0.24 | +0.05 |
| $BC_i$ | 3.90 | 1.65 | +2.25 | −0.37 | −0.35 | −0.02 |
| **NON-AMBLYOPES** | | | | | | |
| SD | 1.22 | 3.90 | −2.68 | −0.13 | −0.20 | +0.07 |
| JC | 2.22 | 3.90 | −1.68 | −0.12 | −0.23 | +0.11 |
| GD | 2.94 | 3.90 | −0.96 | −0.20 | −0.20 | +0.02 |
| AC | 2.22 | 2.94 | −0.72 | −0.11 | −0.18 | +0.07 |
| GR | 1.22 | 2.22 | −1.00 | −0.06 | −0.18 | +0.12 |

Negative peak shifts indicate that the peak for the bad
eye is at a higher spatial frequency than the peak for
the good eye.
Negative slope differences indicate that the slope of
the bad eye's function is flatter than that of the good
eye's function.

Table 5.12. Significant interocular differences
between $\log_e$ contrast sensitivities.

Name            Spatial frequencies:  cycles/deg

Amblyopes

| Name | 0.90 | 1.22 | 1.65 | 2.22 | 2.94 | 3.90 | 5.26 | 7.10 | 9.22 | 11.85 | 16.00 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LS | | | | | | | | SIG | SIG | NT | SIG |
| BD | | | NO SIGNIFICANT DIFFERENCES FOUND | | | | | | | | |
| SL | | | NO SIGNIFICANT DIFFERENCES FOUND | | | | | | | | |
| ML | | | SIG | | | | | | | | |
| AM | | | | | | | | NT | SIG | SIG | NT |
| KD | | | | | | SIG | | NT | SIG | SIG | NT |
| HE | | | | SIG | | | | NT | SIG | SIG | NT |
| PS | | | | | | | SIG | SIG | SIG | SIG | NT |
| $BC_{ii}$ | SIG | SIG | SIG | | SIG | | SIG | NT | SIG | SIG | NT |
| SI | SIG | SIG | SIG | SIG | SIG | SIG | SIG | SIG | SIG | SIG | NT |
| LJ | SIG | | SIG | SIG | SIG | SIG | SIG | SIG | SIG | SIG | NT |
| $BC_i$ | SIG | SIG | SIG | SIG | | | SIG | SIG | SIG | SIG | NT |

Non-amblyopes

| Name | 0.90 | 1.22 | 1.65 | 2.22 | 2.94 | 3.90 | 5.26 | 7.10 | 9.22 | 11.85 | 16.00 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SD | | | NO SIGNIFICANT DIFFERENCES FOUND | | | | | | | | |
| JC | | | | | SIG | | | | SIG | SIG | NT |
| GD | SIG | SIG | SIG | | | | | | | SIG | NT |
| AC | | | | | | | | | | SIG | |
| GR | | | NO SIGNIFICANT DIFFERENCES FOUND | | | | | | | | |

Key:

SIG = Significant interocular difference at this
spatial frequency

NT  = Not tested at this spatial frequency

to 3.90 cycles/deg (mean = 2.38, SD = 1.05), and for
the bad eyes of non-amblyopic subjects the range was
2.22 to 3.90 cycles/deg (mean = 3.37, SD = 0.77).
Good eye slopes for all subjects ranged from -0.37 to
-0.06 (mean =-0.17, SD = 0.07), and bad eye slopes for
amblyopes fell between -0.35 and -0.10 (mean =-0.24,
SD = 0.08) and for non-amblyopes, mean slope =-0.18,
SD = 0.05.

In order to assess the data in Table 5.11, peak shifts
of less than 1.00 were considered negligible, since
these were found in emmetropes (Table 4.1). 5 of the
12 amblyopes had positive peak shifts greater than this
criterion, and one had a greater negative peak shift.
Two of the 5 non-amblyopes had negative peak shifts
greater than the criterion, and none had positive
peak shifts. Taking 0.1 as the criterion level for
slope differences (based on emmetropes' data, Table 4.1),
only two amblyopes and two non-amblyopes exceeded it.

The six amblyopes with positive peak shifts do not
share any obvious clinical features (see Table 5.9, SL,
AM,PS,GB,BC$_{ii}$). Three of the four subjects with notable
slope differences do share a common clinical feature in
that one of the amblyopes (SI) was the only anisometrope
who had never been treated with glasses, or orthoptic
exercises,and the two non-amblyopes (JC and GR) were
under-corrected monocular myopes. There were two other
non-amblyopic subjects with under-corrected refractive
errors (AC and GD), both of whom were astigmatic with
vertical lines being the least affected orientation.
Their contrast sensitivity functions show minimal
interocular differences at spatial frequencies right of

the peak, and their regression lines are almost perfectly superimposed (see fig 5.26). Thus it seems possible that divergent contrast sensitivity functions are obtained if there is an uncorrected refractive error large enough to influence vision at the testing distance used, and of an orientation capable of affecting the gratings used. Similar findings have been reported by Levi and Harwerth (1977), but Fiorentini and Maffei (1976) claimed that the contrast sensitivity deficit caused by refraotive error alone produced a function with a distinct peak shift, but no notable change in gradient. The results of Experiments 5.2 and 5.3, in which the staircase procedure was used to determine contrast sensitivity in real and artificial monocular myopes, are in accordance with the results of the present experiment in this respect. The two amblyopes with uncorrected refractive errors (BC$_i$ and SI) were asked to repeat the experiment with their refractive correction but both had found the procedure too tiring and declined to take part in any further testing.
The spatial frequencies at which the regression lines intersect the abscissa if extrapolated have not been tabulated, because, as in the previous experiments they did not seem to be as highly correlated with visual acuity as expected. The wide variation in cut-off spatial frequencies which is apparent by inspection of the figures may indicate that linear extrapolation is not valid. One possible explanation ɓor its invalidity is that there were individual differences in the shapes of contrast sensitivity functions, and a least-squares linear fit was not the most appropriate. Strong

evidence in favour of the last suggestion is seen in figs. 5.15 and 5.21 where the good eye functions of LS and $BC_{ii}$ appear to flatten out for spatial frequencies between 5 and 10 cycles/deg, and then drop steeply at higher spatial frequencies.

From Table 5.12 subjects can be divided into the following groups:

1) Those with no apparent interocular differences in contrast sensitivity: BD,SL,SD and GR. ML and AC almost fit this category too, each having only one significant interocular difference. Figures showing the contrast sensitivity functions of these subjects have been omitted since they are essentially similar to that of ML (fig. 5.16).

2) Those with contrast sensitivity deficits at high spatial frequencies only: LS, AM, KD, HE, PB and JC.

3) Those with contrast sensitivity deficits at almost all spatial frequencies tested: $BC_{ii}$, SI, LJ, and BC.

The only remaining subject (GD) has deficits at low and high spatial frequencies only. The $log_e$ sensitivity ratios of these groups of subjects are presented for comparison in figures 5.27, 5.28 and 5.29 as smoothed curves. Dotted lines cover spatial frequencies where no significant interocular differences were found, and solid lines are used to indicate that significant interocular differences were found. GD's ratio curve has been added to fig. 5.29 although he does not conform to the characteristics of this group.

The general shape of the ratio curves within each of the above groups is fairly constant. For group (1)
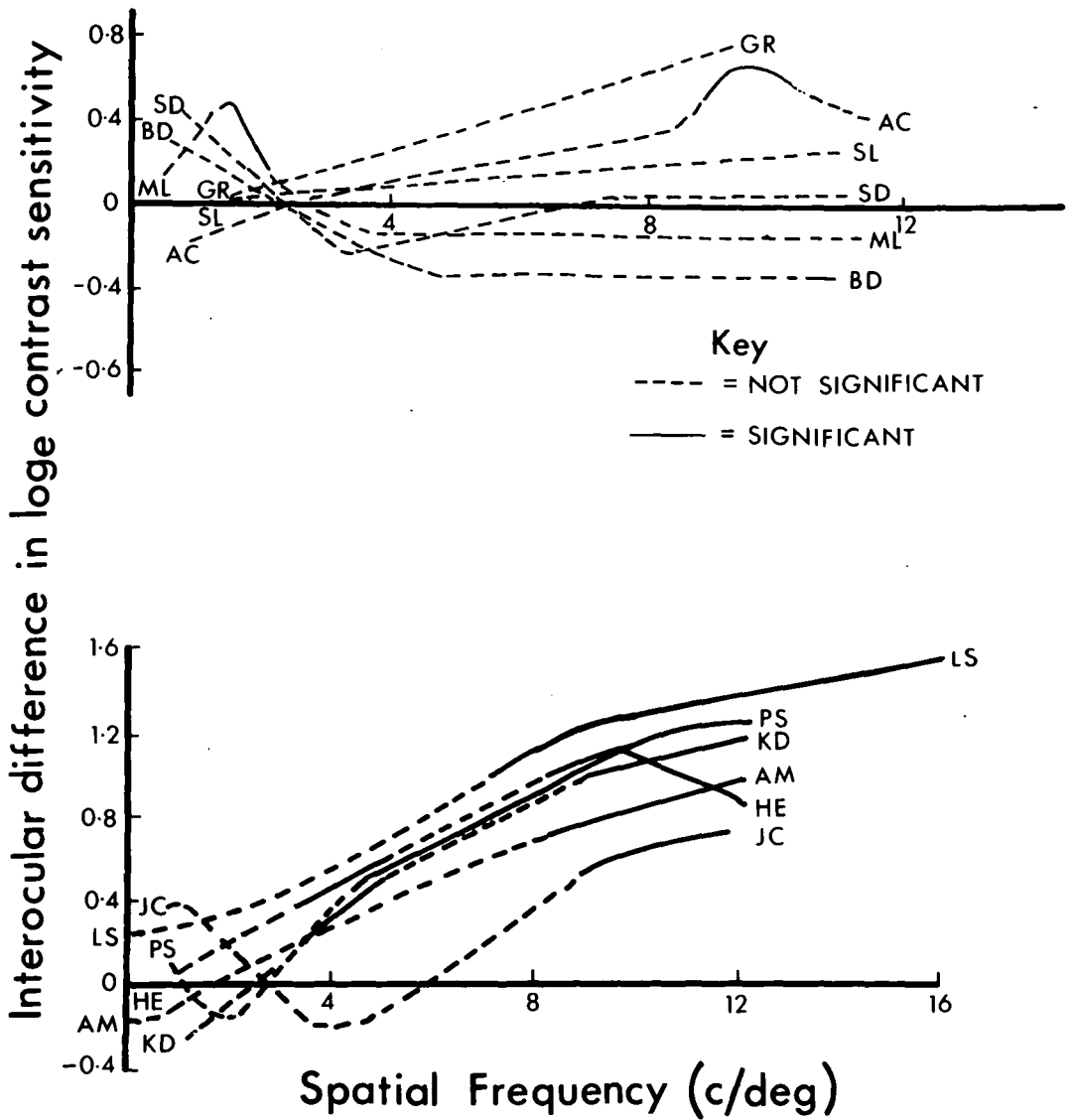
Figure 5.27.

Interocular difference curves of subjects with no significant differences.


Figure 5.28.

Interocular difference curves of subjects with significant differences at high spatial frequencies.
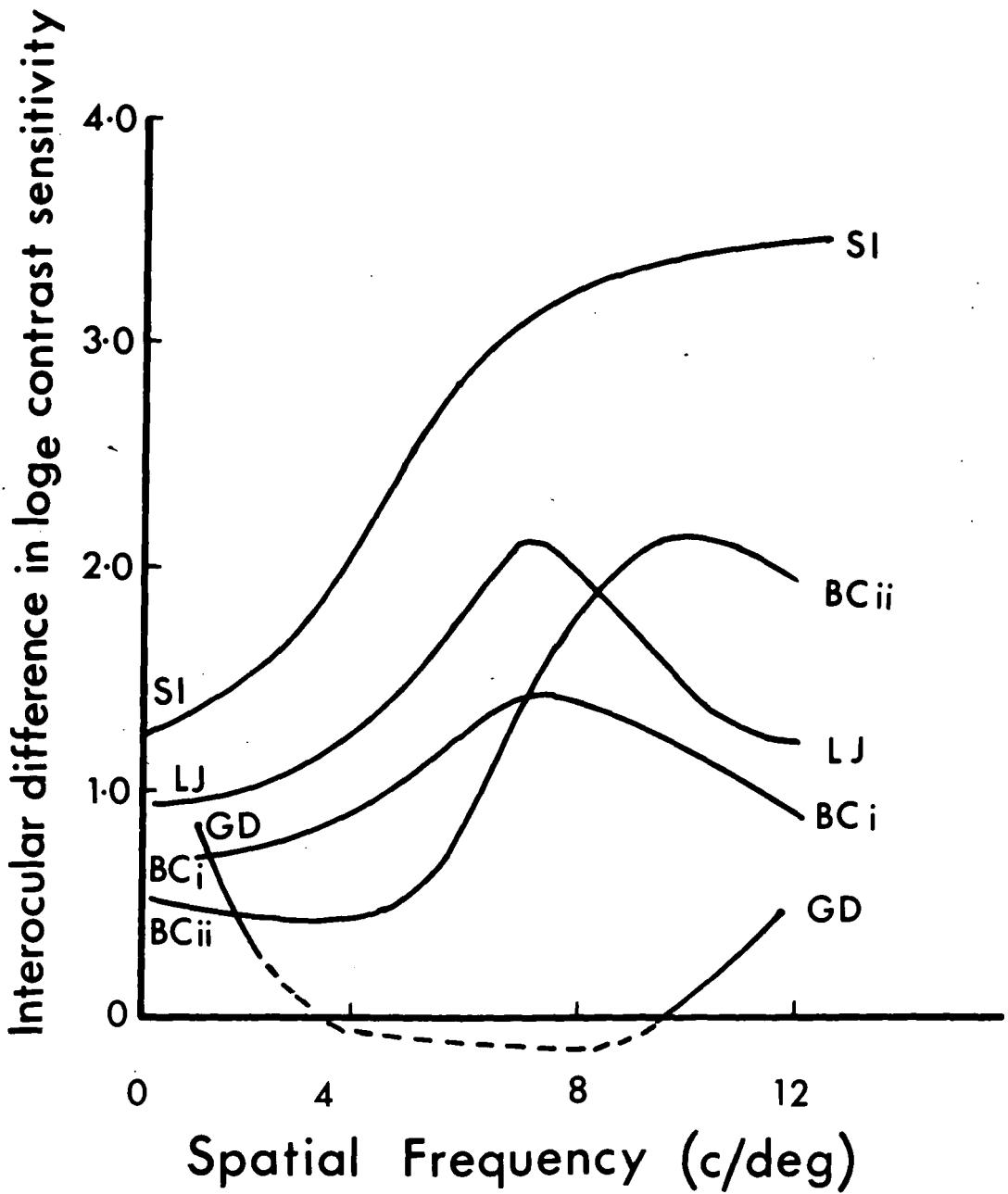
Figure 5.29.

Interocular difference curves of subjects with

significant differences at most spatial frequencies.

all ratio curves remain around the abscissa (fig. 5.27).
For group (2) they all begin around the abscissa and
turn upwards at high spatial frequencies (fig. 5.28).
For group (3) they all begin above the abscissa, then
rise steadily before flattening or falling at high
spatial frequencies. GD's ratio curve is unique (in
this group of subjects) in that it is saucer-shaped,
with a flat portion lying on the abscissa across
spatial frequencies 3 - 9 c/deg.

Four of the amblyopic subjects in this experiment had
taken part in Experiment 5.1, in which contrast sensitivity
functions were plotted by a staircase method. Comparison
of figs 5.6 and 5.17 for AM, figs 5.5 and 5.19 for HE,
and figs 5.3 and 5.21 for $BC_{ii}$ suggests that the
approximate bandwidths over which their amblyopic eyes
show contrast sensitivity deficits are fairly constant
between the two experiments. However the same is not
true for PS (figs 5.7 and 5.20). This discrepancy
cannot be accounted for.

For the amblyopic group of subjects in this experiment
there seems to be some correlation between the degree
of acuity deficit and the bandwidth of the contrast
sensitivity deficit, insofar as the amblyopes listed
above in group 1 are at the top of Table 5.12, while
those in group 3 are at the bottom of the table. But
the relationship is not perfect. LS, who has the
smallest acuity deficit has a greater contrast sensitivity
deficit than the three following subjects in the
hierarchy of acuity deficit. One possible explanation
of this anomaly

might lie in the aetiology of her amblyopia, which
was attributed to an early attack of measles. According
to Regensburg and Henkes (1976) measles can cause
retinal lesions in the macular area; LS's fundi were
examined but no lesions were detected. However she
has such a small acuity deficit that any macular
abnormalities would presumably be sub-microscopic, so
their possible existence cannot be ruled out. Another
ocular complication of measles is encephalitis with
optic neuritis, which may occur monocularly (Srivastava
and Nema, 1963). The effects of macular abnormalities
and retrobulbar neuritis upon contrast sensitivity have
been studied by Sjostrand and Frisen (1977) and Arden
and Gucukoglu (1978) respectively. In both conditions
minimal acuity deficits can be accompanied by extensive
reductions in contrast sensitivity across a wide
spectrum of spatial frequencies.

In the non-amblyopic group the bandwidth of contrast
sensitivity deficit does not appear to be related to
acuity deficit. SD, the fully corrected myope, and
GR, the worst of the uncorrected myopes both showed
no contrast sensitivity deficits. In the case of the
former this is not surprising, and in the case of the
latter it is accounted for by the fact that GR's
-0.75DS refractive error would not have blurred objects
nearer than 1.33 metres, and the grating displays were
presented at 1 metre. However JC's (fig 5.25) and
AC's uncorrected residual refractive errors have
reduced contrast sensitivity at high spatial frequencies.
GD (fig 5.26) also has a loss of contrast sensitivity
at high spatial frequency but more remarkable is his

contrast sensitivity loss at low spatial frequencies
of less than 2 cycles/deg. This cannot be accounted
for.

There is a contradiction between the two analyses of
the results of this experiment presented so far. In
the first analysis, it was suggested that refractively-
induced acuity-deficits produced divergent contrast
sensitivity functions (for spatial frequencies greater
than that at which peak contrast sensitivity occurred),
whereas amblyopic acuity-deficits produced non-divergent,
i.e. approximately parallel functions. If this were
strictly true then in the latter analysis, in terms of
the bandwidth of spatial frequencies affected, one
would expect to find that for amblyopic subjects all
spatial frequencies greater than that at which peak
contrast sensitivity occurred would be affected, and
there should be no amblyopic subjects in group 2 of
the bandwidth analysis (in which only high spatial
frequencies were affected). Five amblyopic subjects
did fall into this group, and inspection of their
functions (figs 5.15, 5.17, 5.18, 5.19 and 5.20)
suggests that although their slope differences were
smaller than the criterion selected from emmetropes'
data, their functions do appear to diverge slightly
as do those of subjects in group 3. The contradiction
can be resolved by assuming that neither the slope
difference analysis nor the bandwidth analysis is
strictly true, but that both account for some of the
different forms of contrast sensitivity deficit found
in amblyopic and non-amblyopic subjects. Thus the
conflict between Levi and Harwerth (1977) and Fiorentini

and Maffei (1976) can be resolved.

Thomas (1978) published contrast sensitivity data from three strabismic amblyopes, and reported that the subject with the smallest acuity deficit only had reduced contrast sensitivity at high spatial frequency while the other two subjects had depressed contrast sensitivity at all spatial frequencies tested. Thus his results were compatible with the bandwidth analysis presented above. Those of Hess and Howell (1977), however, were not. They classified ten strabismic amblyopes into two groups: those with only high spatial frequency losses and those with high and low spatial frequency losses.

