The Dependence of Binocular Contrast Sensitivity on Binocular Single Vision

A thesis submitted for the degree of
Doctor of Philosophy

By

Alison S. Hood

October 1999

Neuroscience and Biomedical Systems
Institute of Biomedical and Life Sciences
University of Glasgow

Contents

Terminology

Abnormal Retinal Correspondence (ARC)	A binocular condition in which the fovea of the fixating (non-squinting) eye corresponds to, and has a common visual direction with, a point other than the fovea of the squinting eye. {see also retinal correspondence.}
Accommodation	The process by which the dioptric power of the eye is altered. Accommodation is effected by an increase in the convexity of the intraocular lens of the eyes.
Accommodative Esotropia	An esotropia, which is affected by the state of accommodation and this, is the primary factor in the aetiology of the squint.
Amblyopia	A condition of diminished visual form sense which is not the result of any clinically demonstrable anomaly (pathology) of the visual pathway and which is not relieved by the prescription and wear of the appropriate refractive correction.
Ametropia	An anomaly of the refractive state of the eye (hypermetropia, myopia or astigmatism, in combination or isolation).
Amplitude of Accommodation	The maximum amount of accommodation which the eye can exert.
Angle of Anomaly	The difference between the objective and the subjective angles of deviation
Aniseikonia	A difference in the size and/or shape of the images perceived by the two eyes.
Anisometropia	A condition in which the refractive state of the two eyes is different.

Anomalous Binocular Single Vision (ABSV)	A binocular condition in which binocular single vision exists in the presence of strabismus. As a consequence of the presence of strabismus the retinal correspondence between the eyes is anomalous (see ARC) and thus ABSV exists.
Beam Splitter	An optical system which separates a beam of incident light into two beams of lesser intensity.
Bifoveal fixation	A binocular condition in which the fovea of the right eye and the fovea of the left fixate on the object of regard.
Binocular Single Vision	The ability to use both eyes simultaneously so that each eye contributes to a common single perception.
Confusion	The simultaneous appreciation of two superimposed images resulting from the stimulation of corresponding retinal points by two different images.
Consecutive Divergence	Divergence of one or other eye in an individual in whom esotropia (or esophoria) was previously present.
Convergent Strabismus	A squint in which one or other eye deviates nasally (see also esotropia).
Corresponding Retinal Points	Retinal points lying in corresponding retinal areas (see retinal correspondence).
Dichoptic Viewing	Viewing a stimulus situated in separate and independent field in binocular vision such that each eye perceives a separate image.
Dioptre	A unit of measurement use to evaluate the refractive power of a lens and/or the optical system.
Diplopia	The simultaneous appreciation of two images of one object.

Divergent Strabismus	A squint in which one or other eye deviates temporally (see also exotropia).
Duochrome Test	A subjective test in which an individual compares the sharpness of a black target on a red background and a black target on a green background. In cases of under corrected myopia or overcorrected hypermetropia the letters on the red background are perceived as being sharper. In overcorrected myopia or under corrected hypermetropia the letters on the green background are more distinct.
Eccentric Fixation	A uniocular condition in which there is fixation of an object by a retinal point other than the fovea. This point, which may be situated on nasal or temporal retina, adopts principle visual direction.
Emmetropia	The absence of a refractive error.
Esotropia	A strabismus in which one or other eye is deviated nasally (also called convergent strabismus.)
Exotropia	A strabismus in which one or other eye is deviated temporally (also called divergent strabismus.)
Fusion	*Sensory fusion*: the ability to perceive two similar images, one formed on each retina, and interpret them as one. *Motor fusion*: the ability to maintain sensory fusion through a range of movements.
Harmonious Abnormal Retinal Correspondence	The angle of anomaly is equal to the objective angle, and the subjective angle is zero.

Non-Accommodative Strabismus	A squint which is not affected by the state of accommodation.
Normal Retinal Correspondence	A binocular condition in which the fovea and areas on the nasal and temporal side of one retina correspond to and have a common visual direction with an area and point other than the fovea of the deviating eye. The pairing of all retinal areas is similarly changed. The condition may occur whichever eye is used for fixation.
Objective Angle of Squint	The angle of misalignment of the visual axes in heterotropia or dissociated heterophoria as measured by the observer.
Panum's Space	A narrow band around the horopter. Objects lying within this space give rise to binocular single vision.
Physiological Diplopia	A type of diplopia, which exists, in the presence of binocular single vision. A near object appears double when a distant object is fixated (heteronymous or crossed diplopia) and a distance object appears double when a near object is fixated (homonymous or uncrossed diplopia).
Principle Visual Direction	Straight ahead projection
Prism Dioptre (^)	A unit which specifies the amount of deviation of an image of an object by a prism.
Retinal Correspondence	A general term relating to the correspondence of retinal points and/or areas.
Retinoscopy	A method by which the refractive state of the eye can be determined using a retinoscope.
Spherical Lens	A lens, the two surfaces of which are spherical.

Spherical Equivalents	The algebraic sum of the value of a spherical correction (DS) and half the value of a cylindrical correction (DC).
Strabismus	Loss of parallelism of the visual axes, viz. squint.
Suppression	The inhibition of the perception of a visual image in one eye in favour of those in the other eye, such as that which occurs in strabismus.