They were unable to find a basis for this distinction in their clinical data, and eliminated degree of abnormality, age of onset, and type and duration of treatment as possible factors. However if their subjects are listed in order of acuity deficit (taking acuity as the mean of given Snellen and Landolt measures), they seem to follow the bandwidth pattern described above. Subjects classified by Hess and Howell as having only high spatial frequency losses all appear high on the list, and those classified as having high and low spatial frequency losses appear at the bottom of the list. One subject, however, has a small acuity deficit and high and low spatial frequency losses. Thus he/she is more aberrant from the pattern than LS in the present experiment. There is no clinical history to account for her aberration.

Further discussion of the data and analyses presented so far follows after description of another experiment,

in which contrast sensitivity functions were obtained from amblyopic children under orthoptic treatment.

5.6. Experiment 5.5: Contrast sensitivity in
                    amblyopic children.

## Subjects

A small sample of amblyopic children was obtained from

the local hospital's ophthalmology outpatient clinic.

These were selected by a hospital orthoptist as being

intelligent and coooperative children who had undergone

some orthoptic treatment with differing degrees of

success.  Their clinical notes are summarised in Table

5.13.

## Table 5.13: Clinical data

| Name | CA (ANISOMETROPIC) | MH (STRABISMIC) | IW (ANISOMETROPIC) |
|---|---|---|---|
| Age at first treatment | 11 years, 6 months | 8 years | 8 years, 2 months |
| VA at first treatment | 6/5,6/30 | 6/60,6/4 | 6/24,6/5 |
| Type of treatment | Glasses: RE:-0.50/+0.50x90 LE:+4.00/+1.25x85 | Permanent patching of left eye | Glasses only for 2 months: RE: +2.00 DS LE: PLANO then patching of LE for 3 hours per day |
| Age at last treatment | Glasses still worn | 8 years, 3 months | Glasses still worn, patching stopped at 9 yrs, 3 months |
| Age at contrast testing | 13 years, 5 months | 8 years, 3 months | 9 years, 5 months |
| VA at contrast testing | 6/4,6/18 | 6/8,6/6 | 6/12,6/5 |

## Apparatus and Procedure

The apparatus was exactly as described for the previous

experiment.  The program controlling grating presentation

was modified to reduce the total testing time per subject.

One further modification allowed the subject to respond
"don't know" instead of making a forced-choice between
the two response buttons. This modification was included
because the first child tested was found to be very
reluctant to make a forced-choice on trials where he had
seen nothing. However, subjects were asked to avoid use
of the "don't know" button as much as possible. The
revised presentation program reduced contrast after each
correct response, as in the previous experiment. After
the first wrong or "don't know" response the same contrast
was presented again. If the response to the repeat
presentation was correct another reduction in contrast
was made, but if the response was wrong or 'don't know'
the occurrence of two consecutive errors was assumed
to indicate that threshold contrast had been reached and
testing of that spatial frequency was stopped. This
modification reduced testing time to about 45 minutes
per subject.

Results

Threshold contrast values were converted to $\log_e$ contrast
sensitivity as before, and the differences between the
two eyes at each spatial frequency were taken to represent
interocular sensitivity ratios. Contrast sensitivity
functions were plotted as before, via a standard package
program. It was not possible to estimate the variance
associated with the threshold estimates in this experiment
due to insufficient data. An approximate assessment of
the significance of interocular differences was made by
testing some of the subjects who had taken part in the
previous experiment. Fig. 5.30 shows, for example, the
results of AM, whose performance with the full forced-

**KEY**

● = Log$_e$ good eye contrast sensitivity

○ = Log$_e$ bad " " "

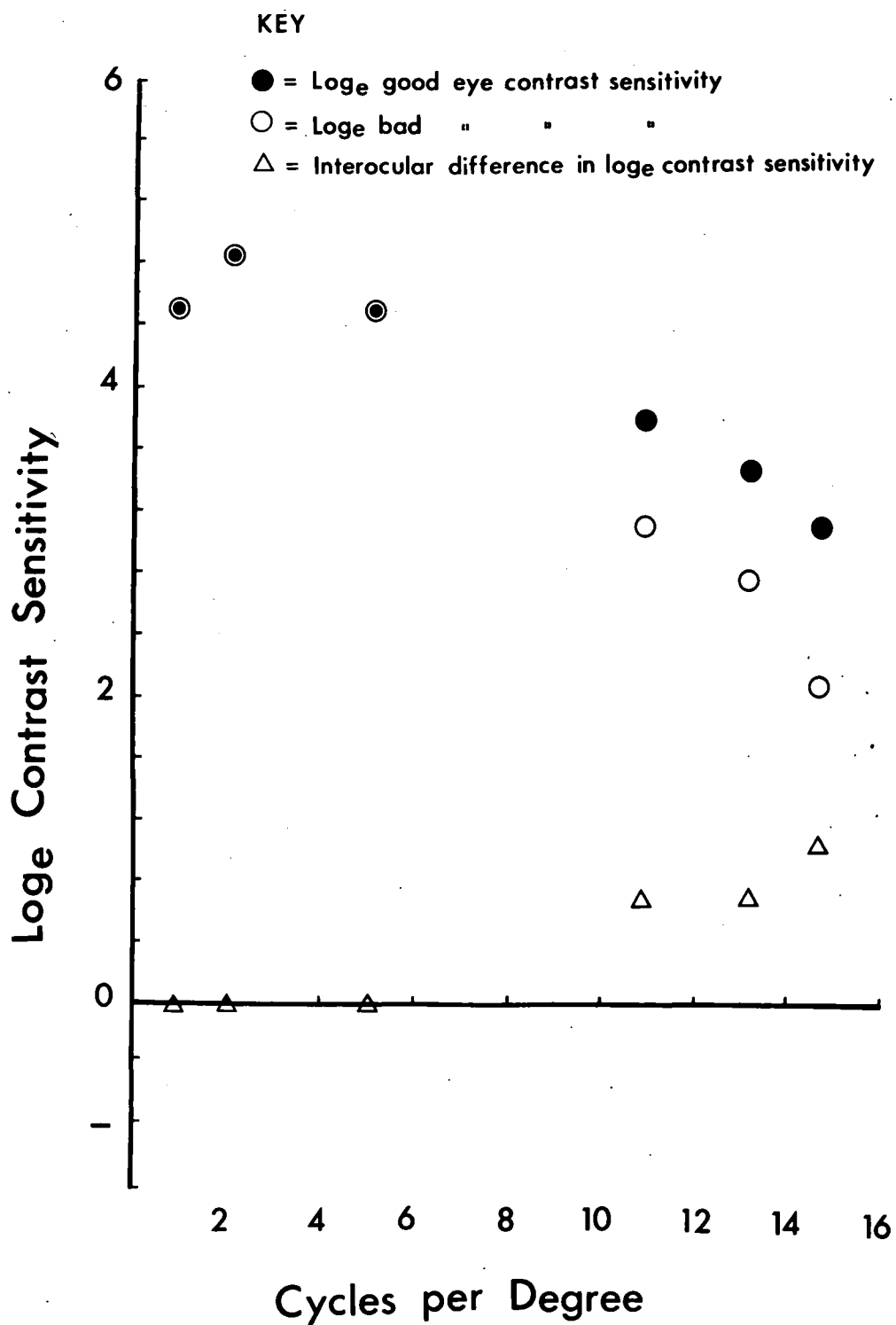△ = Interocular difference in log$_e$ contrast sensitivity

Figure 5.30.

Contrast sensitivity functions of strabismic amblyope AM, by brief testing method.

choice procedure is shown in fig. 5.17. In both experiments only high spatial frequency deficits were found. The functions of the three children are shown in figs. 5.31, 5.32 and 5.33. MH (fig 5.32) appears to have small deficits in the amblyopic eye at low and high spatial frequencies (less than 2 cycles/deg and at 13 cycles/deg); IW (fig. 5.33) has deficits at 5-12 cycles/deg, and CA (fig. 5.31) has large deficits at spatial frequencies above 4 cycles/deg.

## Discussion

The largest deficit is that of CA, and she was the oldest at time of first treatment. The two other subjects were first treated at approximately the same age (8 years) and their deficits are similar in magnitude though not in bandwidth. They underwent two different forms of treatment, MH having had immediate permanent patching of the amblyopic eye for 3 months, while IW wore glasses for 2 months, and later had three hours of patching per day for 11 months. The former treatment produced a dramatic improvement in visual acuity for MH's amblyopic eye (from 6/60 to 6/8) while the latter treatment produced a more conservative result (6/24 to 6/12 in 13 months). The treatment might not be the only factor responsible for the difference in final acuity; the age at which the primary defect occurred is known to contribute to the degree of amblyopia. MH acquired a convergent squint at about 6 years, whereas IW's anisometropia was probably in existence from a much earlier age. These differences in age of onset of the primary defect and type of treatment might also account for the differences in contrast sensitivity losses, or, alternatively, they
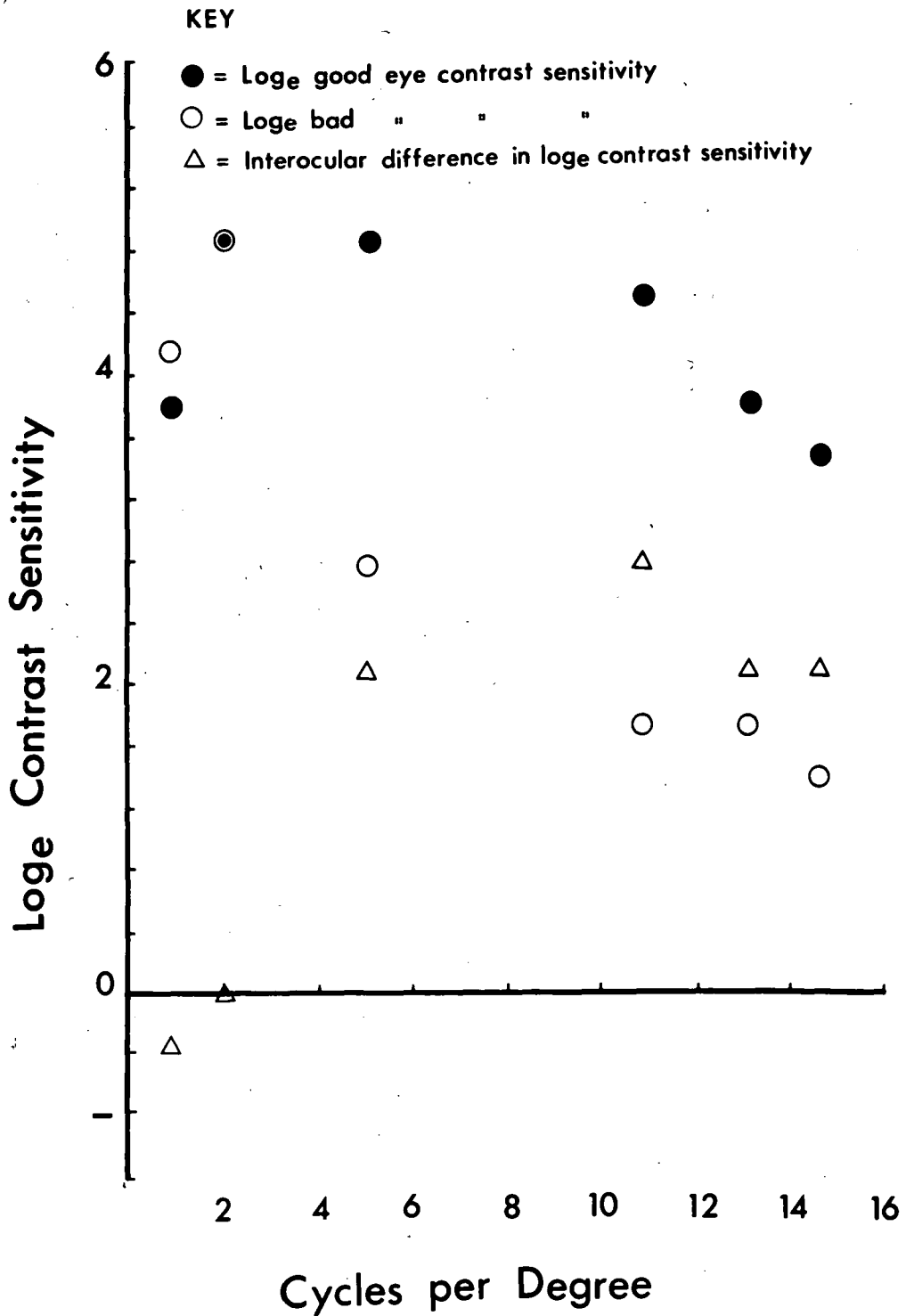
Figure 5.31.

Contrast sensitivity functions of anisometropic amblyope CA, by brief testing method.
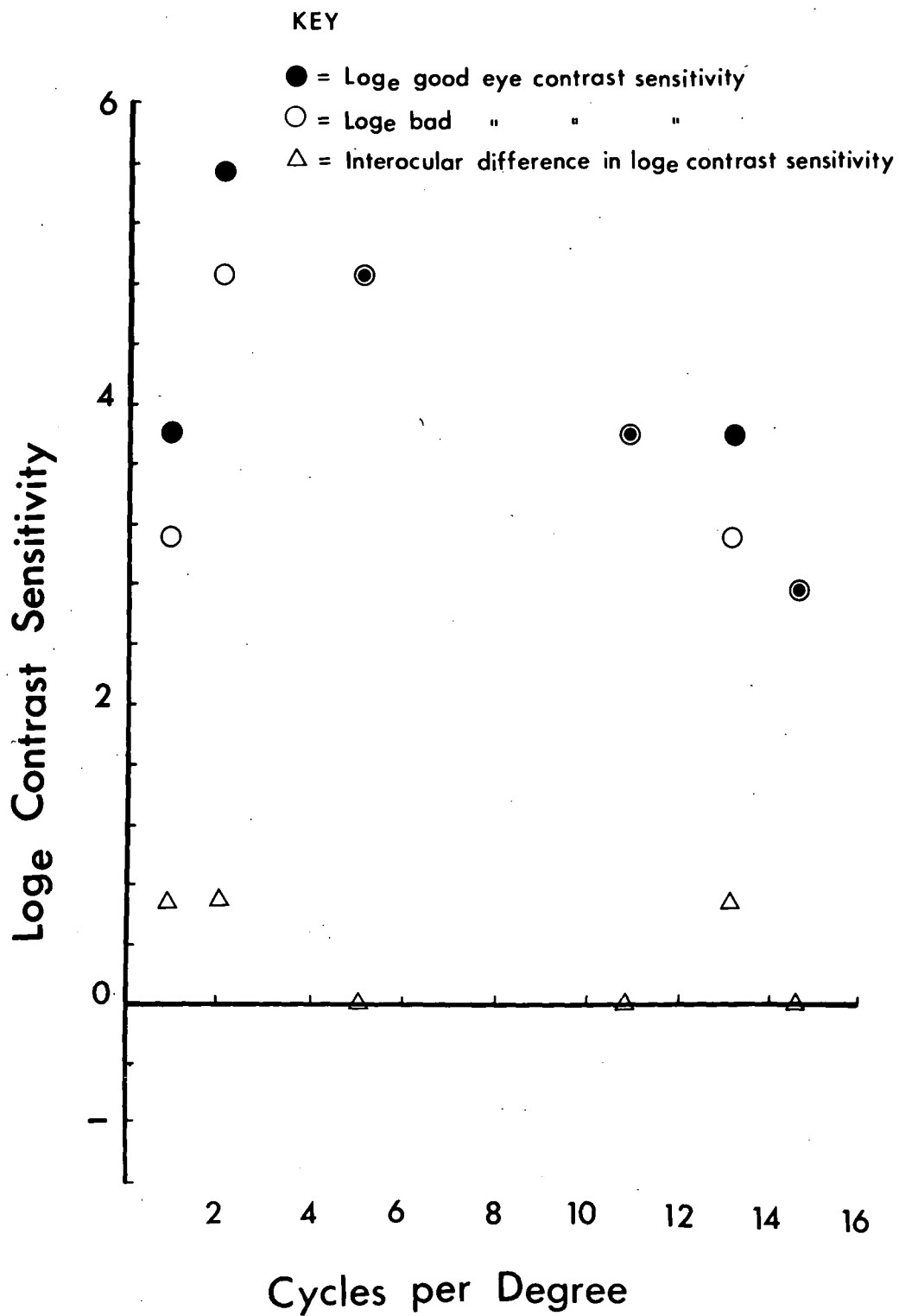
225



Figure 5.32.

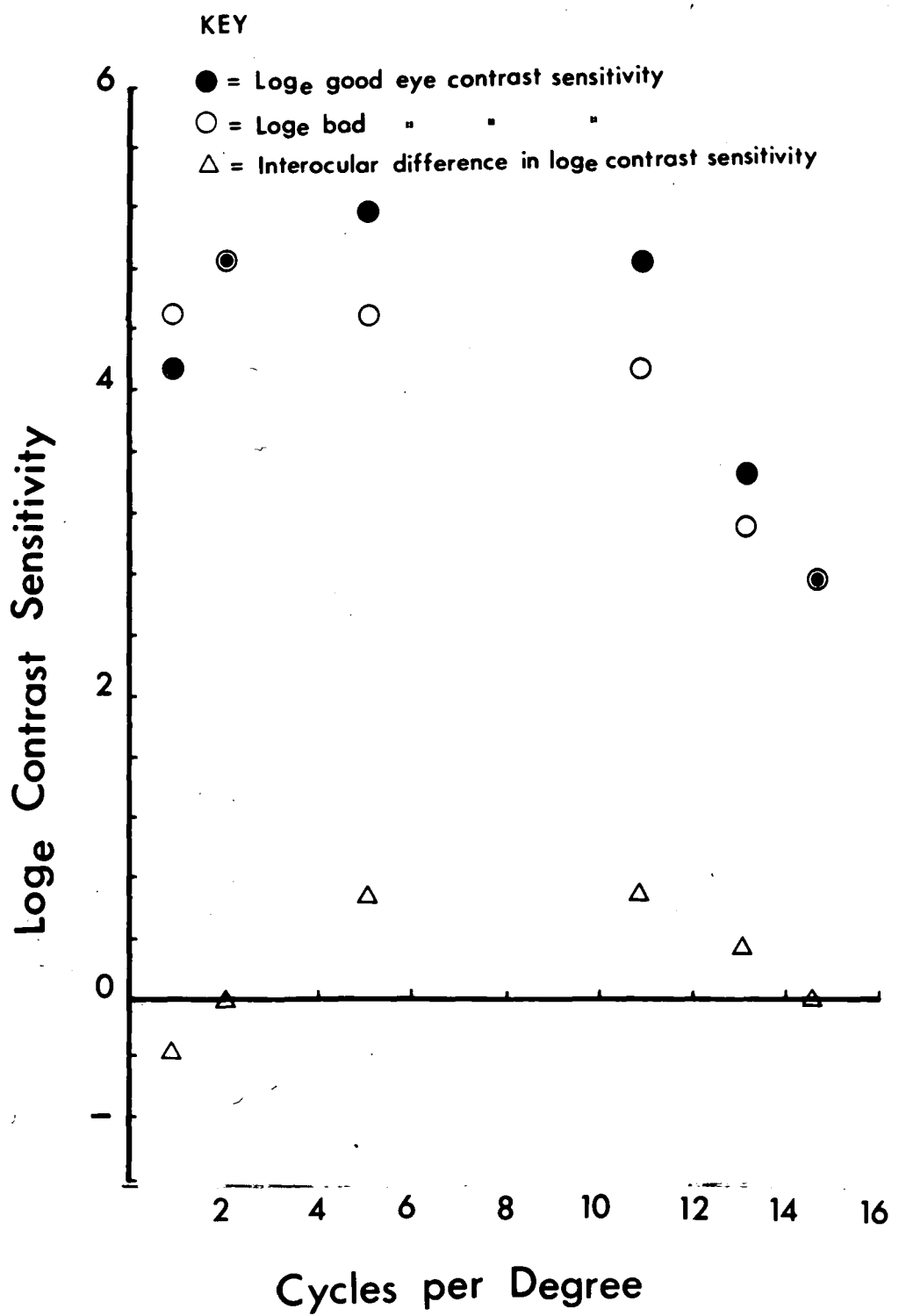Contrast sensitivity functions of strabismic amblyope MH, by brief testing method.

Figure 5.33.

Contrast sensitivity functions of anisometropic amblyope IW, by brief testing method.

might be due to random variation in the data, which, as mentioned previously, was too sparse for variance testing.

Broadly, these results are in line with the bandwidth analysis proposed in the previous experiment, but with so few subjects no firm conclusions are possible. The experiment showed that reasonably reliable contrast sensitivity data can be obtained from young children if testing time is kept to a minimum.

## 5.7. Discussion of contrast sensitivity in amblyopia

The contrast sensitivity data obtained in the above experiments has illustrated, above all, that there is not a simple dichotomy between the type of contrast sensitivity losses suffered by amblyopes and the type suffered by monocular myopes. In addition it has shown that the extent, both in bandwidth and in magnitude, of the sensitivity loss can be, albeit retrospectively, attributed to clinical characteristics of the subject. The amount of data obtained was not sufficient to allow derivation of a fully predictive model of contrast sensitivity loss in amblyopia. Perhaps sufficient data would enable such a model to be developed, but the diversity of possible clinical characteristics would necessitate a vast sample of subjects, all with full, detailed ocular histories. To date, such a study has not been undertaken, but several papers on contrast sensitivity in amblyopes have appeared in the literature recently, and these will now be evaluated in detail in order to determine whether the data presented is compatible with that in the preceding experiments, and with any proposed predictive model of contrast sensitivity loss in amblyopia.

Fiorentini and Maffei (1976) reported that myopic amblyopia impaired contrast sensitivity over the entire spatial frequency spectrum, without changing the shape, or shifting the peak of the function from that of a normal contrast sensitivity function, as defined by data from three emmetropic subjects. They also showed that blurring only impaired contrast sensitivity at high spatial frequencies, and shifted the peak towards a lower spatial frequency. Their ten subjects were not a homogenous

sample in clinical terms, except that they all had large ($>5$ DS) amounts of myopia. Six had interocular acuity differences, but of these, five had sub-normal acuity ($<6/6$) in their better eyes. Two were 'binocular' amblyopes in that they had equally low acuities in both eyes, and the other two were myopic but not amblyopic, and had equal corrected acuities in both eyes better than 6/6. As mentioned above, they did not evaluate contrast sensitivity in terms of interocular differences but referred to a normal curve derived from three emmetropic subjects. Hess and Howell (1977) show that the range of variation in contrast sensitivity found in normal eyes spans about 0.5 log units on the contrast sensitivity scale, so Fiorentini and Maffei's representation of the normal function as a single line is inadequate, and their conclusions regarding the nature of contrast sensitivity losses in myopic amblyopia are therefore not reliable.

Levi and Harwerth (1977) examined contrast sensitivity in four amblyopes, all of whom had anisometropia, and two of whom also had strabismus. They specified four features of the nature of contrast sensitivity loss in amblyopes: 1) that all spatial frequencies are affected and the magnitude of loss is proportional to the spatial frequency; 2) that the peak of the amblyopic eye's function is shifted to a lower spatial frequency than that of the normal eye; 3) that the slope of the low spatial frequency side of the function is flattened; 4) that the cut-off spatial frequency is lower for the amblyopic eye than the normal. They illustrated these features with a figure from one of their subjects, who

had a Snellen acuity of 6/60 in his amblyopic eye.
Figures from their two subjects who had smaller acuity
deficits (6/6, 6/15 and 6/6, 6/24) are not given.  They
found that contrast sensitivity functions like those of
their amblyopic subjects could not be obtained from a
normal eye with 3.00 DS of blurring, or with simulated
eccentric fixation of 2 degrees, or with neutral density
filters, because all three methods failed to degrade low
(0.5 cycle/deg) spatial frequencies.

In experiment 5.4, low degrees of amblyopia were found
to cause only high spatial frequency losses in contrast
sensitivity, as did blurring, eccentric fixation and
filtration in Levi and Harwerth's experiment.  In experiment
5.2, 4.5 DS of blurring did degrade contrast sensitivity
at all spatial frequencies, including 0.5 cycles/deg
(seen fig 5.10).  Perhaps greater degrees of eccentric
fixation and neutral density filtration would have done
the same, thus replicating the contrast sensitivity
functions of the severely amblyopic subject  in Levi and
Harwerth's study.  It is noteworthy that, for a normal
eye, photopic visual acuity 2 degrees from the fovea is
about 6/12, and an eccentricity of 14 degrees is required
to lower visual acuity to 6/60 (the acuity of Levi and
Harwerth's illustrated amblyope ), according to Mandelbaum
and Sloan (1947), (cited by Pirenne, 1962).

In summary, the weakness of Levi and Harwerth's discussion
of amblyopic contrast sensitivity lies in the fact that
their sample of subjects all had severe acuity deficits,
and they attempted to match the contrast sensitivity
deficits of these subjects with insufficient amounts of
blurring, etc.

Hess and Howell's (1977) two-type classification of amblyopia on the basis of bandwidth of contrast sensitivity loss has already been discussed, and their data has been re-interpreted in the same way as that of Experiment 5.4.

Thomas (1978) found that "as amblyopic acuity diminished, the differences between amblyopic and non-amblyopic functions became more extensive. The amblyopic deficits were now (for the worse of two amblyopic subjects) apparent at low and middle spatial frequencies as well as at the high." This observation, based on measurements from only three subjects has been substantiated by the data in Experiment 5.4. Thomas also found similarities between foveal contrast sensitivity of amblyopic eyes and peripheral contrast sensitivity of normal eyes, the eccentricity of the peripheral point being related to the amblyopic acuity. He suggested that this might be due to the amblyopic central retina having diffusely organised, "immature", receptive fields similar in size to those normally found in peripheral retina, maturation having been halted by lack of adequate stimulation due to some ocular defect.

In Chapter 4 the importance of contrast sensitivity data as tools in the study of mechanisms of visual perception was discussed. The data presented here have certain implications for theories concerning the mechanisms of amblyopia.

The 'lack of use' or deprivation theory (Worth, 1903) and the suppression theory (Maddox, 1907) have been tentatively reconciled by Ikeda and Wright (1974) who suggested that the former might account for changes in

the visual system at a retinal or pre-cortical level, while the latter might account for cortical events.

If active suppression is the means by which amblyopes acquire their acuity and contrast sensitivity deficits, a broad spectrum contrast sensitivity loss would be expected. The data presented above clearly contradicts this, since several subjects show losses at high spatial frequencies only. The possibility that active suppression of the amblyopic eye's input occurs during binocular viewing cannot be ruled out, but its role in causing amblyopia is in question.

Turning to deprivation theory, the evidence from meridional amblyopia suggests that the effects of deprivation can be very specific. One might expect that all amblyopes would have contrast sensitivity deficits proportional to their abnormal visual experience. For example, an anisometropic amblyope with high hypermetropia in one eye would be deprived of sharply focussed images, i.e. high spatial frequencies, so his contrast sensitivity at low spatial frequencies should be unaffected. Of the 6 anisometropic amblyopes in Experiment 5.4, one ($BC_{ii}$) had unknown refractive errors because she wore contact lenses, four (KD, SI, LJ, SL) had large amounts of astigmatism, and only one (BD) had hypermetropia with minimal astigmatism. BD had no significant interocular differences in contrast sensitivity at spatial frequencies up to 12 c/deg, but his acuities (Table 5.9) show that his amblyopic eye was deficient at higher (30-45 c/deg) spatial frequencies. Of the four astigmatic hypermetropes, one (SL) was very similar to BD, one (KD) had contrast sensitivity deficits at spatial frequencies above 4 c/deg,

and the other two had deficits at <u>all</u> tested spatial
frequencies.  SI's data should be viewed with caution
since she was tested without her refractive correction
(of which she was intolerant).  The data of BD, SL and
KD support the hypothesis that the effects of deprivation
on the developing visual system are frequency-specific,
while the data of LJ contradicts it.

The alternative hypothesis, that deprivation prevents
maturation of the visual system (as suggested by Thomas,
1978) is supported by data on contrast sensitivity in
infancy.  Atkinson, Braddick and Moar (1977) showed
that up to three months of age an infant's contrast
sensitivity is markedly lower than that of a normal adult
across the entire spatial frequency spectrum.  At six
months of age (Harris, Atkinson and Braddick, 1976)
contrast sensitivity to low spatial frequencies  ($<1$
cycle/deg) reaches adult levels, while contrast sensitivity
to higher spatial frequencies remains lower.  Perhaps
amblyopes with large acuity deficits, who show contrast
sensitivity losses at all spatial frequencies (as in Levi
and Harwerth, 1977; Thomas, 1978; Fiorentini and Maffei,
1976; Hess and Howell, 1977; and Experiment 5.4 above)
acquired their visual obstacles in their first three
months of life, and amblyopes with smaller acuity deficits
and only high spatial frequency contrast sensitivity
losses acquired their's later than 6 months.  The
relationship between amblyopic acuity and age of onset
of obstacle to proper vision was first tabulated by
Worth (1903).  In conjunction with the data on infant
contrast sensitivity described above, it provides an
explanation for the apparent link between acuity deficit

and bandwidth of contrast sensitivity deficit. Odd subjects, like LS in experiment 5.4, and CN in Hess and Howell (1977), who lie outside the general pattern, might have additional physiological defects contributing to their contrast sensitivity losses (see discussion of LS above).

Thus it seems possible that the perceptual consequences of amblyopia might be defined by the state of maturity of the visual system at the time when an obstacle to normal development first arises.* The mechanism by which the obstacle prevents normal development cannot be determined from the evidence available. Recent reports by Hess (1979) and Rentschler, Hilz and Brettel (1979) that amblyopes have normal spatial frequency channels do not help to resolve these theoretical uncertainties.

* It is also possible that amblyopia might cause loss of visual abilities which have already developed.

## 5.8. A clinical contrast sensitivity chart.

### Introduction

The inadequacy of the Snellen chart as a measure of visual function has been discussed (Chapters 1 and 5), and the desirability of measuring contrast sensitivity over a wide range of spatial frequencies has been demonstrated by a number of clinical papers (cited in section 5.1). These all reported contrast sensitivity studies in which elaborate laboratory apparatus and lengthy psychophysical procedures were used, since clinical methods of testing contrast sensitivity had not been designed.

The aim of this experiment was to design and evaluate a contrast sensitivity chart for clinical use. Soon after the experiment began, Arden (1978) described a clinical contrast sensitivity test of his own design which has since been used in several studies of patients with visual abnormalities. His test apparatus comprises 6 printed vertical sinusoidal gratings of spatial frequencies 0.2, 0.4, 0.8, 1.6, 3.2 and 6.4 c/deg when viewed from 57 cms. Contrast of each grating decreases from top to bottom logarithmically, by 0.08 log units per cm over 22 cms. An arbitrary linear contrast scale from 1 (low contrast) to 20 (high contrast) is included on the edge of each printed grating, and the range of contrasts covered in each grating is dependent on spatial frequency. Testing procedures used by different investigators have varied. Arden (1978) tested normal subjects by covering each grating in turn with an equiluminant card, and withdrawing the card so that the low contrast edge of the grating appeared first. The position at which the subject first detected the grating was noted for each spatial frequency,

and the arbitrary contrast scores for the 6 gratings were summed. Arden and Gucukoglu (1978) used a similar procedure on patients with retro-bulbar neuritis and found that the average of their total scores for affected eyes was significantly greater than for unaffected eyes. Minassian et al (1978) used only two of the plates (0.8 and 3.2 c/deg) and tested each eye of each subject repeatedly until two consecutive scale readings were identical. Both methods of administration were reported to be quick and reliable.

The test apparatus to be described is completely different from Arden's, and the two will be compared later.

Apparatus

In designing the apparatus the following requirements were considered:

1) It should be easily understood by naive observers, including children and illiterates.

2) It should be administerable by anyone capable of administering a Snellen test.

3) The duration of testing should be brief.

4) The apparatus should be simple and inexpensive.

In order to fulfil the first two criteria the illiterate E test was selected as a basis for the design. In the illiterate E test a high contrast E is presented at one of four orientations in a standard Snellen chart format, with character size varying from 50 min arc to 5 min arc (subtended at a viewing distance of 6 metres). The E has no seriphs but the central limb is shorter than the outer two. Recognition of the orientation of the E is not a simple resolution task since the E differs from a square wave grating in two respects: the shorter central limb, and the connecting spine. These extra features facilitate

recognition, and particularly differentation between the two horizontal orientations and the two vertical ones. It is therefore erroneous to consider that the minimal E size detected represents resolution threshold precisely.

A chart (shown in fig 5.34) was constructed in which the E's varied in size and contrast. One E from each line of a standard illiterate E chart was photographed. Prints were made using 8 different exposure times to produce different densities of pigmentation, and hence different contrasts. It is important to note that mean luminance varied with contrast, as shown in Table 5.14.

### Table 5.14

| Contrast | 0.7 | 0.56 | 0.45 | 0.4 | 0.31 | 0.23 | 0.17 | 0.1 |
|---|---|---|---|---|---|---|---|---|
| Mean luminance (foot-lamberts) | 5.9 | 6.4 | 6.9 | 7.3 | 7.7 | 8.2 | 8.6 | 9.0 |

The effects of mean luminance on contrast sensitivity have been discussed (Chapter 4) and reference to Watanabe et al (1968) suggests that within this range of mean luminances contrast sensitivity to medium spatial frequencies (2-6 c/deg) is almost unaffected. At low spatial frequencies ($<$ 2 c/deg) lower mean luminance increases contrast sensitivity, and at high spatial frequencies ($>$ 6 c/deg) higher mean luminance increases contrast sensitivity. Thus the combined effect of the variation in mean luminances used should result in elevation of both ends of the contrast sensitivity function, resulting in a general flattening.

## Subjects

Eight amblyopes and two undercorrected myopes were tested. Brief clinical details are given in Table 5.15. Fuller details can be found in Table 5.9, except for subject GB who was an anisometropic amblyope who first wore glasses (without occlusion) at 8 years of age.
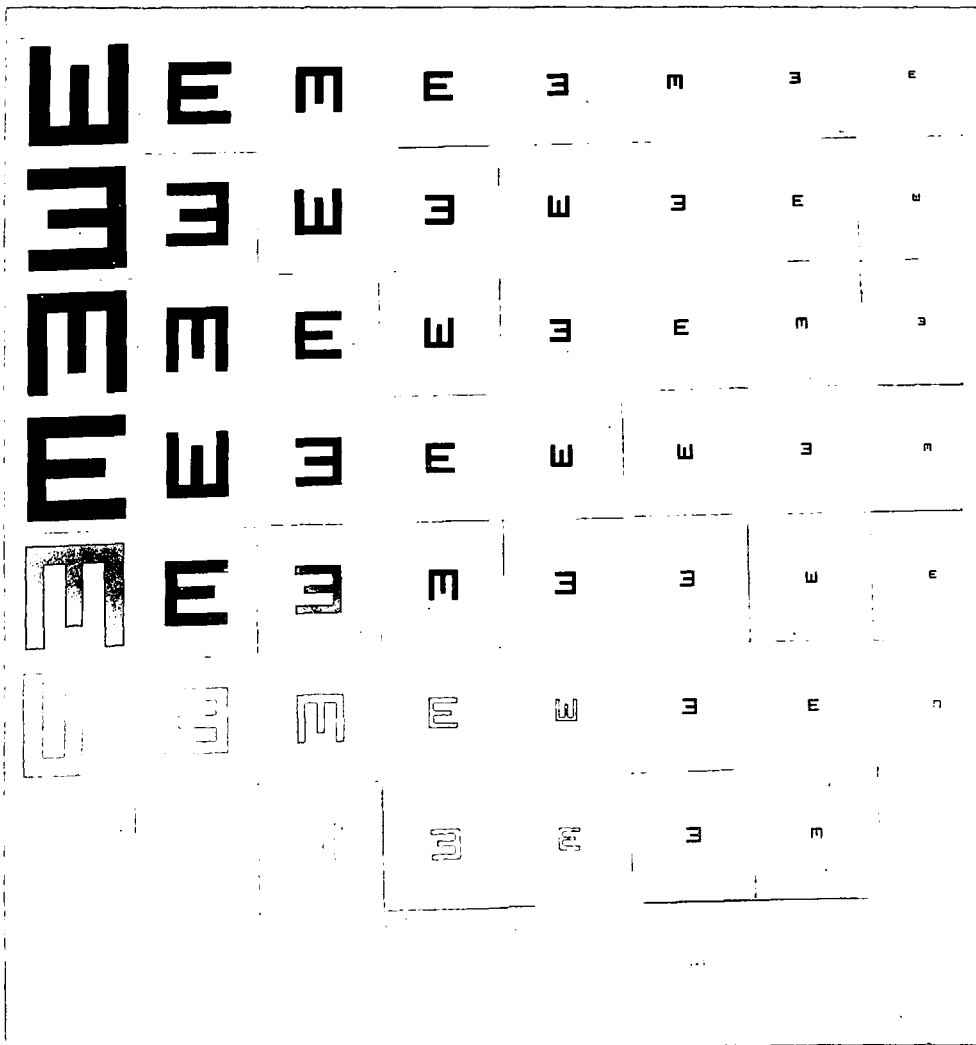
Figure 5.34.

Variable contrast E chart.

## Table 5.15

| Name | Corrected acuities | | Clinical condition |
|------|------|------|------|
| Amblyopes | RE | LE | |
| GB | 0.8 | 2.0 | anisometropic amblyope |
| BD | 0.7 | 1.0 | anisometropic amblyope |
| BC | 20.0 | 1.0 | anisometropic amblyope |
| KD | 0.8 | 1.5 | anisometropic amblyope |
| SI | 1.0 | 1.5 | anisometropic amblyope |
| ML | 0.8 | 1.4 | anisometropic amblyope |
| AM | 0.8 | 1.5 | strabismic amblyope |
| PS | 0.8 | 2.0 | organic amblyope |
| Myopes | | | |
| AC | 0.7 | 1.0 | undercorrected myopic astigmatism |
| SD | 0.8 | 1.5 | undercorrected myopia |

## Procedure

Each subject was tested with each eye, and was required to describe the orientation of each E by stating whether its three limbs were pointing left, right, up or down. All subjects scanned the chart from left to right beginning with the top row. Their responses were recorded on a grid by the experimenter, who could not see the chart. No second attempts were allowed, but "don't know" responders were encouraged to make one guess.