List of Abbreviations

ABSV	Abnormal binocular single vision
ARC	Abnormal retinal correspondence
BSV	Binocular single vision
BEO	Both eyes open
BS	Beam Splitter
Bin	Binocular
CRT	Cathode ray tube
CSF	Contrast sensitivity function
D	Dioptre
DC	Dioptre cylinder
DS	Dioptre sphere
DVD	Dissociated vertical deviation
ERG	Electro-retinogram
FL	Fixating with the left eye.
FR	Fixating with the right eye.
LE	Left Eye
Led	Light emitting diode
LGN	Lateral geniculate nucleus
NRC	Normal retinal correspondence
PCT	Prism and cover test
PERG	Pattern electro-retinogram
PVER	Pattern visually evoked response
RE	Right eye
SPCT	Simultaneous prism and cover test

v	Volts
VA	Visual acuity
VER	Visually evoked response
^	Prism Dioptre

List of Figures

List of Tables

Abstract:

This study involved the determination of the effects of binocular viewing on contrast sensitivities in 11 normal subjects and in different categories of amblyopes. These were simple anisometropic amblyopes (n=9), micro-esotropic amblyopes with anomalous BSV (n=6), esotropic amblyopes with anomalous BSV (n=3) esotropic amblyopes without BSV (n=5), exotropic amblyopes without BSV (n=2) and a group of non-amblyopic strabismics (non-amblyopic esotropes without BSV (n=4); non-amblyopic exotropes without BSV (n=2).

An ophthalmic examination was carried out on all individuals. The examination procedures undertaken comprised determination of the visual acuity, subjective refraction, the results of which were confirmed by retinoscopy, and assessment of uniocular fixation patterns. The state of BSV, the direction and magnitude of the angle of deviation, the amplitude of accommodation and pupillary diameter were also determined. The subjects were accordingly placed into the appropriate groups on the basis of the results of the ophthalmic examination.

Measurement of uniocular and binocular contrast sensitivities in response to stationary vertical sinusoidal grating patterns were undertaken. The stimulus display consisted of a Tektronix 5103 cathode ray tube (CRT) with a screen subtense of 2 degrees. Mean contrast threshold values were measured for monocular and binocular viewing over the range of spatial frequencies studied which varied between 8c/deg to 40c/deg depending on the group being examined.

Analysis of the data resulted in a regrouping of the participants. Consequently the normal and the simple anisometropic groups comprised 9 individuals in each; amalgamation of the micro-esotropic amblyopes with anomalous BSV and the esotropic amblyopes with anomalous BSV resulted in a group of nine strabismic individuals with anomalous BSV, designated esotropic amblyopes

with anomalous BSV. Esotropic amblyopes without BSV now comprised seven individuals; non-esotropic amblyopes without BSV numbered two and the exotropic amblyopes without BSV comprised four subjects.

The results after regrouping showed that, first, the binocular contrast sensitivities exceeded those obtained monocularly for the better eye in the groups in which normal or anomalous BSV was present. A mean percentage enhancement, averaged over the range of spatial frequencies, of 13% was recorded in the regrouped normal subjects; 35% in the simple anisometropic amblyopes; 38% in the esotropic amblyopes with anomalous BSV. In each case, the increase was significant ($P<0.01$).

The groups without BSV recorded a mean percentage loss in binocular contrast sensitivities compared with those of the better eye. This loss ranged from 6% to 26%.

When bifoveal stimulation was effected, by prismatic correction in the strabismic groups both with and without BSV, a significant loss in binocular contrast sensitivity occurred. The mean percentage reduction, over the range of spatial frequencies studied, ranged from 25% in the regrouped esotropic amblyopes with anomalous BSV to 43% in the regrouped non-amblyopic esotropes without BSV. Control prism experiments confirmed that the addition of a glass prism of between 2^ and 8^ before one or both eyes did not adversely influence the binocular contrast sensitivity outcomes. However, the larger prismatic corrections of 10^ and 12^ did exert a small degradative effect on the contrast sensitivities but this did not affect the overall outcome of the experiments.

In the normal group and the simple anisometropic amblyopes in whom the prismatic experiment was not feasible, dichoptic viewing experiments were undertaken in which the grating display was viewed foveally by one eye while the other eye was stimulated nasally at 2 degrees eccentric from the centre of the fovea.

These dichoptic viewing experiments, showed that in these non-strabismic subjects, in whom normal BSV was present, no reduction in the contrast sensitivities previously recorded for monocular foveal viewing was caused by presentation of the eccentric grating pattern to the other eye. On the other hand, in strabismic groups bifoveal viewing caused a mean percentage reduction in contrast sensitivity of between 24% in the esotropic amblyopes with anomalous BSV and 39% in the esotropic amblyopes without BSV. In all cases, the mean percentage loss was significant.

The conclusions reached were, first, in individuals with BSV (normal or anomalous), binocular enhancement of contrast sensitivities occurred. However, strabismic amblyopes without BSV and non-amblyopic strabismics without BSV did not exhibit enhanced binocular contrast sensitivities; on the contrary, binocular contrast sensitivities were reduced compared to those obtained through the better eye. Furthermore, when bifoveal stimulation was effected, a further reduction in binocular contrast sensitivity occurred.