## Results

All subjects reported the orientations of all E's correctly with their good eyes, and all subjects made errors with their bad eyes. In fig 5.35 these errors are represented as histograms, with contrast increasing from 1 to 8 on the ordinate and letter size reducing from 1 to 8 on the abscissa. Each histogram is thus a direct representation of the E chart as shown in Fig 5.34. Both amblyopes and myopes made

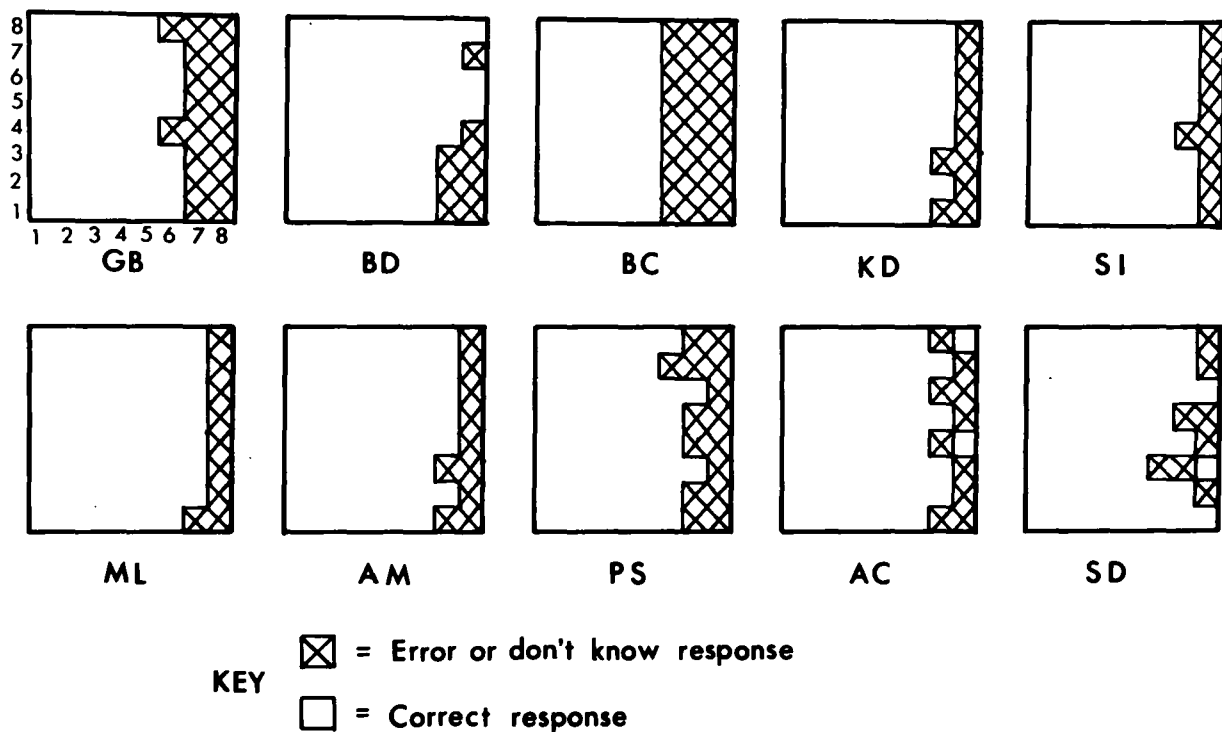KEY  ⊠ = Error or don't know response

☐ = Correct response

Figure 5.35.

Errors made by ten subjects (8 amblyopes and 2 myopes; see Table 5.15 for further details) in recognising orientation in a variable contrast E chart.

Subjects BC and SI had previously shown contrast sensitivity deficits across a broad band of spatial frequencies (see figs. 5.22 and 5.24).

errors on the smaller letters only. They showed a strong tendency to err on all letters of the same size regardless of contrast variation. Low contrast E's did not seem to be less detectable than high contrast E's of the same size, except for subject BD whose errors are clustered in the low contrast small letter corner.

Discussion

The variable contrast E chart described above failed to detect differences in contrast sensitivity for letters of different sizes. This might be attributable to the variation in mean luminance which has been described earlier; at high spatial frequencies (small letters) increases in mean luminance increase contrast sensitivity. An alternative explanation might lie in the small number of contrast levels used. Time did not allow reconstruction of the E chart with a correction of mean luminance variations, and the addition of more contrast levels would have made the chart (already 84 cm square) extremely cumbersome.

In Arden's (1978) clinical contrast sensitivity chart mean luminance was kept constant and contrast was varied smoothly. One modification of Arden's chart which might be worth evaluating would be presentation of gratings at different orientations to detect meridional anisotropies.

Conclusions

Arden's contrast sensitivity test would be a better screening tool than the one designed by the author, but since contrast sensitivity deficits do not seem to be classified by type of visual defect (see introduction to Chapter5), its diagnostic value would be smaller than that of the TNO stereo-test.

## Chapter 6: Overview and Conclusions

In this chapter the data presented so far will be collated with a view to summarising some of the perceptual consequences of amblyopia. In addition, the theoretical and practical implications of the findings will be discussed, and some suggestions for further research will be proposed.

### 6.1. Space perception, stereopsis and contrast sensitivity in amblyopia.

Experiments described in Chapter 3 led to two conclusions: 1) that amblyopia does not prevent three-dimensional perception of space, but that it does slightly reduce the precision of judgements of spatial relationships; 2) that amblyopes cannot perceive depth when it is only cued by inter-retinal disparity, i.e. they lack stereopsis.

In Chapter 5, experiments on contrast sensitivity in amblyopes produced the tentative conclusion that the extent of contrast sensitivity loss, both in bandwidth and magnitude, suffered by an amblyopic eye is dependent on the level of maturity of the visual system prior to the advent of an obstacle to further normal development.

Amblyopic subjects who took part in computer-controlled contrast experiments also tried the stereopsis tests. They showed no rank-order correlation between bandwidth of contrast sensitivity loss and stereopsis as measured by the Titmus test (Spearman $\rho = 0.29$, N = 12) or the TNO test (Spearman $\rho = 0.45$, N = 12), suggesting that these two perceptual deficits of amblyopia might be consequences of different aspects of the condition.

All the experiments described so far have evaluated the perceptual consequences of amblyopia in restricted laboratory conditions. In order to arrive at an understanding of its perceptual consequences in normal

environments it is necessary to consider which of the
laboratory restrictions would not normally be imposed,
and the most obvious of these is monocular occlusion.

Under binocular viewing conditions the effects of
amblyopia on contrast sensitivity would be negligible since
the non-amblyopic eye's normal contrast sensitivity would
mediate normal contrast perception.  Although binocular
viewing was advantageous to amblyopes in the second space
perception experiment they were significantly worse than
non-amblyopes at judging the precision of alignment of
three rods.  However, there were other important restrictions
in this experiment which reduced the number of cues available
for the task, such as the lack of motion parallax, overlay,
texture gradients, and perspective cues.  In the falling
beads experiment, with more cues, some amblyopes performed as
well as emmetropes.  It is conceivable that in an environment
providing a full array of monocular and binocular spatial
cues amblyopes perceive spatial relationships as precisely
as non-amblyopes.  Their lack of stereopsis can only hamper
perception in very restricted visual situations where inter-
retinal disparity is the only available cue.  Examples of
such situations cited by Ogle (1962d) include topographic
mapping from aerial photographs, measurement of stellar
parallax and inspection of suspected counterfeit currency.

In summary, amblyopia would seem to have little impact on
perception of space and contrast for subjects with one non-
amblyopic eye.  The perceptual world of an amblyope without
a non-amblyopic eye might be expected to be more seriously
affected, since contrast sensitivity  would be reduced,
as would sensitivity to monocular spatial cues. (See
footnote).

The availability of suitable subjects for a study of
amblyopes who have lost their good eyes is limited.  About
0.004% of accidents reported to the Factory Inspectorate in
1969 (by a work-force of 9,000,000) involved loss of an eye
or permanent impairment of its sight.  Assuming an incidence
of 4% for amblyopia, and a probability of 50% that the non-
amblyopic eye would be the one affected, one would expect
to find only 7 subjects from a work-force of 9,000,000 and
perhaps a few more from non-industrial accidents.
Although the perceptual consequences of amblyopia appear to
be minimal, its practical consequences are not.  These will
be discussed in a later section, after evaluation of the
theoretical implications of this research.

Footnote

I have recently heard of one such monocular amblyope, who
lost his good eye in an accident in his mid-twenties.  He
reported that his ability to make judgements of spatial
relationships improved dramatically over a period of a few
months, so that he felt that his perceptual abilities were
fully restored to their original levels in all respects,
except for the loss of visual field.

## 6.2. Theoretical implications

In this section the foregoing work will be discussed in relation to theories of amblyopia, and an important new theory of space perception.

Integration of the data presented in this thesis with theories of amblyopia has been attempted in previous discussions (Chapters 3 and 5), and can be summarised as follows:

1) Lack of normal binocular visual experience in early infancy (as caused by strabismus, anisometropia, or measles) can prevent the full development of binocular visual functions. This results in deficits of space perception in situations where only limited spatial information is available. A mechanistic elaboration of this conclusion cannot be derived from current evidence but the importance of the roles of vergence control and contrast sensitivity is supported by Marr and Poggio's (1979) theory, which will be described and discussed later.

2) Lack of normal monocular visual experience in early life can prevent the normal development of the deprived eye, such that its contrast sensitivity function remains at a level appropriate to the age at which the obstacle to normal visual experience arose.

3) Recent reports by Hess (1979) and Rentschler et al (1979) that amblyopes have normal populations of spatial frequency channels imply that the consequences of visual deprivation in human amblyopia are not neurophysiological but functional, and once again a mechanistic explanation is impossible.

### 6.2.1. Marr and Poggio's (1979) theory of human stereo vision.

A recent paper by Marr and Poggio (1979) "provides a theoretical framework for most existing psychophysical

and neurophysiological data about stereopsis." Briefly, they propose a five-step algorithm in which each eye's image is filtered, then edges are localised and matched, to produce a '2½-D sketch'. The filtering process occurs at different levels of coarseness, with coarse channels controlling vergence movements in order to bring fine channels into correspondence since stereopsis only occurs in Panum's areas. Processes contributing to the '2½-D sketch' interpret disparity, motion, shading, texture, and contour information.

All (except texture) of these classes of information were available in the falling beads experiment, in which amblyopes performed as well as non-amblyopes. In the three-rods experiment motion and texture were absent, and amblyopes performed less well than non-amblyopes. In the Titmus stereo-test only disparity and contour information were given and amblyopes were almost entirely unable to perceive depth, and in the TNO stereo-test where disparity was the only cue amblyopes' scores were even worse. Thus there seems to be a relationship between the number of sources of information available and the quantitative precision of space perception or stereopsis.

In the three-rods test amblyopes were found to gain some advantage from binocularity, even though they lacked stereopsis as measured by the Titmus and TNO tests. The hypothesis that they used the binocular proprioceptive information provided by convergence and/or accommodation was proposed to account for this finding. The role of vergence movements is important to Marr and Poggio's (1979) model of space perception, as described above.

In a recent paper Kenyon, Ciuffreda and Stark (1979) claimed that amblyopes and strabismics did not make normal fusional

vergence movements when tracking a moving object, but used accommodative vergence and a saccade to achieve fixation with the dominant eye. The relative efficiencies of these two techniques is not mentioned in the abstract referred to, and Marr and Poggio (1979) do not differentiate between the two types of vergence, so the implications of Kenyon et al's (1979) finding for Marr and Poggio's (1979) model cannot be assessed.

An alternative approach to examining amblyopes' space perception requires consideration of their contrast sensitivity characteristics. Experiments described in Chapter 5 indicated that detection of high spatial frequencies was hampered by fairly small amounts of amblyopia, and in Marr and Poggio's (1979) model this insensitivity would negate the value of making controlled vergence movements to bring fine channels into correspondence. Thus only coarse information on disparity, motion, shading texture and contour would be interpreted by amblyopes with monocularly reduced contrast sensitivity for high spatial frequencies. The falling beads and three rods experiments probably did include some coarse information, and the Titmus stereo-test items also have low spatial frequency components, but the TNO stereo-test items are almost entirely of fine granular random patterns. This analysis might account for the differences in amblyopes' performances in the four experiments described in Chapter 3.

An alternative explanation of amblyopes' lack of stereopsis lies in the possibility that they lack cortical disparity detector cells (e.g. as suggested by Blakemore and van Sluyters, 1974), but this depends heavily on neurophysiological evidence from animal research; no

parallel evidence has been found from human brains; although psychophysical data on interocular transfer (e.g. Movshon, Chambers and Blakemore, 1973) does suggest that stereo-blind subjects have reduced binocular interaction in their visual systems.

## 6.3.  Practical implications of the findings presented.

The results of experiments described in this thesis generally suggest that the amblyope's everyday life is unlikely to be affected as a consequence of his/her perceptual losses. However, there is one important respect in which the amblyope might suffer because of his/her ocular condition: visual screening for several jobs now includes tests of stereopsis, with apparently little regard for the relevance of stereopsis to the work task.  It can be argued that in times of high unemployment the employer has the right to select the best available workforce, but for the amblyope this can mean exclusion from jobs which he/she could perform as well as a non-amblyope.  This restriction of the amblyope's freedom of choice of work is one important reason why the goals of preventing or successfully treating amblyopia must be relentlessly pursued.

Towards these ends the clinician requires means by which to detect amblyopia early enough for successful treatment, or preferably, means by which to detect ocular defects likely to result in amblyopia in young infants.

An adequate screening tool for the diagnosis of amblyopia is already available in the form of the TNO stereo-test (see Chapter 3 and Walraven, 1975), but methods of assessing visual function in infancy are not yet refined enough for reliable clinical application.

In the following chapter some pilot studies directed towards developing a method of screening infants for contrast sensitivity losses are described.

## 6.4. Suggestions for further research.

The investigations described in this thesis could be extended in two primary directions:

1) to further understanding of visual perception in amblyopes,

2) to further understanding of the mechanisms of amblyopia.

In the first direction comparative assessment of amblyopes' perceptual skills against those of non-amblyopes in normal visual situations (as opposed to controlled laboratory conditions) would have obvious practical value. If amblyopes were found to be significantly worse at certain visual tasks the use of random dot stereograms in screening applicants for jobs requiring such tasks would be vindicated. Further understanding of the perceptual consequences of amblyopia would also be valuable in making an economically determined choice between prevention or attempted cure of amblyopia.

In the second direction, further studies of contrast sensitivity in populations whose ocular histories are fully documented would test the validity of the hypothesis that the contrast sensitivity of an amblyopic eye is dependent on the age of onset of the obstacle responsible for amblyopia. Alternatively, or additionally, the hypothesis could be tested by means of a longitudinal study of contrast sensitivity changes in a population large enough to include a sample of amblyopes. In the following chapter some pilot studies directed towards devising means of testing contrast sensitivity in infants are described.

# CHAPTER 7: VISUAL SCREENING IN INFANCY

## 7.1.  DEVELOPMENT OF VISUAL CAPACITIES.

The human visual system is functional at birth.  Even premature infants (seven months gestation) demonstrate light sensitivity by an avoidance movement (Spooner, 1969). Full term neonates are capable of fixating and tracking large high contrast targets (Brazelton, Scholl and Robey, 1966).

However, neurophysiological development of the visual pathways is not complete at birth.  Myelination of the lateral geniculate bodies and superior colliculus continues into the first post-natal months (see discussion in Bronson, 1974) and some cortical areas (e.g. temporal lobes) are myelinated throughout the first ten years of life (Yakovlev and LeCours, 1967).  Neuronal growth also continues postnatally, for example, in the neocortex, and occipital and temporal lobes (Conel, 1939, 1941, 1947).  Additionally, some lateral geniculate cells do not reach their adult size until the 24th postnatal month (Hickey, 1977).

The eye also shows considerable postnatal development.  Like the brain, and unlike the body, it increases in size most rapidly during the first two years of life (Spooner, 1969). Substantial changes in all its optical components and dimensions produce smaller refractive changes than one might expect.  The neonate eye is generally slightly hypermetropic (Cook and Glasscock, 1951) and quite astigmatic, (Howland et al, 1978).  The hypermetropia increases in the first seven years of life and then decreases, (Slataper, 1950) while the astigmatism decreases gradually to adult levels

(Mohindra et al, 1978).

It seems feasible that the combination of neurophysiological development and refractive changes might affect visual capacities, such as visual acuity, contrast sensitivity and stereoscopic vision. Interest in the nature-nurture controversy motivated psychologists to investigate those capacities, and clinicians tried to establish age-norms for diagnostic use. Their findings varied widely, according to the techniques used. Early clinical estimates based on detection of small objects suggested acuities around 0.4 cycles per degree at four months and 0.7 cycles at 6 months (Chavasse, 1939).

Laboratory studies using optokinetic responses produced significantly better acuities, ranging from 0.9 cycles at birth, to 6 cycles at 6 months (Fantz, Ordy and Udelf, 1962; Gorman, Cogan and Gellis, 1957). Fantz, Ordy and Udelf (1962) compared their results with data they obtained using a fixation preference technique (explained in section 7.3.2.1), and found the two sets of estimates were closely comparable. Dayton et al (1964) produced a remarkably high acuity estimate (4 cycles) for neonates, using optokinetic nystagmus, but this has never been replicated.

Recently cortical evoked potential recordings have been used to determine thresholds of resolution. Both Marg et al (1976) and Sokol (1978) found a rapid rise in acuity, approaching adult levels by 6 months. Contrast sensitivity studies also indicate that adult levels of performance are attained by this age (Harris et al, 1976). Acuity estimates can be extracted from contrast sensitivity measurements by extrapolating the function to 100% contrast. Some such

estimates are shown in Fig.7.1 which summarises the main findings reported. Dobson and Teller (1978) and Dobson, Teller and Belgum (1978) discuss some of the discrepancies between measures based on different techniques.

Clinical and experimental evidence has shown that abnormal early visual experience can cause permanent loss of visual function (i.e. amblyopia; see Chapter 2). The data above proves that the visual system is still developing during the early months and years of life, so the hypothesis that visual development can be arrested by abnormal stimulation is supported. If different components of the visual system mature at different rates, it seems possible that they have different critical periods (see Chapter 2) of susceptibility to abnormal stimulation. This would account for the discrepancies between definitions of the limits of the critical period by different investigators.

The possibility that the human visual system is susceptible to different types of abnormal visual experience at different ages necessitates detection and treatment of each and every visual defect as soon as possible after it arises, so that normal visual development can proceed. This necessity has been recognised clinically since 1903, and attempts to put it into practice are described in the following section.

Approximate adult acuity level

Cycles per degree

Months of age
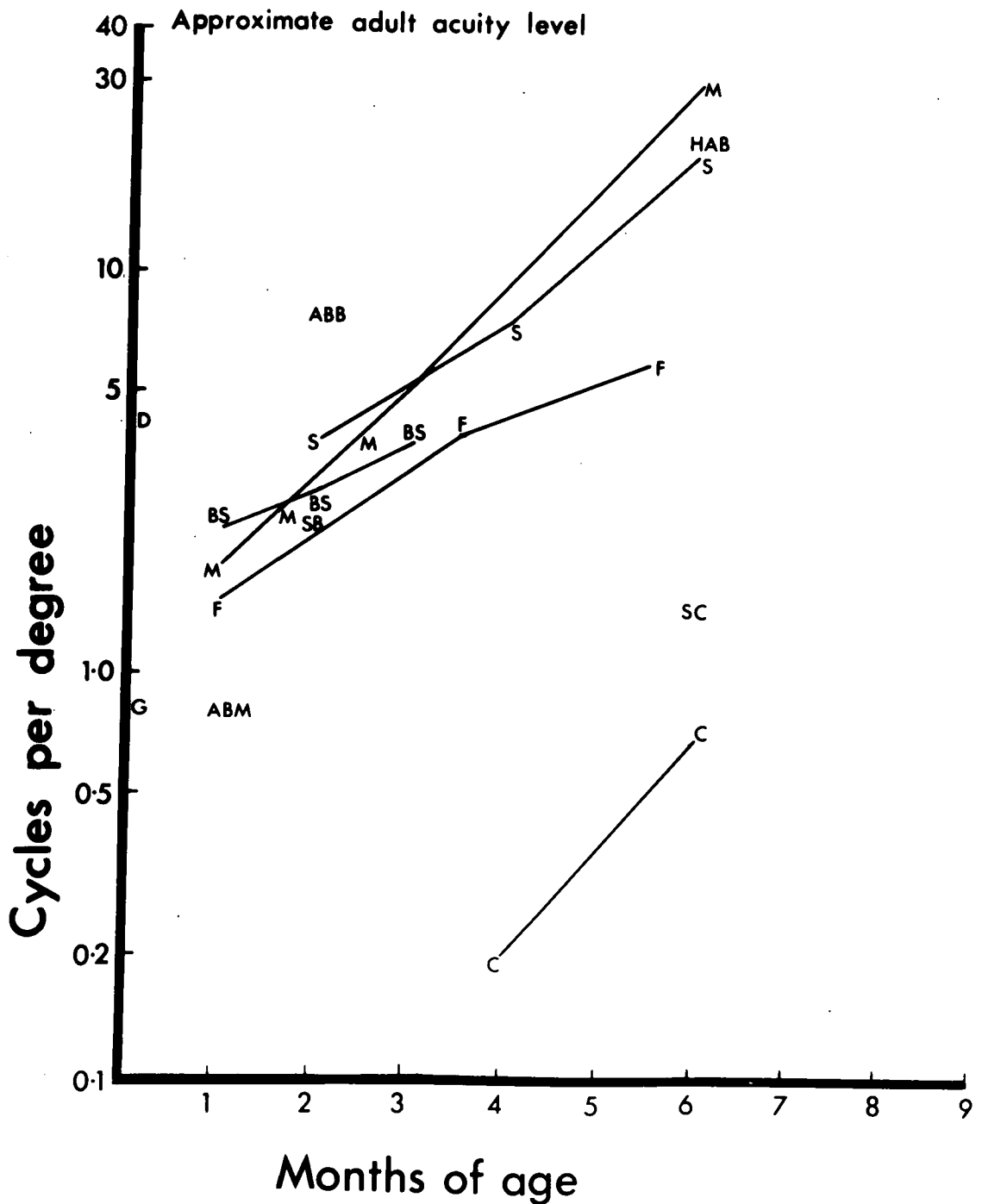
Figure 7.1. Estimates of visual acuity in infancy
Key to initials and methods used:

ABB = Atkinson, Braddick and Braddick (1974): contrast
      sensitivity measurement by fixation preference
      technique.
ABM = Atkinson, Braddick and Moar (1977): contrast
      sensitivity measurement by fixation preference
      technique.
BS  = Banks and Salapatek (1978): contrast sensitivity
      measurement by fixation preference technique.
C   = Chavasse (1939): acuity estimate from detection of
      small objects.
D   = Dayton et al (1964): optokinetic nystagmus and
      electro-oculography.
F   = Fantz, Ordy and Udelf (1962): optokinetic nystagmus
      and fixation preference.
G   = Gorman, Cogan and Gellis (1957): optokinetic nystagmus.
HAB = Harris, Atkinson and Braddick (1976): contrast
      sensitivity measurement using evoked potentials.
M   = Marg et al (1976): evoked potentials.
S   = Sokol (1978): evoked potentials.
SC  = Schwarting (1954) tracking small objects.

## 7.2. THE NEED FOR VISUAL SCREENING IN INFANCY.

The importance of early detection and treatment of amblyopia was recognised by Worth (1903), who presented data showing that treatment effectiveness was primarily dependent upon the time-lag between onset of the squint (or other obstacle) and beginning of treatment. Minimisation of this time-lag was at that time dependent on parental detection of the defect, coupled with immediate seeking of ophthalmological advice. Inevitably, many defects went undetected, and many parents were advised that their children would outgrow their squints without intervention.

The extension of the National Health Service in 1946 provided infant welfare and school medical services, and the Ministry of Education recommended that all five-year-olds starting school should undergo vision screening. The success of this preventative measure was evaluated by Sutcliffe (1958) who examined 1500 15-year-old school leavers in 1956. 6.4% of this sample had reduced (less than 6/9) visual acuity in one or both eyes. Assuming that they had all benefitted from visual screening at age five, Sutcliffe concluded that the Ministry's preventative measure was not having a significant impact on the incidence of amblyopia. She later (1960) investigated the value of lowering the screening age to 3 years but found that 5.5% of screened three-year-olds were already amblyopic, and these did not respond to treatment. Later studies have shown that for early screening to be maximally effective the screening age would have to be lower. Wesson (1961) tabulated the outcome of treatment of 187 strabismic patients classified into two age groups. Equal right and left acuities were acheived by 64% of those first

examined before their second birthday, and only 38% of those first examined after their second birthday. Romano (1975) suggested that the length of treatment required for amblyopia to be eradicated is proportional to the age of the child when treatment begins; thus a four-year-old might require four months of treatment whereas a one-year-old might be 'cured' in one month. He cites two studies of the effectivity of surgical correction of strabismus (Parks, 1968; and Taylor, 1972) in which stereopsis was achieved by a high proportion of children treated before their second birthdays but by none of those corrected later (total sample of 143 cases).

Whether effectiveness of treatment of amblyopia depends on time-lag between onset and treatment, or simply on the age at which treatment begins, the practical implications of the vast body of clinical, psychophysical and physiological evidence which has accumulated throughout this century are clear. Visual screening must be undertaken as soon as practically possible. Knowledge of this fact, which has been repeatedly reinforced, has not yet motivated a large scale screening programme. Bain (1977) reported that developmental screening of children by GPs often excluded tests for visual acuity or checks for squints. Table 7.1 shows the percentages of children tested at each of three ages.

Table 7.1

| Age | 7-10 months (n=79) | 24 months (n=81) | 48-54 months (n=91) |
|---|---|---|---|
| VA tested | 61% | 32% | 67% |
| Squint tested | 39% | 25% | 31% |

A leading article in the British Mediaal Journal (1977) advocated a primary assessment of visual development at 8 months, followed by further more detailed examination at 2½-3 years and 4-4½ years. MacLellan (1977) describes a scheme in Oxford which approaches this ideal, and reports on its success in MacLellan (1979). Nonetheless, a series of letters in the British Medical Journal (Gardiner, 1977a; Cameron, 1977; Ingram, 1977a; Gardiner, 1977b; Mulholland, 1977) illustrate the general concern, in clinical circles, about the absence of a national programme of screening similar to the Oxford one. Ingram, (1977b) considers that screening at three years never became established because it required objective techniques which were time-consuming, expensive and unreliable. In later papers (Ingram, 1977c; Ingram and Walker, 1979; Ingram et al, 1979) he proposes cycloplegic refraction as an alternative screening technique on the grounds that existing approaches have not been sufficiently successful in eradicating amblyopia (Ingram, 1979).

There is undoubtedly an urgent need for a screening tool which can be used to detect visual defects in infants younger than two years, and preferably at eight months, since this is the age at which general developmental screening is carried out in most baby clinics. Ingram's proposal of refraction under cycloplegia would require expert (i.e. ophthalmological) administration, whereas current organisation of infant welfare services would favour a technique administrable by non-experts (such as health visitors). The next section therefore reviews some techniques which have been used to assess visual

function in infancy, either clinically or experimentally, and the following section describes the author's attempts to design a screening tool which fulfils certain criteria which are listed later.

## 7.3.  TECHNIQUES USED IN THE ASSESSMENT OF VISUAL FUNCTION IN INFANCY.

Techniques designed to assess visual capacities in infancy have used a variety of responses as indicators of discrimination.  Bond (1972) presents a broad review of the field.  This section will concentrate on examples of techniques used to measure accommodative responses, visual acuity, contrast sensitivity and stereoscopic vision.

### 7.3.1.  ACCOMMODATION

Haynes, White and Held (1965) used dynamic retinoscopy to examine the accuracy and flexibility of the accommodative system of infants during the first four months of life. They found the infants in this age group were extremely cooperative in maintaining steady fixation at the target which was attached to the retinoscope.  They measured the accommodative response to stimuli at four different distances between 8 cms and 100 cms.  Infants less than one month old seemed unable to adjust their accommodation to match the position of the fixation target; they appeared to lock their accommodation on a point about 19 cms from their eyes.  Flexibility of accommodation was found in the middle of the second month, and by the fourth month accuracy had reached adult levels.  Salapatek, Bechtold and Bushnell (1975) suggest that the apparent  inflexibility of infant accommodation shortly after birth may be an artefact.  They found that the visual acuity of infants at this age was about 2 cycles/deg.  The primary stimulus for accommodation is high spatial frequency information.  Low spatial frequency information is not noticeably degraded by optical blurring (see Chapter 4) and so the infant, who can only detect low spatial frequency information, has no stimulus to accommodate to improve the clarity of the image.

The implications of these two studies are relevant to the problem of designing a screening tool for infants. The main point they illustrate is that the stimulus used must be sufficiently interesting to ensure steady fixation and accurate accommodation, and that it must contain spatial information which is within the resolution limits of that age group.

## 7.3.2. VISUAL ACUITY.

Early studies of infant visual acuity were designed to solve the nature-nurture controversy. They tend to be experimental rather than clinical, and the techniques described are frequently too complex for clinical purposes. However they have provided useful data about the development of visual acuity during infancy, and some aspects of the methodology may help in the design of a simple screening device.

## 7.3.2.1.

Fantz (1956) developed the fixation preference technique: an infant was assumed to discriminate between two simultaneously presented stimuli if it showed a tendency to look directly at one image more than the other. Fantz (1958) found that patterned stimuli were preferred to plain ones. Fantz and Ordy (1959) used this finding to estimate infants' visual acuity. They reduced the width of stripes in the patterned stimulus until no fixation preference remained. This they concluded was because the infant could no longer discriminate between the striped stimulus and the plain one, and therefore the stripe width had fallen below the threshold of resolution acuity. Bower (1972) argues that the fixation preference technique only measures the presence of discriminative

responses, and to infer perceptual ability from these responses is invalid. It is plausible to assume that very fine patterns do not elicit a fixation preference because they are not sufficiently captivating but still resolvable. Fantz and Miranda (1975) found a preference for curved shapes over straight edged shapes in neonates. This may substantiate Bower's opinion that striped patterns are not the optimal stimuli for determining resolution acuity since they are not optimally captivating.

### 7.3.2.2.

Gorman, Cogan and Gellis (1957) used <u>optokinetic nystagmus</u> as a response measure. OKN is a characteristic sequence of involuntary eye movements which is elicited by the presence in the visual field of a horizontally moving scene. The sequence of movements consits of a pursuit phase and a faster refixation phase in the opposite direction. Studies of OKN are reviewed by Kestenbaum (1957) and Reinecke (1961). Gorman, Cogan and Gellis used a black and white grating pattern which moved over the supine infant through an arc of 180 degrees, so that the stripes were vertical and the movement horizontal from the infant's viewpoint. The presence of OKN eye movements indicated that the gratings were being resolved, and a threshold grating frequency was determined. Dayton, Jansen and Jones (1962) added an electro-oculogram to record eye movements instead of a human observer.

The relationship between OKN thresholds and visual acuity in adults and children has been repeatedly investigated (Nicolai, (1954), Weigelin et al, (1955), Ohm, (1956), Schumann, (1961). Reinecke and Cogan (1958) report a correlation (0.664) between Snellen acuity and OKN threshold acuity, and to account for

this correlation they draw attention to the fact that OKN involves the same neural pathway as form vision. Slater (1974) supports this view, but Lewkonia (1969) was unable to find any significant correlation at all. Glaser (1975) and Marg et al (1976) point out that there are in fact considerable differences between the neural pathways involved in OKN and form vision, (these are schematically illustrated by Blackwood, Dix and Rudge (1975)) and suggest that caution must therefore be exercised in making quantitative inferences about visual acuity from OKN evidence.

Amigo (1972) postulates that the mechanisms of vernier acuity may produce artificially high acuity results when gratings are used to elicit OKN and he proposes that spots would be more appropriate stimuli. Catford and Oliver (1973) followed this suggestion in designing their clinical apparatus for assessing acuity in infancy. The "Catford Drum" presents a single spot which travels horizontally through about 10 cms in one direction and then returns to its original position more quickly. This two-phase movement aims to replicate OKN and thus to elicit it more easily than a regular periodic oscillation. A series of spots of

However, it is more likely that it elicits smooth pursuit movements.

different sizes are calibrated in acuity units, and these can be presented in any order.

Catford and Oliver reported a high correlation between Snellen acuity and the size of the smallest spot eliciting OKN, for adult subjects tested both with and without neutral density filters. Khan et al (1976) were less satisfied with the acuity predictions they obtained from the Catford Drum. They found that the correlation between

spot size and Snellen acuity only held for normal subjects with Snellen acuities better than 2.5 mins.arc. Neutral density filters or convex lenses altered the gradient of the regression line so that the Catford Drum gave acuities three times higher than subjective methods. The regression line obtained from diseased eyes (without field defects) was almost parallel to the subjective acuity axis. The use of a spot stimulus may be the cause of some of these difficulties. The detection of a grating depends upon resolution acuity, whereas the detection of a spot is dependent upon the relative luminances of the spot and the background. A low resolution optical system cannot detect a narrow-barred grating at all but a spot can be detected regardless of its size if contrast is sufficiently high. It follows that spot size cannot be simply correlated with resolution acuity.

7.3.2.3.

The third important technique which has been applied to investigations of infant acuity is the measurement of visually evoked cortical potentials (VEPs) by Marg et al (1976), Sokol and Dobson (1976) and Sokol (1978). A relationship between visual acuity and VEP amplitude and latency was first demonstrated by Harter and White (1968), and the amplitude decrement with reducing visibility is the factor used in acuity estimation. Marg et al (1976) claim that the VEP technique has advantages over behavioural measures because it overcomes attentional problems. Wastell (1978) on the other hand emphasises the importance of attentional effects upon the amplitude of the VEP. Ludlam and Meyers (1972) streamlined the technique reported by Millodot and Riggs (1970) in order to make it more clinically useful. They reduced the number of stimulus exposures from

about 300 to 20, so that one eye could be assessed in 20 minutes. Their subjects included infants and retardates. Millodot (1977) maintained that the complexities of instrumentation and data analysis limit the clinical applicability of VEP technology, and Bostrom, Keller, and Marg (1978) found that refractive measurements using VEP's were not as reliable as currently practised clinical procedures for objective refraction.

### 7.3.2.4.

Methods of assessing infant acuity which have evolved within a clinical environment are less technologically sophisticated than those so far outlined. Harrison's (1975) review of techniques currently in clinical use includes the simple <u>Bead test</u>: tiny cake decorations (2-3 mms.) are placed on a flat surface 30 cms from the infant, and the discriminatory response is reaching for and picking up the beads. Sheridan (1973) designed a similar test using small balls ranging from 1-5 cms. diameter. These are rolled across the infants field of view at a distance of about 3 metres the discriminatory response is visual or bodily pursuit of the balls. Sheridan (1963) lists a series of visuomotor responses which should appear in an infant's repertoire at certain stages between the 4th week and 24th month of visual development is normal. None of these methods purport to provide precise quantitative information about visual acuity, and their value lies in their detection of gross defects of visual function.

### 7.3.3. CONTRAST SENSITIVITY.

Visual acuity measurements only indicate the status of the visual mechanisms responsible for handling high spatial frequency stimuli. More detailed information about visual function

is obtained by measuring the visibility of stimuli which
vary in contrast as well as size. Such measurements produce
a <u>contrast sensitivity function</u> (CSF) which shows the
threshold contrasts for stimuli (usually gratings) of
different spatial frequencies. (See Chapter 4).
Atkinson, Braddick and Braddick (1974) obtained the CSF of
a 2-month-old infant by using a modified fixation preference
technique. They presented a sine-wave grating stimulus
paired with a non-patterned stimulus of equal mean luminance.
A "blind" observer watched the infant's behaviour, particularly
fixations, and guessed the location of the grating stimulus.
The contrast of the grating was varied until a threshold was
found; this was taken as the point at which the observer's
guesses were 70% correct. 8 different grating sizes (spatial
frequencies) were used. Approximately 400 trials were
necessary to obtain the CSF, and these were spread over a
period of about 12 days. The CSF was considerably different
from that of an adult. Banks and Salapatek (1976) plotted
CSFs for five two-month-olds. They also used a fixation
preference technique, but had two observers recording the
location of the infants' first fixation only. They defined
thresholds as the contrast at which both observers were
correct for 75% of trials, 200-300 trials were presented
to each infant to obtain a CSF from five spatial frequencies.
Atkinson and Braddick (1976a) reported CSFs (partly described
in Atkinson, Braddick and Moar, 1977 ) using the same
technique on infants between one and three months old. They
found a rapid improvement in contrast sensitivity over this
period. They also used pictures of faces as stimuli
instead of gratings, and paired them with blurred pictures.

There was a fairly high correlation between grating acuity and picture acuity (acuity was taken to be the spatial frequency at which threshold contrast was 100%). Banks and Salapatek (1978) describe further CSFs for one-three month olds, using their methods outlined above. Their results corroborate those of Atkinson and Braddick (1976a), and Atkinson, Braddick and Moar (1977).

Harris, Atkinson and Braddick (1976) assessed the contrast sensitivity of a six month old infant using both fixation preference and evoked potential recordings. The two methods produced similar results. They concluded that the six month old infant has adult levels of contrast sensitivity for low and medium spatial frequencies, but not for high ones. They suggested that the measurement of contrast sensitivity by means of visually evoked potentials might be a useful diagnostic technique for detecting visual problems in infancy, and later applied it to a study of neonates (Atkinson, Braddick and French, 1979) in which they found that contrast sensitivity showed little improvement in the first five weeks of life.

7.3.4. STEREOSCOPIC VISION AND DEPTH PERCEPTION.

Relatively few studies have been directed towards determining age norms for depth perception or stereoscopic vision in infancy. Fantz (1961) applied his fixation preference technique (outlined in section 7.3.2.1.) to this problem, and found that infants aged between 1 and 6 months preferred to fixate a sphere rather than a circle. The most effective cues for solidity discrimination appeared to be texture and brightness gradients, Binocularity seemed to reduce discrimination in infants under three months and enhance it in those over three months. Bower's (1966) perceptual studies, using operant conditioning techniques, demonstrated that

infants aged 6-8 weeks were unable to detect differences in size and distance, and that motion parallax and binocular disparity cues were more important than pictorial cues. Bower (1971) found that newborn infants reached out to touch and grasp real and virtual objects, and they were very disturbed by the intangibility of the virtual ones. Atkinson and Braddick (1976b) employed their fixation preference technique (see section 7.3.3.) and a habituation recovery technique to study the discrimination of binocular disparity cues by two-month-old infants, using random dot stereograms (see Chapter 3). Three out of four subjects seemed to possess the ability to detect binocular disparities of about 2000 secs arc.

Romano, Romano and Puklin (1975) attempted to plot stereo-acuity against age for children between 1½ and 13 years. They obtained poor responses to Polaroid stereograms from children under 3 years, but attributed this to a lack of comprehension rather than a lack of stereopsis.

7.3.5.  SUMMARY.

Responses which have been employed as indicators of visual function are: preferential fixation, optokinetic nystagmus, visually evoked cortical responses, habituation of sucking, and other operantly conditioned behaviours.

In selecting one response from this array for use in a screening tool the following factors require consideration:

1) The response must be one which can be easily elicited from infants  of around 8 months.

2) It should be minimally vulnerable to the "state" of the infant: wakefulness, attentiveness, cooperativeness etc.

3) It should be detectable by a non-specialist observer (e.g. health visitor or G.P.).