This study has thus shown that binocular contrast sensitivities are augmented compared with monocular contrast sensitivities when BSV is present, but are decreased when BSV is absent. Furthermore, correction of the angle of squint in strabismics, whether BSV is present or not, further reduces the binocular contrast sensitivities.

1.0. INTRODUCTION

It is well known that strabismus (squint) or anisometropia (unequal refractive error between the eyes) in early childhood may lead to impaired vision in the squinting or more severely ametropic eye. Furthermore, there may be impairment of binocular single vision (BSV), which is the ability to appreciate a single, fused image from the two separate monocular images. It is commonly believed that this represents an absence of a contribution from the affected eye in that the contribution is either disregarded or actively suppressed (Lyle and Wybar, 1967). The present study has examined, more closely, the effects of squint and anisometropia on binocular function expressed in terms of the binocular contrast sensitivity in response to the detection of vertical sinusoidal grating patterns of different spatial frequencies. In the course of this study it has been necessary to pay special attention to the type of amblyopia present and to the status of binocular single vision.

Accordingly, in this introduction an account is given of:

1. the nature of BSV and its abnormalities.
2. the types, consequences and treatment of strabismus, anisometropia and amblyopia.
3. the neural substrate of amblyopia.
4. the application of contrast sensitivity measurements to the investigation of the different types of amblyopia.

1.1 Binocular Single Vision (BSV)

The majority of individuals have the ability to combine the neural signals emanating from the two eyes, in response to the same visual scene, to produce BSV. The control of the position of the eyes thus becomes essential in order to ensure that the image falls onto the corresponding part of each retina. This is illustrated diagrammatically in Figure 1 which shows the Veith Muller Horopter Circle. This circle passes through the point of fixation and the posterior nodal point of each eye, which is the position of the centre of a single lens representing the summation of the different refractive surfaces of the ocular

media and is thus the point through which incident rays of light pass unrefracted. Theoretically, an infinite number of horopter circles exists, dependent upon the distance of the point of fixation from the eyes. For the horopter shown in Figure 1, all objects positioned on it, even though they are not at the point of fixation, produce images which fall onto what are defined as corresponding retinal points. Hence, the nasal part of one retina corresponds with the temporal part of the other retina and vice versa (normal retinal correspondence). Under normal circumstances, a single, fused image of each object is perceived, thus justifying the term BSV.

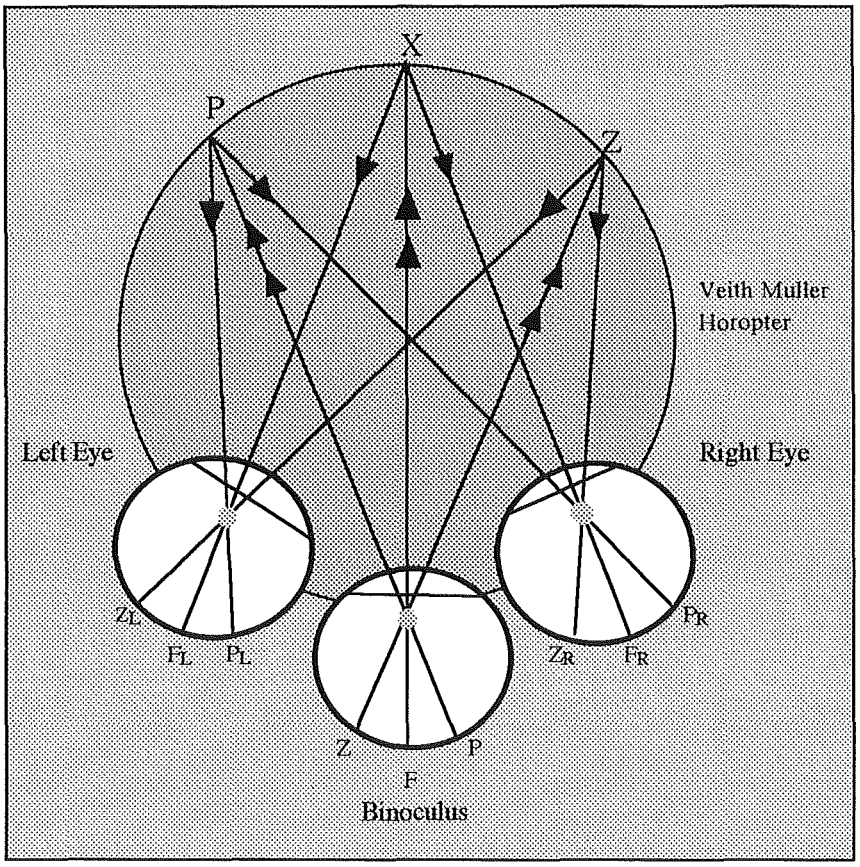


Figure 1. The Veith Muller Horopter.

The objects, represented by P, X and Z, lying on the horopter stimulate corresponding retinal points in the left and right eyes. Incident rays are denoted by single arrows, and outward arrows mark the projection of the direction of gaze from the binoculus. The binoculus, which is the cyclopean projection as if left and right eyes were superimposed to form a single "cyclopean" eye, shows the superimposition of Z_L / Z_R at Z, F_L /F_R at F and P_L / P_R at P, thus resulting in the appreciation of single images at Z, F and P respectively.

Conversely, if an object is positioned either in front of or behind the horopter, *i.e.*, possesses a positional disparity, the images fall onto non-corresponding retinal points *i.e.*, the images have a retinal disparity which results in double vision or diplopia. More specifically, this phenomenon is called physiological diplopia since it is normal for all individuals with BSV to experience it. Physiological diplopia can be easily demonstrated by looking at a pen held directly in front of the eyes, about 6 inches away. Another pen, of different colour, is placed a few inches behind the first pen. When the pen closer to the eyes is fixated, diplopia of the more distant pen becomes apparent. This is uncrossed or homonymous physiological diplopia (Figure 2).

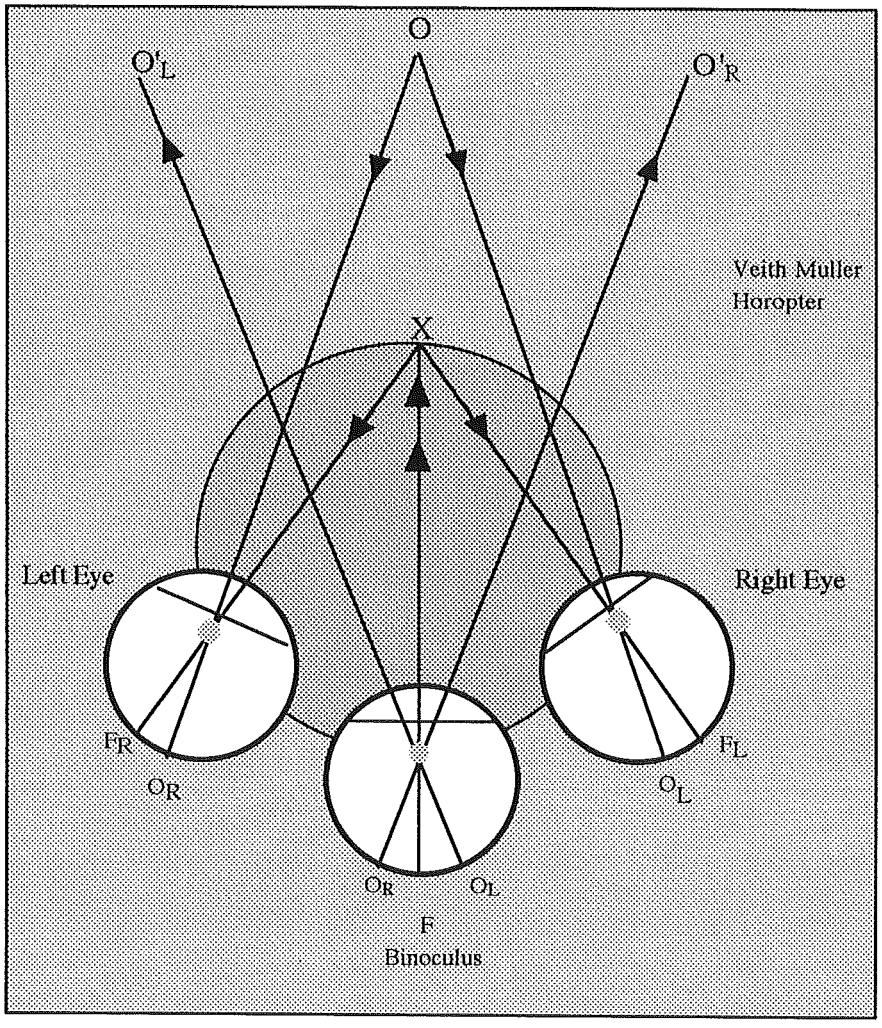


Figure 2 Diagram illustrating the phenomenon of homonymous physiological diplopia. The explanation of this diagram is contained within the text.

The image of object O, which is located more distant than the horopter circle (Figure 2), stimulates non-corresponding points on the two retinae, O_L and O_R with the result that the diplopic images O'_L and O'_R are perceived to lie on either side of O. As the non- corresponding points lie on the nasal retinae, the image seen by the left eye, O'_L, is on the left of the visual axis and that seen by the right eye, O'_R , is on the right of the visual axis, *i.e.* they are uncrossed.