4) Assessment should be brief, in order to reduce the likelihood of loss of infant cooperation. This would also add to the appeal of the tool to the busy practitioner.

5) The technique should be reliable, in order to minimise over- or under- referrals and to avoid the need for repeated assessments.

6) The screening tool should be portable and inexpensive.

The following section describes the author's preliminary investigations of methods by which the above criteria might be met.

## 7.4.  PRELIMINARY INVESTIGATIONS.

### 7.4.1.  ACCOMMODATION.

When testing infant acuity it is important to know whether
the stimulus  used is sufficiently interesting to attract
fixations and sufficiently detailed to elicit an appropriate
accommodative response.  The stimulus must also lie within
the infant's sphere of visual interest (see Haynes, White
and Held, 1965; Wetherford and Cohen, 1973).

In order to familiarise myself with these features of studying
infant visual behaviour I made some observations on a five-
month-old boy.

### Method

Retinoscopy is an objective method of measuring refractive
states.  Static retinoscopy is used to measure total
refractive error while the subject fixates a distal point,
approximating infinity.  Dynamic retinoscopy is used to
measure accommodative responses, and the subject's plane
of fixation is varied within a proximal range of about 30
to 80 cms.  If the accommodation exerted is appropriate
for the fixation distance, no movement is seen in the reflection
from the retina.  The fixation target in dynamic retinoscopy
is usually a small Snellen chart attached to the retinoscope
itself.  The retinoscope used in this study did not include
such a fixation target.

### Procedure

The infant was seated upon his mother's knee in a darkened
room.  He was given about 5 minutes to adapt to the darkness.
The author then turned on the retinoscope light and attracted
the infant's attention to it, by waving it around.  The
infant followed the light quite consistently.  The author
then began to attempt measurements, by observing retinal

reflections from a distance of about 50 cms. from the infant's face. However the light was now quite stationary and no longer seemed to capture the infant's attention sufficiently. He became restless and irritable and no retinoscopic evaluation was possible.

A second attempt was made in an illuminated room, since his mother thought that he may have found the darkness stressful. Once again he was encouraged to fixate the moving retinoscope light and then measurements were attempted. Improved fixation was achieved this time. Two possible reasons were: firstly he was more at ease in the illuminated environment, and secondly he could now see the observer's face, which was more interesting than the retinoscope light.

Results and discussion

Brief dynamic retinoscopy at a range of distances (30 to 80 cms) demonstrated that he was capable of exerting appropriate accommodative efforts at times. It seems probable that these good results were obtained when he was captivated by the observer's face. However when his attention wandered the retinoscopic findings varied widely.

This initial encounter with an infant subject was valuable in several respects. It showed the importance of choosing stimuli and testing conditions which elicit the desired responses consistently and easily. It also made the author aware of the problems of "state": wakefulness, restleness, etc. and their impact on observations.

## 7.4.2. VISUAL ACUITY.

Of the various response measures reviewed above, OKN was considered to be the one which promised to fulfil most of the criteria listed as desirable features of a screening tool. It is a reflex response and therefore requires least subjective cooperation. In addition, it is an all-or-none response, consequently it should be quite easy to detect thresholds between its occurrence and cessation.

Having selected OKN as the response measure, various different techniques of stimulus presentation and response observation were designed and studied. Gratings were selected as the most appropriate stimuli for obtaining a measure related to resolution acuity. (See Chapter 1).

7.4.2.1.

<u>Pilot Study 7.1: Observing OKN elicited by drifting gratings</u>
<u>on an oscilloscope.</u>

<u>Apparatus</u>

Drifting sine wave gratings were generated on a Telequipment
D52 oscilloscope by methods similar to those described in
Chapter 4. The rectangular display covered an area of
approximately 100 $cm^2$. Drift speed and spatial frequency
were variable.

<u>Subject</u>

The five-month-old boy used in preliminary observations of
accommodation was again used as a subject. He was 7 months
old when this pilot study was completed. He was seated on
his mother's knee with his eyes approximately level with the
centre of the oscilloscope face. He was alert and placid and
cooperative.

<u>Procedure</u>

The oscilloscope display was set to a low spatial frequency,
high contrast grating drifting at a speed of 10 cycles per
second. A testing distance of 1m was selected so the
oscilloscope face subtended approximately 6 degrees. Drift
speed was varied throughout its range (1cps-25cps) and the
spatial frequency was altered (0.5-10.0 cycles per degree).
However none of these high contrast displays succeeded in
holding the infant's attention for more than a second or two,
and no OKN was detected.

<u>Modification 1</u>

A second testing distance of 0.5 m. was then tried, in the
hope that the increased subtense of the stimulus field
(12 degrees) would improve its attraction. Once again speed
and spatial frequency were varied, but the infant still failed

to fixate the oscilloscope face or to produce any OKN.

Modification 2.

The subject had previously demonstrated that he preferred
a light environment to a dark one, so the room illumination
was increased.  However this added another distraction: he
could now see the observer's face behind the oscilloscope.

Modification 3

The observer concealed herself behind a screen and observed
the infant via a telescope (3X).  This technique also proved
fruitless since the infant's gross body movements kept taking
him outside the telescope's field of view.

Discussion

This first pilot study produced no useful data because OKN
was not detected at all.  Two possible reasons for this were
considered; firstly the stimuli may not have been appropriate,
and secondly the observation techniques may not have been
sufficiently sensitive.

Stimulus characteristics were compared with those reported
previously.  Gorman, Cogan and Gellis (1957) tested newborn
infants using a striped band which filled the subject's field
of view completely, as did Dayton et al, (1964).  Testing
distances in these two studies were 15 cms and 25 cms
respectively.  The grating sizes and speeds reported by both
groups were in the same range as those used in this pilot
study.  So the two variables which differed most from those
previously reported were stimulus area and testing distance.
In this pilot study  the small oscilloscope screen and the
long testing distance may have rendered the stimulus
uninteresting to the infant.

Observation techniques were also compared with those of
previous workers.  The majority of OKN studies used direct

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observation by trained personnel. Dayton et al (1964) recorded eye movements using electro-oculographic apparatus, and found the results were comparable to those obtained by direct observation.

## Conclusions

Having assessed the variations from previous successful techniques, it appeared that stimulus field size was the most likely reason for the failure of the first pilot study. In addition the author felt that her limited experience of detecting OKN in infants necessitated an observation technique which would allow retrospective evaluation of the subjects' performance. The second pilot study was designed to override these two shortcomings.

### 7.4.2.2.

### Pilot study 7.2: OKN with reflected gratings.

### Apparatus

In order to increase the stimulus area, a new method of grating presentation was designed. The apparatus is schematically shown in fig.7.2. A slide of a square wave grating was projected on to a plane mirror which was driven by a variable speed motor connected to its medial axis. The mirror oscillated periodically and the image of the slide reflected on to a ground glass screen was of a grating drifting in alternate directions, horizontally. The total stimulus field size and hence the spatial frequency of the grating could be varied by altering the distance between projector and mirror, or by changing the slide. Slides were not photographically produced since this was technically too difficult; they consisted of 'Letraset' lines stuck on glass slide mounts.

For observation, a video camera with a 4X telephoto lens was used, so that the subject's performance could be evaluated retrospectively. Playback magnification was about 10x. Infra-red illumination was used so that room illumination could be kept low enough to prevent peripheral distractions from competing for the infant's attention.

### Subjects

The child used in Pilot Study 7.1 was now eight months old. He, and another boy aged 7 months were tested.

### Procedure

The infant was seated on his mother's lap with his eyes level with the centre of the oscillating mirror at a distance of 40 cms. A high contrast grating (0.5 cycles/deg) oscillating at 3 grating cycles per second was presented. The stimulus
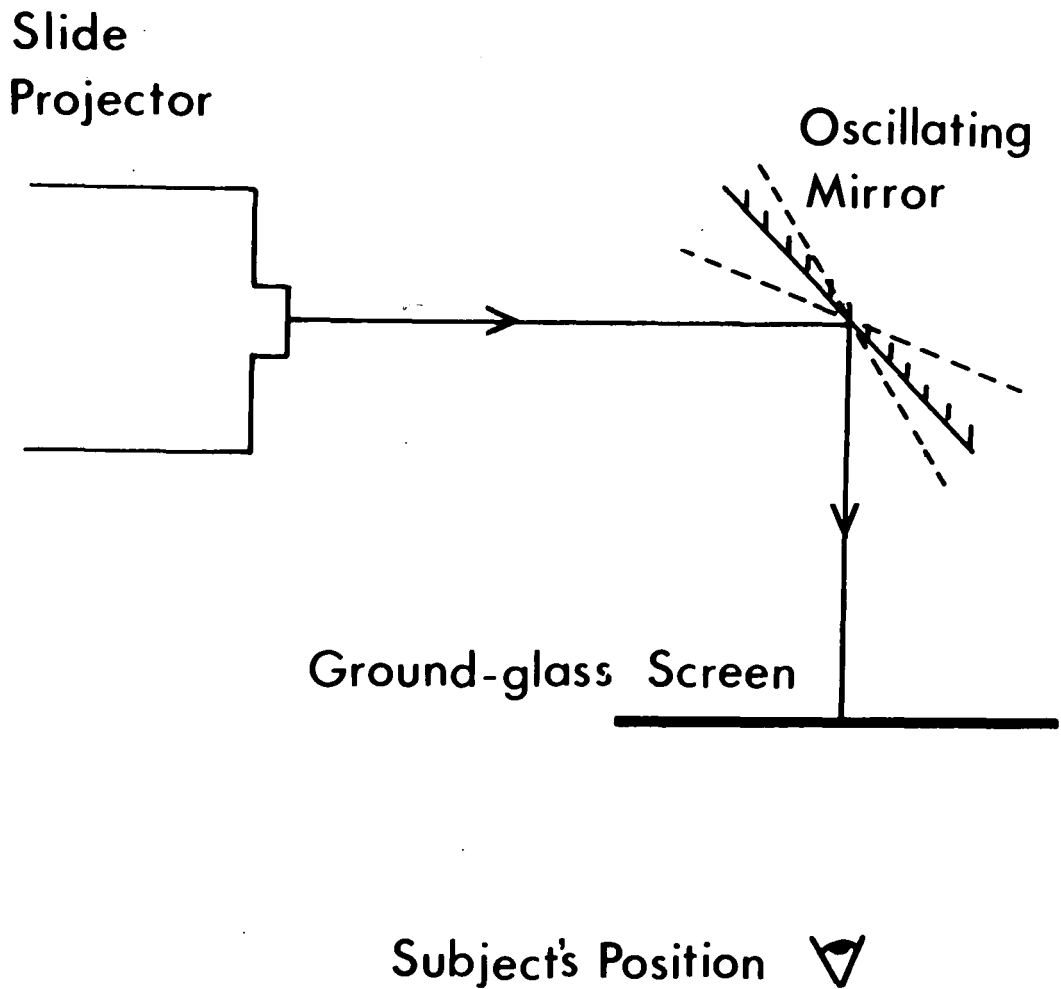
Figure 7.2.

Apparatus used in Pilot Study 7.2. Slides of square-wave
gratings produced with 'Letraset' lines were projected
via an oscillating mirror onto a ground glass screen.

subtended about 50 degrees horizontally and vertically. The video camera was directed at the infant's face. Mother assisted by trying to keep his head as still as possible, without distressing him. Stimulus parameters were verbally recorded on the video-tape. Both subjects were too mobile and evaded the camera's field of view frequently.

## Modification 1

A seat was constructed to reduce the problems caused by gross body movements. Shown in Fig.7.3,it consisted of an infant car seat, with restraining belts,mounted in a stable wooden structure of variable height. This improved fixation behaviour slightly: both subjects were seen to look in the direction of the grating, but no OKN was detected either directly, or on the video-tape.

## Modification 2

Further immobilisation of the infant was achieved by adding a soft padded head restraint to the seat. This kept the subject's head pointing forward. No noticeable improvements were observed. The subjects were both fixating the grating occassionally but they struggled to explore the rest of their visual environment as well.

## Modification 3

In an attempt to channel the infant's visual attention towards the screen, 'blinkers' were added to the head restraints; these restricted the subject's field of view considerably (to about 100 degrees). However they also caused both infants considerable distress, so they were abandoned.

## Discussion

Observation problems seemed to multiply as more restraints were imposed. These restraints were necessary because the observation system (video camera) was not very mobile. The
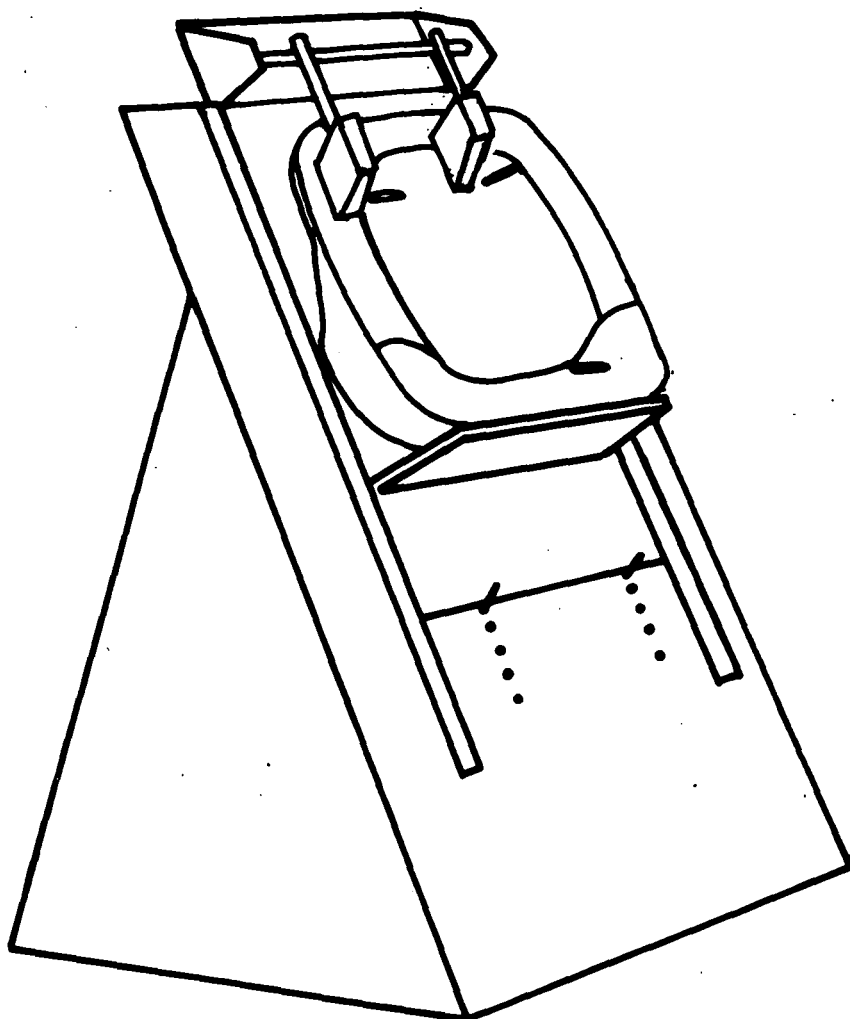
Figure 7.3.

Adjustable infant chair constructed from a standard infant car-seat mounted on a stable base. Blinkers were added in an attempt to reduce peripheral distractions, but were later removed as they distressed the infants.

advantage of a magnified record of eye movements were
weighed against the disadvantages arising from restraints.
A number of observations on adult subjects demonstrated to
the author that she was able to detect OKN equally well by
direct viewing and from a 10X magnified video image.
As before, stimulus parameters were compared with those
described in the literature. Catford and Oliver (1973)
described an optokinetic drum for clinical use. Instead
of gratings their drum displayed a single black spot which
oscillated with a fast sweep in one direction and a slower
return in the opposite direction. This motion replicates
OKN. The stimulus field size in their drum was smaller
than any so far described here: it subtended 15 degress
horizontally and 5 degrees vertically at a testing distance
of 60 cms. In clinical practice it is frequently used at
half this distance for young infants, which results in a
doubling of its angular subtense. Thus the two major
differences between the apparatus used in Pilot Study 7.2 and
the Catford Drum were: the nature of the motion and the
nature of the stimuli.

Conclusions

This pilot study may have been unsuccessful for any of the
following reasons:

i) physical restraints may have reduced the infant's
   cooperativeness

2) periodic oscillation may not stimulate OKN

3) gratings may not be as effective as spots in captivating
   the infant's attention.

In designing the next pilot study these points were taken
into consideration. However grating stimuli had been selected
as the most appropriate for evaluating visual acuity (see

Chapter 1) and these were retained.

7.4.2.3

<u>Pilot Study 7.3:   OKN with a rotating drum of gratings</u>

<u>Apparatus</u>

This apparatus was designed to give a single continuous motion in one direction.  This type of motion is known to stimulate OKN, the classic example being telegraph poles seen from a moving train.  Fig.7.4 shows the apparatus: a transparent cylindrical perspex tube (height 25 cms, diameter 15 cms.) mounted on a variable speed motor so that it rotated about its longitudinal axis.  Against the inner surface of the tube was a piece of paper with a high contrast (black and white) vertical square wave grating (0.5 cycles per cm.) drawn on it.

<u>Subjects</u>

Four subjects were tested.  They were all members of one family: two boys aged one year, and nine years, and two girls aged four years, and six years.  None had any known visual defects.

<u>Procedure and findings</u>

Testing procedure varied according to the age of the subject. The youngest child was the one most relevant to the study, and he was tested first.  He was seated in the infant seat, described above, without the head restraints and blinkers. The laboratory was normally illuminated.  His mother reported that he was used to sitting in infant car seats and he seemed quite placid when strapped in.  The drum was placed at his eye level at about 40 cms, giving a grating spatial frequency of 0.3 cycles per degree.  The drum subtended approximately 30 degs horizontally and 40 degs vertically.
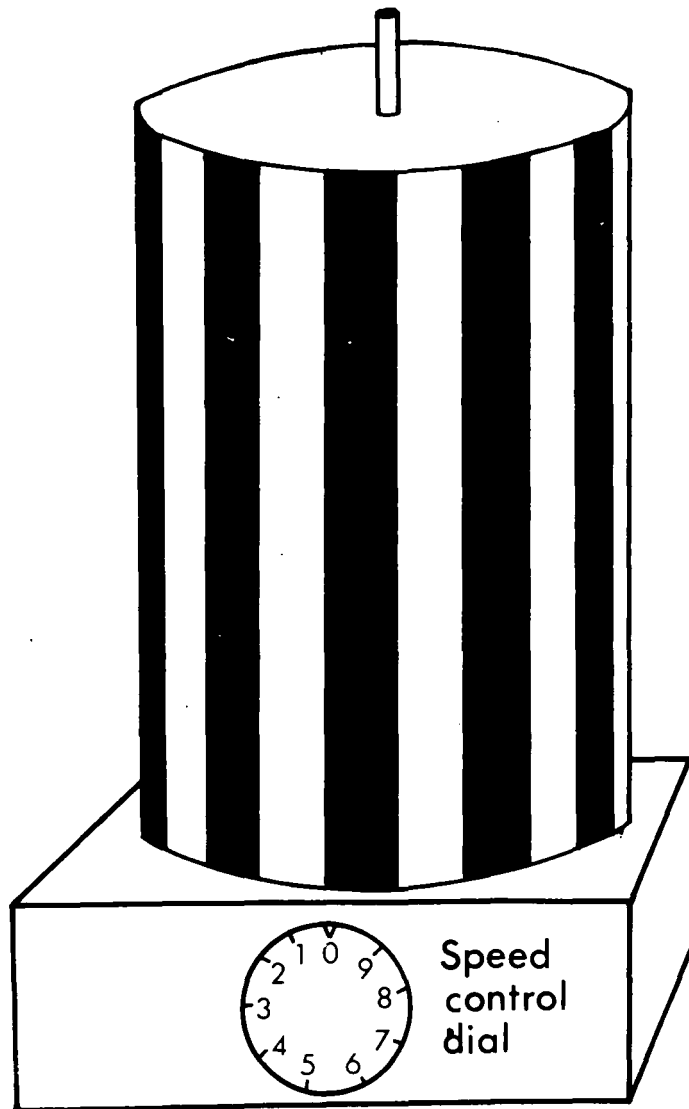
Figure 7.4.