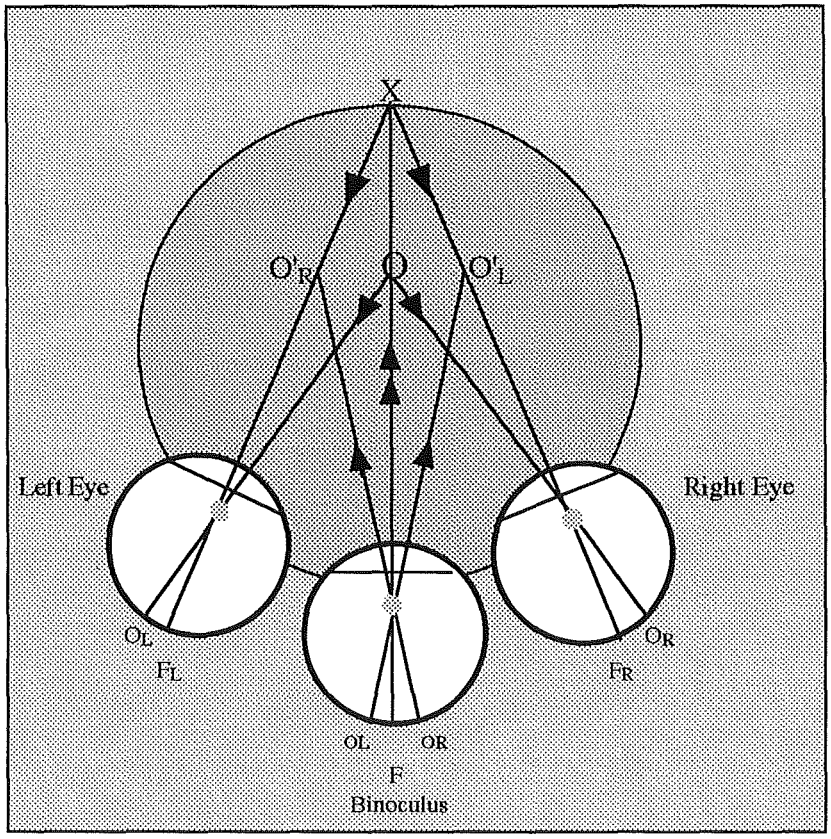


Figure 3 Diagram illustrating the phenomenon of heteronymous physiological diplopia. The explanation for this diagram is contained within the text.

Crossed or heteronymous physiological diplopia is appreciated when the more distant pen is fixated. In Figure 3, the fixation object O stimulates the points O_L and O_R on the two retinae. As these non-corresponding points (O_L and O_R) lie on temporal retinae, the image of O seen by the left eye, O'_L, is to the right of O and that seen by the right eye, O'_R, to the left of O *i.e.* they are crossed.

However, there does exist a zone in front of and behind the horopter where the positional disparity can be tolerated such that a single fused image is still perceived. This region extends to about 13.5 to 23.0 min arc around the central point of fixation (foveal region) (i.e between ~7 and 12 mins arc in front of and behind the fixation point (Mitchell, 1966) and increases, elliptically with eccentricity (Ogle, 1962). This area is known as Panum's Area (Figure 4).

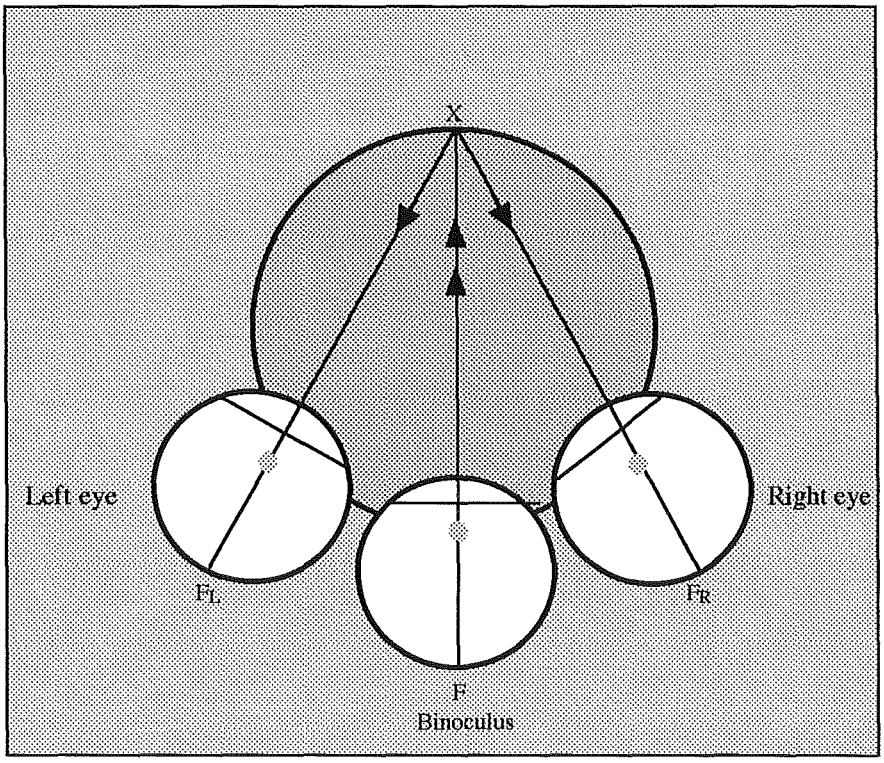


Figure 4. Diagram illustrating the dimensions of Panum's Area in space represented by the black dotted line (not to scale).

Hence, BSV depends, critically, on the correct alignment of the two eyes so that the image of the object of fixation falls onto the fovea of each eye. In a normal person, viewing an object such that it results in images which fall onto non-corresponding retinal points leads, promptly and effectively, to realignment of the eyes to effect bifoveal viewing and the maintenance of BSV. In order to attain BSV, it is therefore necessary for the ocular motor control system and the extra-ocular muscles to function normally.

As well as the correct alignment of the two visual axes, it is also essential for there to be optimal refraction of the object of regard to produce a sharply

focused image on each fovea. Thus, accommodation of the eyes, to obtain sharp focus of the object, is associated with convergence of the eyes to effect BSV of the near object. This association is referred to as the accommodation-convergence linkage (Lyle and Wybar, 1967). It will be described later how operation of this linkage can be responsible for the disruption of normal BSV. It therefore follows that an abnormality of ocular alignment may result in the disruption of BSV. There are two categories of ocular misalignment. These are now described.

1.1.1 Eye Position at Rest (Heterophoria)

In a normal person, either in darkness or when BSV is suspended on viewing different visual scenes, the eyes assume a "resting" position in which the directions of gaze may be misaligned. This is referred to as heterophoria. Normally, heterophoria is of no consequence since, when viewing a normal visual scene, the two eyes are brought into correct alignment to effect BSV.

For the purposes of the present discussion, two main groups of heterophoria are addressed: exophoria or latent divergence (the eyes deviate in an outward direction) and esophoria or latent convergence (the eyes deviate in an inward direction) (Figure 5). The presence and nature of an heterophoria can be detected by dissociation of the visual inputs into the two eyes. Figure 5 illustrates the results of the cover test applied to a case of esophoria in which the eye under the occluder deviates nasally. When the dissociation ceases by removal of the occluder, the ocular motor control system realigns the eyes so that they return to their normal position to effect bifoveal viewing and, thus, normal BSV.

In exophoria, when an occluder is placed in front of one eye, this eye deviates temporally. When the occluder is removed, the previously occluded eye moves nasally to take up foveal fixation. The other eye moves temporally under cover but moves nasally to take up foveal fixation when the occluder is removed, *i.e.* the converse sequence of movements to those shown in Figure 5 occurs.

Heterophoria may become a problem if there is, for example, a large amount of exophoria so that on viewing a distant object there must be contraction of the relevant extra ocular muscles simply to bring the eyes into parallel alignment. Therefore, when viewing a near object, the individual cannot exert sufficient convergence so that appropriate alignment of the eyes is not attained and diplopia is experienced.

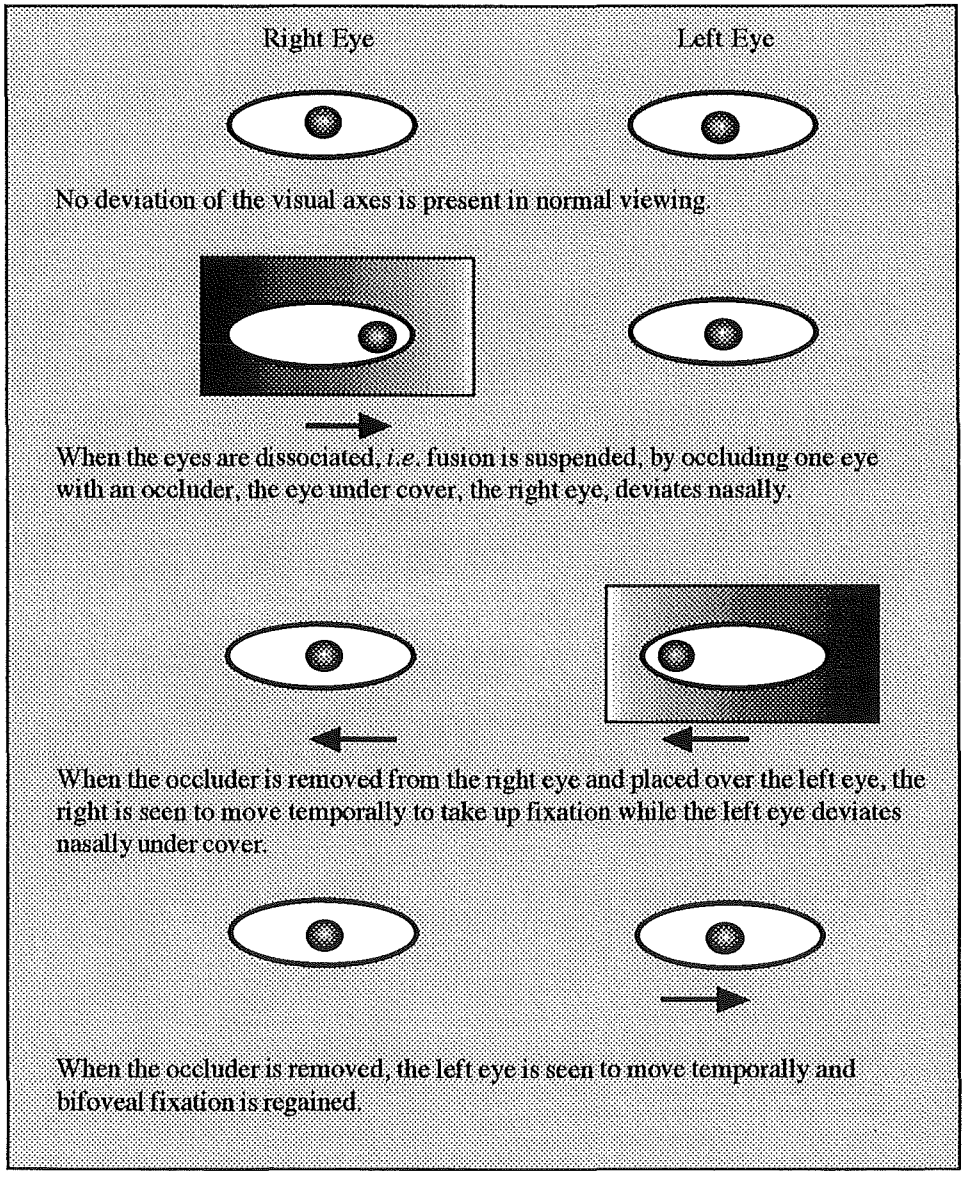


Figure 5. Dissociation of the visual input resulting in movement of the eyes during cover test in a case of esophoria or latent convergence. In this and related Figures, the eyes are positioned as if for distance viewing; the outline of the eye viewed front-on is shown by the ellipse and the pupil shown by the stippled small disc. The shaded rectangle represents the occluder.