Apparatus used in Pilot Study 7.3. Rotating striped drum with variable speed control.

One experimenter watched the infant's eyes, while another
attracted his attention towards the drum and varied its
rotation speed between approximately 3 and 15 grating
cycles per second.  OKN was detected briefly during the
first few seconds of testing.  Testing distance was
reduced to 20 cms in order to re-capture the infants
attention, but this failed to interest him and he became
restless.

He was removed from the seat and allowed to explore the
laboratory while the other three children were tested.
Each in turn was placed on a chair of the appropriate
height, so that the drum could be placed at his/her eye
level.  Drum speed and testing distance were varied randomly
for all three subjects, and OKN was detected in all of them
over wide ranges of distances and speeds.  Duration of
attention to the drum increased with increasing age.
The one-year-old was then replaced in the infant seat
and the room was darkened in order to attempt video-recording.
Once again a range of rotation speeds and testing distances
were tried, but he was still restless, and also distressed
by the darkness.

Discussion

This pilot study demonstrated conclusively that the author
was able to detect OKN by direct observation, and thus the
complexities of video-recording were not advantageous.
Successful detection of OKN in the one-year-old child was
encouraging; however he had only attended to the drum
briefly and no quantitative assessments were possible.
Optimum rotation speed was not determined, and neither was
the effect of varying testing distance.  Quantitative

assessment of visual acuity by this method would require the use of a range of different gratings. Changing the paper strip inside the drum and retesting several times would extend the procedure well beyond the attention span of young infants. Additionally finer gratings would probably be suppressed and ignored (Ohm, 1956). Further, speed and grating spatial frequency would have to be coordinately selected in order to standardise the number of lines passing the subject's eyes per second (Reinecke and Cogan, 1958).

Conclusion

To avoid these complications I decided to assess the feasibility of measuring contrast sensitivity instead of visual acuity, by varying contrast instead of spatial frequency.

## 7.4.3. CONTRAST SENSITIVITY.

Laboratory studies of contrast sensitivity in infancy have all aimed at obtaining a contrast sensitivity function which relates contrast sensitivity to spatial frequency (see section 7.3.3). A large number of measurements are necessary to achieve this end (e.g. 400 trials in Atkinson, Braddick and Braddick, 1974; and 200 - 300 trials in Banks and Salapatek, 1978). Such extensive procedures are obviously not appropriate for screening.

To reduce the duration of testing in the following study, spatial frequency was held constant and only contrast and rotation speed were varied.

Figure 7.5.

Horizontal section through rotating drum used in

Pilot Study 7.4. See text for detailed description.

level producing a high contrast grating with a spatial frequency of 0.3 c/deg. One experimenter controlled speed and brightness and also observed the subjects eye movements. This was preferable to using two experimenters because the need to report observations verbally was eliminated. (These verbal reports had proved distracting to the infants in Pilot Study 7.3). All subjects were tested until they became restless.

## Findings

The 13-month-old subject showed OKN at a range of speeds for high contrast gratings only. The 8-month-old subject did not attend to the drum at all. She was distracted by the surroundings which were novel to her. (The 13-month-old had been attending the laboratory since he was five-months-old). The four-year-old child showed OKN over a wide range of contrasts and speeds. No thresholds were determined.

## Discussion

Improved results may be due to the age and experience of the 13-month-old subject. The new, younger subject did not show any OKN at all. However, brief investigation of the 4-year old child seemed to be promising. Although it was impossible to find a threshold speed or contrast (probably because the grating was too coarse) her OKN became intermittent as contrast was reduced.

## Conclusion

If the grating spatial frequency used was closer to resolution threshold, a contrast threshold might be obtained. The following study tested this hypothesis.

7.4.3.2.

<u>Pilot Study 7.5: a larger grating display.</u>

<u>Apparatus</u>

A further increase in stimulus size was included in this
design, with the aim of capturing the interest of younger
infants. The new apparatus is shown in fig.7.6. A square
wave grating was produced in a similar manner to that
described in the previous section. Thin white paper strips
were stuck on to translucent tracing paper. The paper
formed a band which was carried by two cork rollers, on of
which was driven by a variable speed motor. The striped
band passed across an aperture 30 cms by 27 cms which was
illuminated by three parallel tungsten tubes. Their light
was diffused by means of a matt white perspex plate. The
tubes were wired to a rheostat so that illumination could
be varied. Fig.7.7 shows how rheostat voltage affected
the luminance of the dark and light components of the
grating. A plane mirror was mounted over the aperture
and this reflected the moving grating towards the subject.
The angle of inclination of the mirror could be adjusted
according to the infant's angle of recline; thus the
grating could always be made to appear straight ahead of
the subject.

<u>Subjects</u>

Three female infants were tested, aged 7, 11 and 12 months.

<u>Procedure</u>

A subject was seated in the infant seat in a normally
illuminated room. The grating image was about 75 cms
away from her face, so its total subtense was about 20
degrees, and the grating spatial frequency was 0.65 cycles
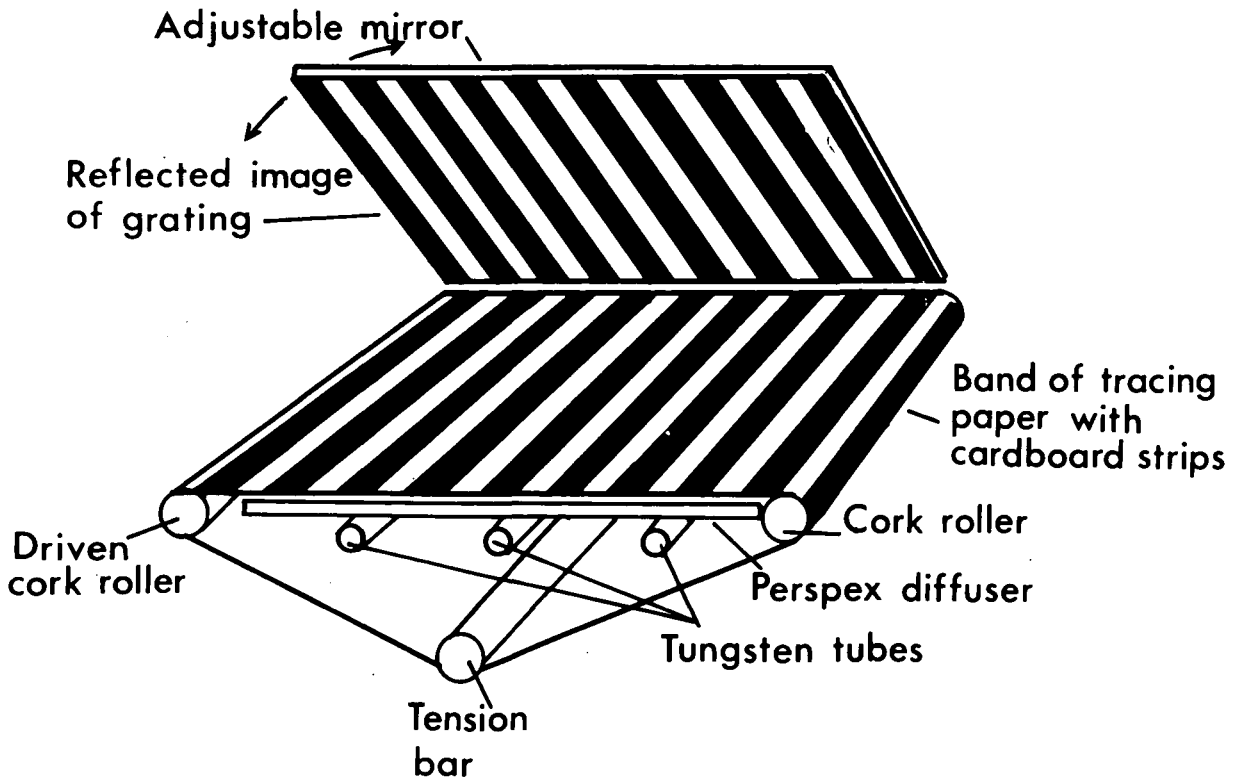
Figure 7.6.

Apparatus used to present drifting square-wave gratings in Pilot Study 7.5. See text for detailed description.
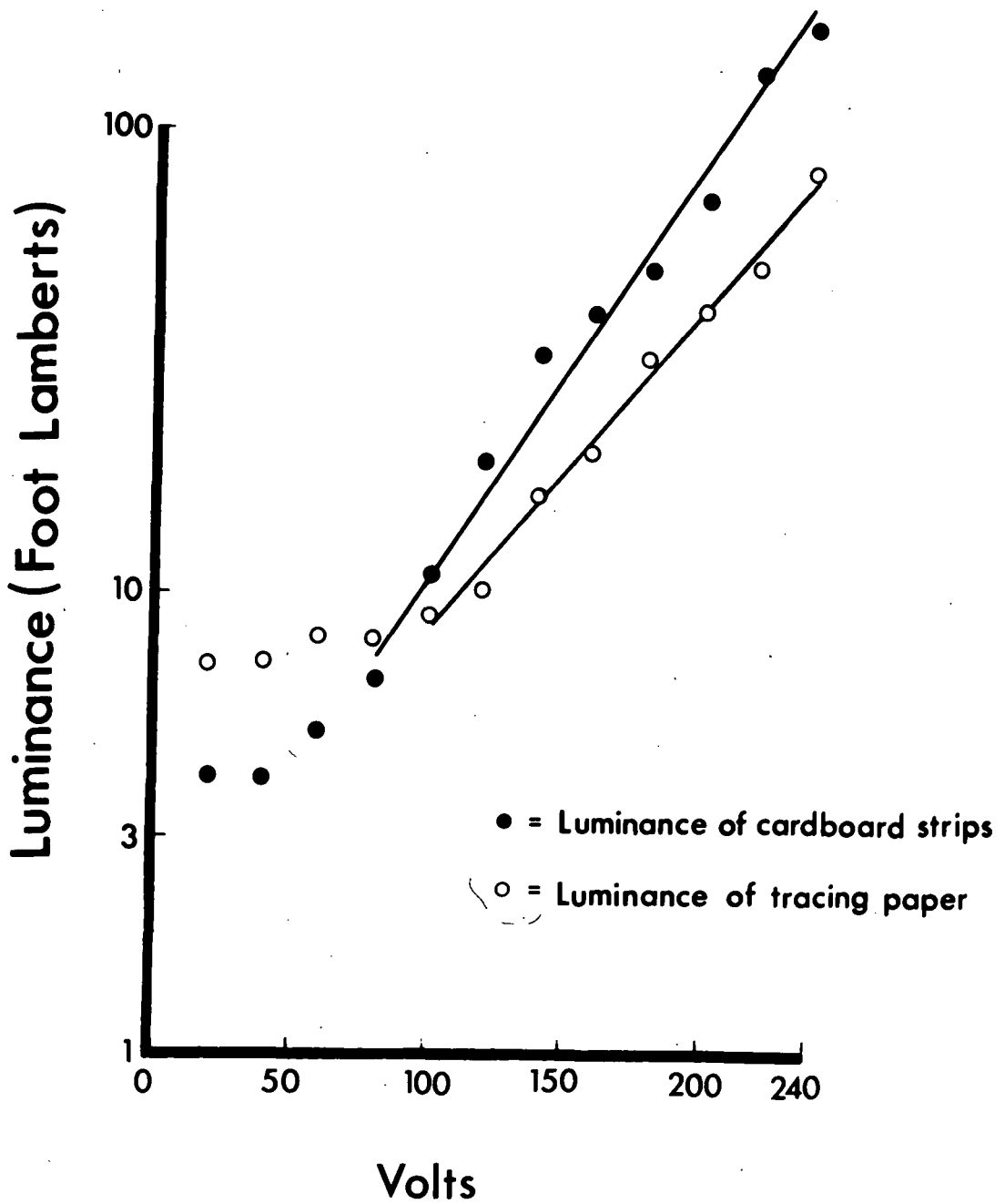
Figure 7.7.

Relationship between luminance and voltage for dark and light half-cycle of the square-wave grating used in Pilot Study 7.5. Regression lines fitted by eye.

per degree. The apparatus was switched on at maximum speed (7.5 grating cycles per sec.) and maximum illumination (contrast = 0.4). Rheostat voltage was then reduced until OKN ceased. Threshold voltage levels were recorded for as many speeds as possible until the subject became restless.

## Results

The 7-month-old produced no useful data at all. OKN was detected intermittently but its presence was governed by her attention and not the stimulus parameters.

8 threshold estimates were made with the 11-month-old. These are plotted in fig.7.8. Contrasts were calculated from the luminances shown in fig.7.7 using (Lmax-Lmin/ Lmax + Lmin). The relationship between rheostat voltage and contrast is shown in fig.7.10.

The one-year-old also produced 8 contrast threshold estimates and these are shown in fig.7.9.

## Discussion

Both responding subjects were most captivated by high speed (> 4 grating cycles per sec.) gratings. These elicited OKN at minimum contrast (0.1). At slower speeds higher contrasts were necessary.

A grating of 0.65 cycles per degree has an absolute threshold contrast of about 0.01 for adults and six-month-olds (Harris, Atkinson and Braddick, 1976). Such low contrasts were not possible with this apparatus, so the absolute contrast threshold was not determinable. If a finer grating had been used, threshold contrast may have fallen within the limited range available (0.1 - 0.4). Harris, Atkinson and Braddick's (1976) data suggests that spatial frequencies around 5 - 10 cycles/deg would be most appropriate for six-month-olds, and
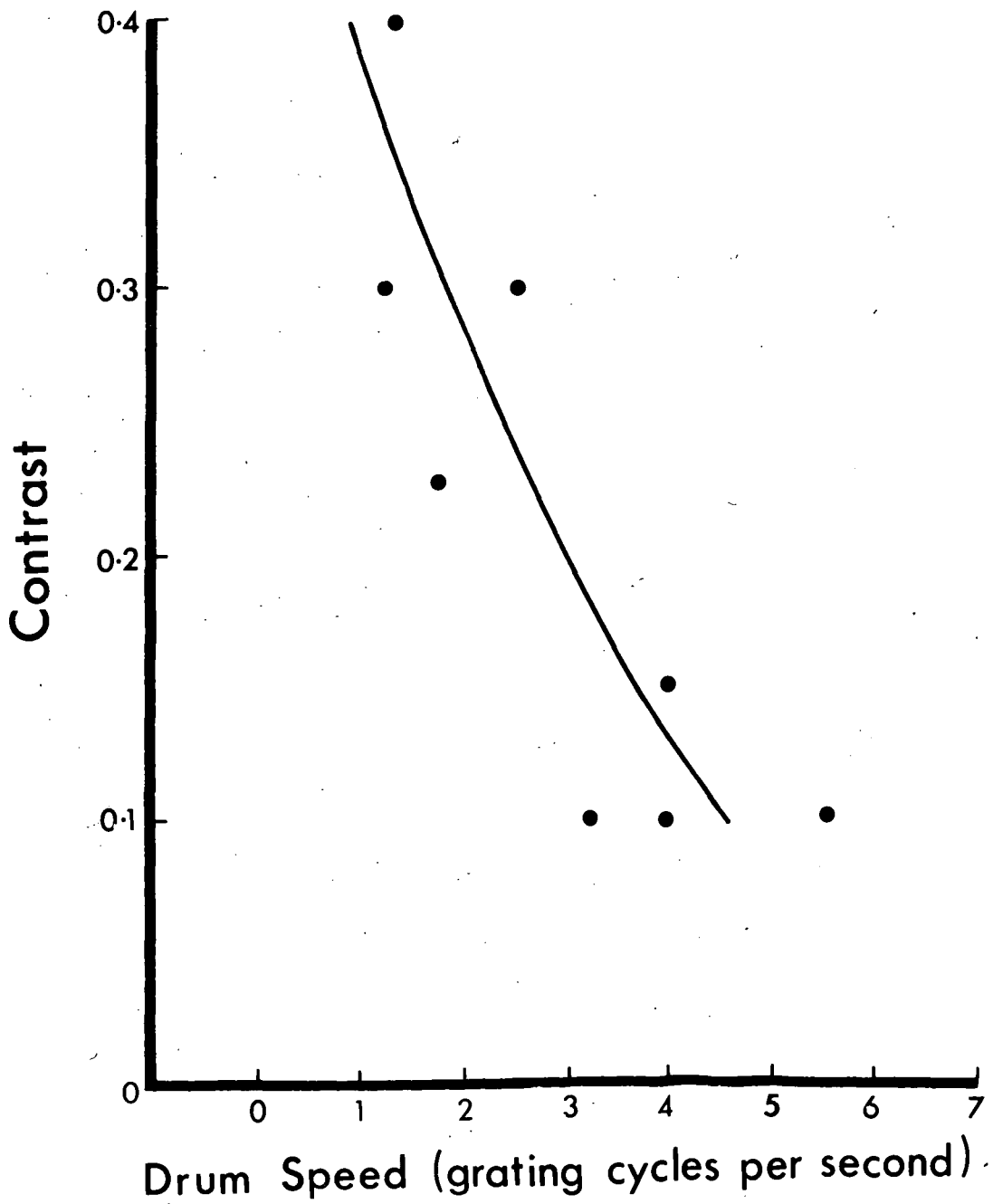
Figure 7.8.