1.2 Heterotropia

This is a different category of misalignment which is present under normal viewing conditions. For example, paresis of an extra-ocular muscle(s) of one eye may produce a persistent misalignment of that eye under normal viewing conditions. This is also referred to as strabismus or squint of which the two main types are esotropia, in which one eye is deviated inwards, and exotropia, in which one eye is deviated outwards.

Furthermore, a clear distinction must be made between a strabismus which arises in adult life and one which occurs during, what is termed, the critical period of visual development. This is the early post-natal period during which the visual system is developing and is susceptible to change and this is usually accepted as being the first years after birth. The presence of heterotropia in childhood may give rise to impaired visual acuity in the affected eye. For example, in a young child with a squint, for distance viewing, one eye is aligned whilst the other eye is misaligned. As a consequence of this, the visual acuity in the misaligned eye does not develop normally, and may be well below the normal standard of 6/6 in terms of Snellen acuity. This reduction in vision is called amblyopia (blunt vision). The present study is thus concerned with squints which have arisen in childhood. An additional complication is that BSV may be anomalous or indeed absent. Both amblyopia and either anomalous BSV or the absence of BSV, are frequently encountered in strabismus.

As well as the amblyopic strabismics, in many exotropes and in some esotropes, visual acuity may actually be normal if the individual is able to fixate with each eye in turn (alternating fixation); however, BSV would not be present since simultaneous viewing of the same object with the two eyes could never occur.

Furthermore, strabismus has a clearly defined origin. Some squints, esotropic and exotropic, arise from extra-ocular muscle disorders. These cases are classified as non-accommodative strabismus. In other cases, the squint is

associated with anomalies of accommodation and thus do not arise from extra-ocular muscle disorders *per se*. These constitute accommodative strabismus. (Lyle and Wybar, 1967; Duke-Elder, 1973; Burian and von Noorden, 1981). For instance, in a long sighted individual (hypermetropia - a refractive error in which the rays of light come to a focus behind the retina, frequently due to a shortened eyeball) focus for distance may be attained by increasing the power of accommodation. As there is a link between accommodation and convergence, this may lead to convergence which is inappropriate for distance viewing. This type of strabismus is therefore known as accommodative esotropia.

These different types of squint which are represented in the summary diagram in Figure 6 are now described more fully.