Relationship between grating contrast and drum speed at
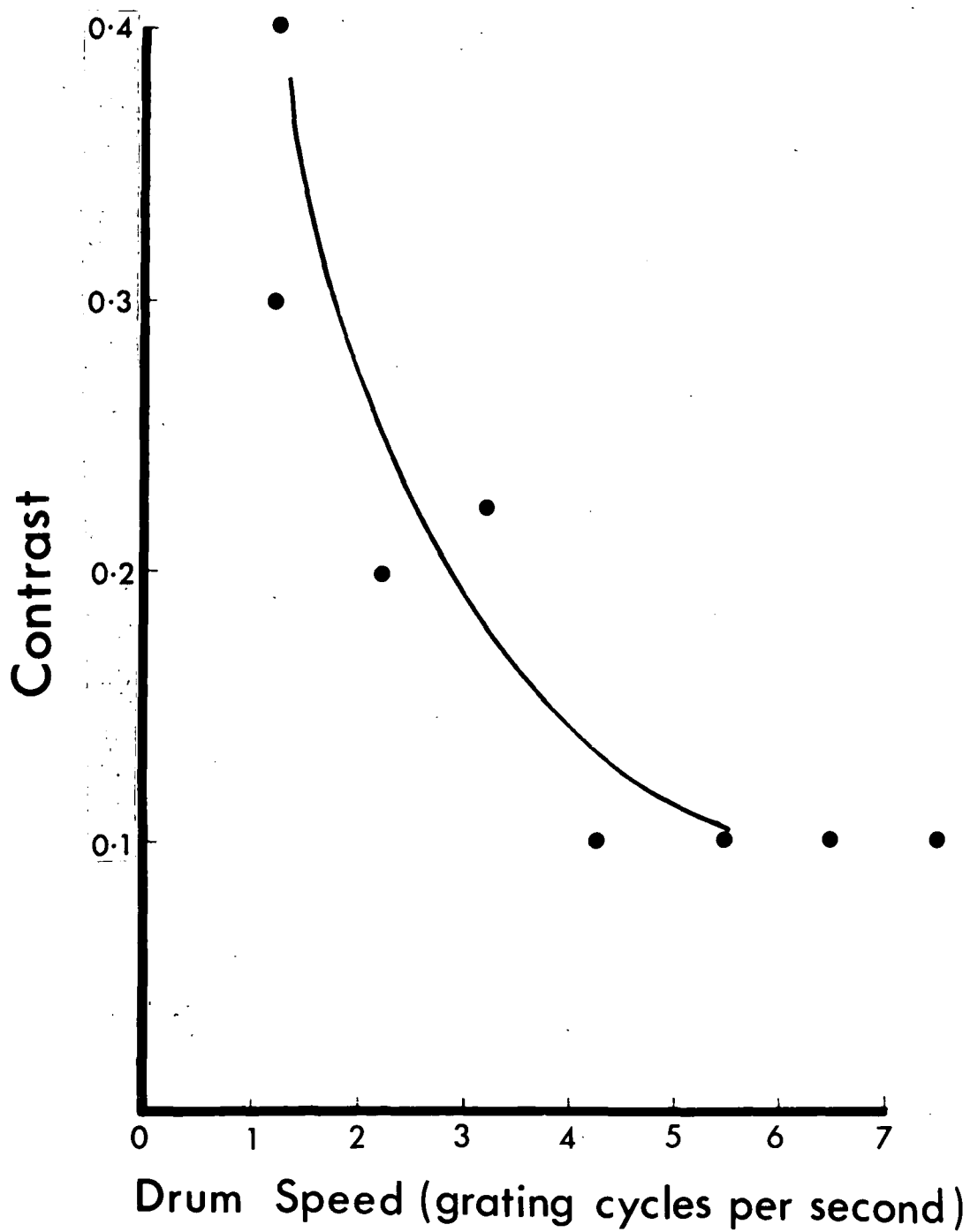OKN thresholds for an eleven-month-old girl.

Figure 7.9.

Relationship between grating contrast and drum speed at

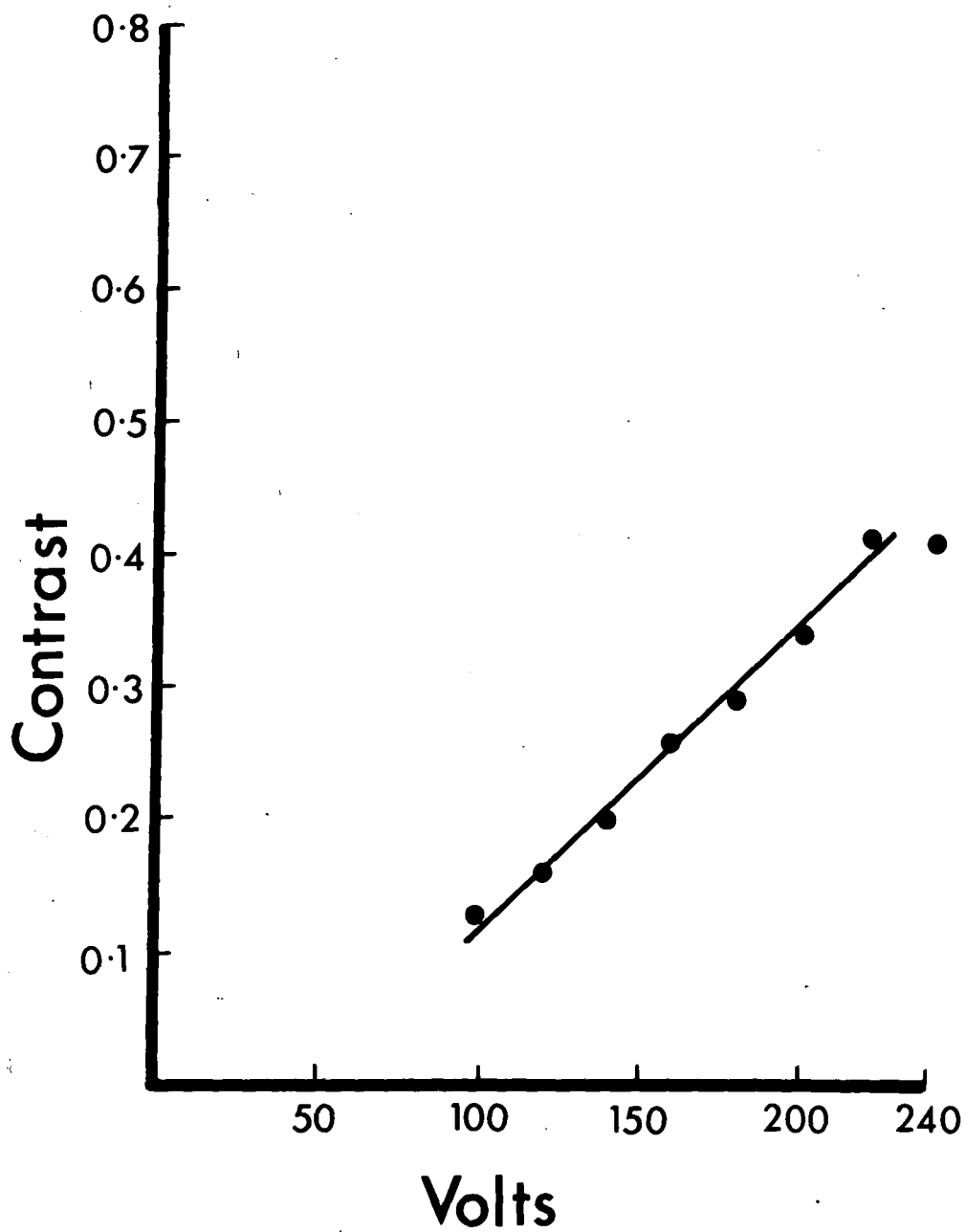OKN thresholds for a twelve-month-old girl.

Figure 7.10.

Relationship between contrast and voltage calculated from luminances plotted in figure 7.7.  Regression line fitted by eye.

10 - 30 cycles/deg for adults. There is no data in the literature on contrast sensitivity of infants older than six months, although Atkinson and Braddick (1976a) report that a 2½-year-old child has approximately adult contrast sensitivity. Thus the appropriate spatial frequency range for 6 - 12 month olds probably lies in the region of 5 - 20 cycles per degree.

## Conclusion

An increase in grating spatial frequency is necessary to obtain absolute contrast thresholds with this apparatus. This could be acheived by increasing testing distance, at the expense of stimulus field size, or by making finer grating bands.

### 7.4.3.3.

### Pilot Study 7.6: Modified Catford Drum

### Introduction

Before embarking upon further development of the apparatus
used in the previous study, I decided to adapt if for use
as a modified Catford Drum. The clinical drum presents a
series of spots of different sizes, each in turn traversing
a 10 cm horizontal aperture, with a faster speed in one
direction than the other. In this study the two speeds were
equal and both spot size and contrast were variable.

### Apparatus

The apparatus used in Pilot Study 7.5 was modified. The
grating band was replaced by a band of tracing paper upon
which were stuck five white paper spots, diameters 1,2,4,8,16
mms. The illuminated aperture was reduced to about 15 x 10 cms
with a matt black mask. A photocell was mounted on the lower
surface of the mask, and this was connected via a series of
relays to the driving motor. Black tape strips were stuck at
intervals along the tracing paper band such that they were
never visible in the aperture, but passed beneath the photocell.
Each time a black strip passed the photocell, light from the
tungsten tubes was obliterated. The photocell detected this
change in luminance, and triggered a change in the direction
of the motor. The black strips were situated such that a
directional change occurred each time one of the spots reached
the edge of the aperture. (see fig.7.11). Thus each spot
traversed the aperture back and forth until the tungsten tubes
were switched off, at which point the tracing paper band
moved in the direction it had been travelling in immediately
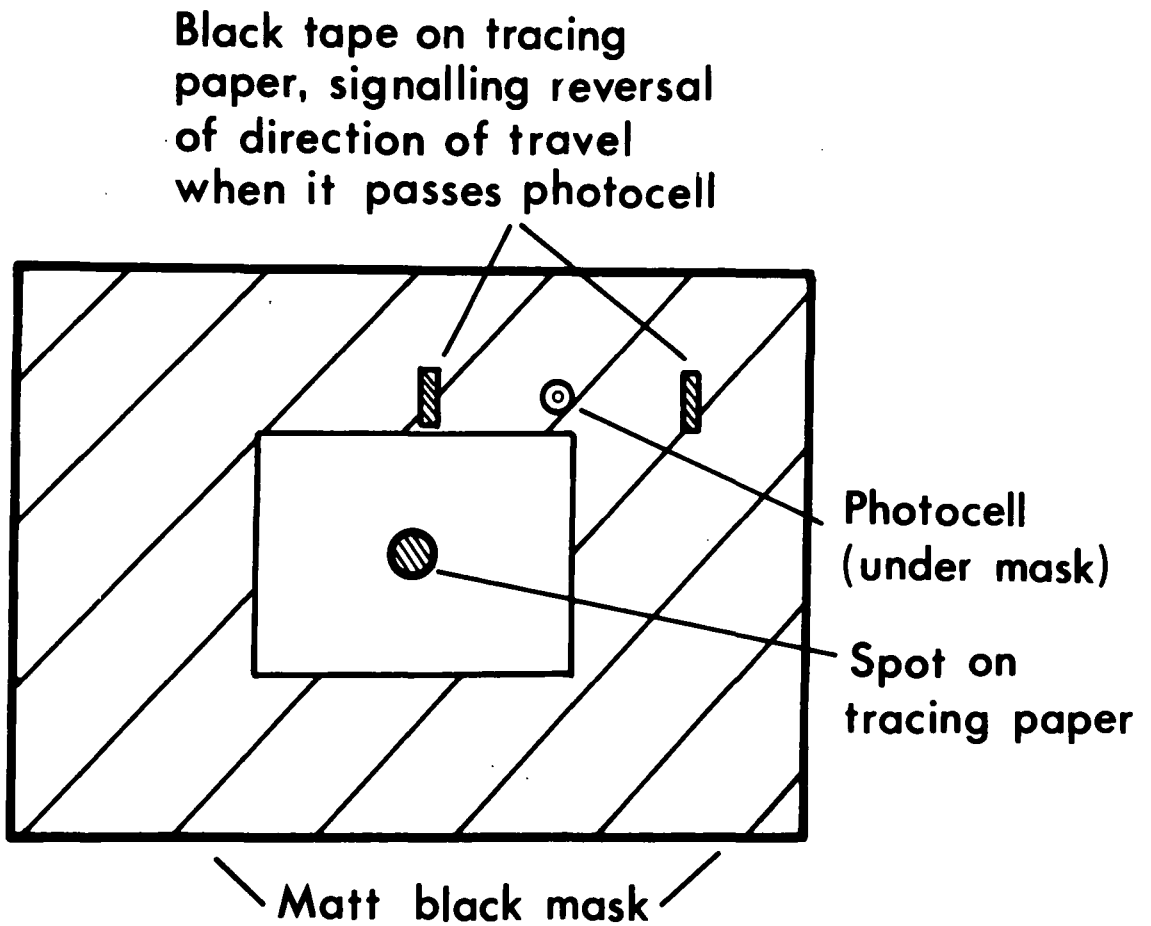prior to switching off.

Figure 7.11.

Modification to apparatus shown in Figure 7.6., to present

drifting spots as in the Catford Drum.  See text for

detailed description.

## Subjects

The three subjects were those used in Pilot Study 7.5.

## Procedure

The subject was seated in the infant seat described previously, in a normally illuminated room. The aperture was about 75 cms away from her face, subtending approximately 10 degs. The largest spot was presented, traversing the aperture, at maximum contrast (0.4) and then luminance was reduced by means of the rheostat until OKN ceased. The voltage was recorded, and the tungsten lights were switched off. The largest spot moved out of the aperture and the second one came into view. Before it had completed its first crossing of the aperture, the illumination was switched on again to give maximum contrast. The entire sequence was repeated with each of the five spots. Contrast thresholds were recorded once for each spot size. Further measurements were not possible because the subject became restless.

## Results

OKN was only detected with the two older subjects. Their contrast thresholds are recorded in fig.7.12, against spot subtense. Neither responded to the smallest spot size. The other four spot sizes elicited OKN within the contrast range.

## Discussion

The relationship between spot size and contrast is similar to that which has been established between spatial frequency and contrast. The cut-off spot size for maximum contrast (0.4) is around 5 - 10 mins arc for these two subjects. Harris, Atkinson and Braddick (1976) found a spatial frequency of about 10 cycles/degree produced a contrast threshold of 0.4,
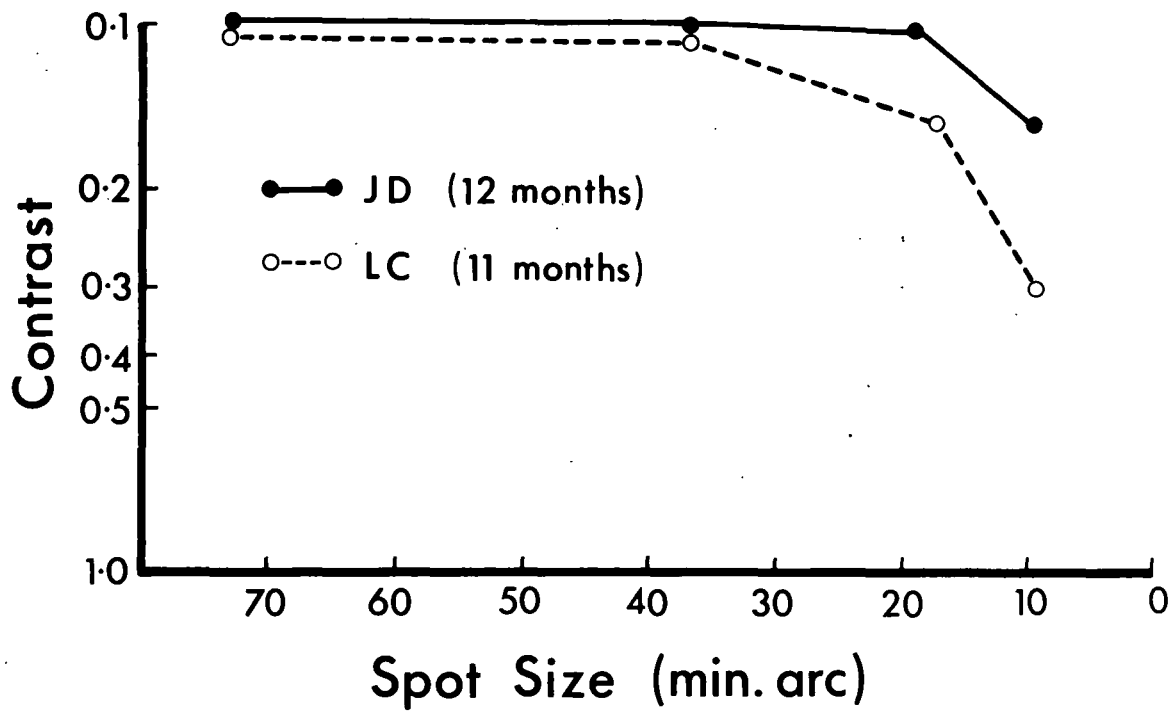
Figure 7.12.

Contrast sensitivity functions of two infants,

determined from OKN thresholds with drifting spots.

in six month olds.  Each cycle in a 10 c/deg grating subtends
6 mins arc.  It seems possible that threshold spot size may be
related to grating resolution , or visual acuity, as claimed
by Catford and Oliver (1973).  Alternatively, and more
parsimoniously, these results can be  considered comparable
with those of Lewkonia (1969) who did not find a close
correlation between visual acuity and the size of the smallest
spot eliciting OKN, but claimed that production of OKN by a
given spot size predicted the approximate range within which
visual acuity would lie.  However, Khan, Chen and Frenkel's
(1976) evaluation of the Catford Drum found that it could
only predict visual acuity for subjects with normal vision or
myopia; it failed to predict the low acuities of amblyopic or
diseased eyes.  In conclusion, gratings would still seem to
be the ideal stimuli for visual screening.

7.4.4.

SUMMARY OF EXPERIMENTAL FINDINGS

Investigations of accommodation, visual acuity and contrast
sensitivity in infants between 5 and 13 months old have
yielded some interesting preliminary results.  These are:

1) Infants in this age range are capable of accommodating
   appropriately for fixation distances between 30 and 80
   cms if the fixation target is sufficiently interesting
   to capture their attention.

2) Factors hampering visual acuity assessment by observation
   of OKN mainly relate to subject restlessness, or problems
   of 'state'.  Parameters which were adjusted to achieve a
   captivating stimulus were: environmental illumination,
   peripheral distractions, physical restraints, testing
   distance, stimulus field size, stimulus speed, and nature
   of stimulus motion (continuous or oscillatory).

Three different stimulus presentation designs were tried.
The third one provided some positive results on children
between one and 9 years old, but no quantitative assessments
of acuity.

3) Contrast sensitivity was measured using two types of
   stimuli:gratings and spots.  Two grating presentation
   systems both elicited OKN in infants around one-year-old,
   but not in younger ones.  In the grating studies no absolute
concontrast thresholds were found because the gratings used
   were too coarse.  However contrast sensitivity functions
   for two one-year-olds were plotted from data obtained from
   spot stimuli, and these seemed to be compatible with
   previously reported functions.

## 7.5.  PROPOSALS FOR FURTHER RESEARCH

Of the various alternative methods of visual screening reported above, contrast sensitivity measurement seems to hold the most promise for further development.

The apparatus described in Pilot Study 7.5 (fig. 7.5) might be adapted to allow determination of absolute contrast thresholds; the range of contrasts presently available is rather limited.  This could be extended by using thinner paper to make the band, and thicker paper for the strips. The tracing paper used was grey, while the strips were white, so at low illumination levels the relationship between them reversed (see fig. 7.6).  Whiter tracing paper and/or greyer strips would possibly extend the low contrast range.

Defects of contrast sensitivity are commonly either high spatial frequency losses, or broad spectrum losses (see Chapter 5).  The normality of an infant's contrast sensitivity might therefore be briefly assessed from threshold determinations at two spatial frequencies:  one near the expected peak of the function (around 1-2 c/deg) and one nearer to the high spatial frequency cut-off point (around 5-10 c/deg).  These two measurements would detect reduced sensitivity of both the common types.

A speedier assessment of contrast sensitivity may be available from the apparatus described in Pilot Study 7.6 (figs 7.5 and 7.10), which is essentially a Catford Drum with contrast variable in addition to size.

In the studies described all measures were made binocularly. For screening purposes, interocular differences are more important than absolute measurements, since rates of

development may vary between subjects but presumably should not vary between the two eyes of one individuāl. Comparison of OKN responses by alternate covering of each eye might have one of two results: it may shorten testing time by removing the need for recording threshold points, or it may cause distress to the subject and prevent any successful assessment at all. Clinical experience with the conventional Catford Drum includes both these outcomes. Development of a non-distressing method of monocular occlusion would benefit both research and clinical workers.

Another branch along which this research might be developed has recently been suggested by Fox, Lehmkuhle and Leguire (1978), who described moving random dot stereograms which elicited OKN. They suggested that their apparatus might form the basis of an objective test of stereopsis and this would be a useful means of assessing binocularity in infants, once normative data on the development of stereopsis has been obtained.

The author hopes to follow up some of the above proposals in post-doctoral research based in local infant welfare clinics, and some progress has already been made in similar directions by Dobson et al (1978) and Fulton et al (1978).

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