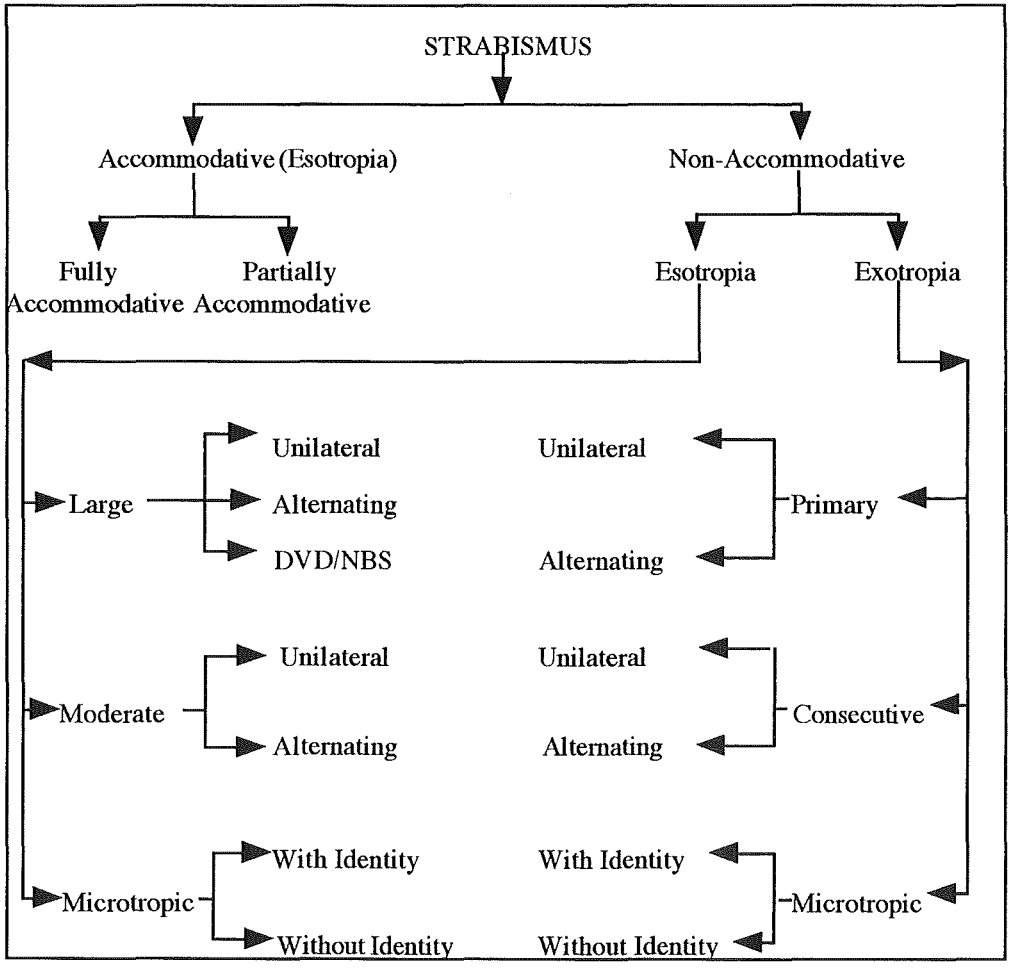


Figure 6 Summary diagram of types of strabismus.

1.2.1 *Accommodative Esotropia*

As described earlier, esotropia often arises as a consequence of uncorrected hypermetropia. An individual who has uncorrected hypermetropia will experience blurred vision. As a result of this, accommodation is increased in order to attain a sharp focus. However, accommodation, as previously stated, is linked to convergence of the eyes so that accommodative convergence also occurs. This can be quantified.

If an individual has an inter-pupillary distance (distance between the centre of the pupils in each eye) of 6.0cm, theoretically, each eye must turn inwards (adduct) three prism dioptres when accommodating on an object one metre from the eyes (*i.e.* exerting, notionally, 1D of accommodation (Lyle and Wybar, 1967)). In normal practice the amount of convergence might vary slightly so that for every 1D of accommodation between 3 and 5 prism dioptres of accommodative convergence are initiated. This is called the AC/A ratio. Therefore, if an individual is 4D hypermetropic, 4D of accommodation would be expected to be exerted to see clearly at infinity, while additionally between 12 and 20 prism dioptres of accommodative convergence would occur. When a near object is fixated at 0.3 metre(m), 7.3D of accommodation (4D for distance plus 3.3D for near) are exerted at 0.3m to see clearly and between 22 and 36 prism dioptres of accommodative convergence is initiated. If a child can reduce the amount of convergence whilst maintaining an appropriate amount of accommodation (negative relative fusional vergence) no esotropia will develop (negative relative fusional vergence is normally automatically exerted by young children who frequently exhibit hypermetropia of 3D). If, however, a child cannot exert a sufficient amount of negative relative fusional vergence a convergent squint of varying magnitude will occur.

However, an appropriate spectacle correction will remove the need for excessive accommodation, therefore excessive convergence will not occur and normal alignment of the visual axes should result. The individual will therefore exhibit normal BSV with the spectacle correction. However, on removal of the glasses, a blurred retinal image is once again appreciated, excessive accommodation occurs and consequently, a convergent squint becomes apparent (Lyle and Wybar, 1967; Duke-Elder, 1973; Mein and Trimble, 1991). This type of accommodative esotropia which is absent when the hypermetropia is corrected but present when the refractive error is uncorrected is called a fully accommodative esotropia. In some types of accommodative esotropia, however, an additional factor, such as contracture and thus over action of the medial rectus muscle, is superimposed upon the accommodative reason for the squint. As a result, the child may still exhibit an esotropia with spectacles. In these cases the angle of convergence is smaller in magnitude than that without spectacles, *i.e.* the esotropia has been partially corrected. These squints are referred to as partially accommodative esotropias.

In the partially accommodative type of esotropia in which the squint is only partially correctable, orthoptic exercises may improve the child's negative relative fusional vergence and thus allow control of the deviation either with spectacles or without spectacles and in many cases under both circumstances.

If a convergent squint arises for other reasons, it is referred to as non-accommodative esotropia. The cause of this type of strabismus is more complicated than in accommodative esotropia.

1.2.2 *Non-Accommodative Strabismus*

The cause of the majority of non-accommodative squints is unknown however, in some case squint is inherited. It is not uncommon for children with squinting

parent(s) or other family members to develop a strabismus in early childhood.

Anatomical abnormalities in muscle insertion(s), muscle structure and muscle size may also be responsible for the development of strabismus. (Lyle and Wybar, 1967; Duke-Elder, 1973; Mein and Trimble, 1991; von Noorden, 1996).

Trauma may also give rise to squint. Esotropia may occur due to trauma during a difficult birth in which oxygen deprivation occurs (hypoxia or anoxia) and/or when a forceps delivery has been necessary when one or both lateral rectus(i) muscle(s), or their blood supply or the innervating nerve(s), (abducens) may be damaged. As a result of impaired lateral rectus(i) function, reduced abduction occurs and a convergent squint results.

Prematurity, resulting in an under developed ocular-motor system at a time when the infant is exposed to visual information may give rise to squint (Kervick, 1986).

Post-natally, direct injury to the eye or the extra-ocular muscles, *e.g.* after trauma resulting in echymosis (black-eye) and/or hyphaema (blood in the anterior chamber) may also cause strabismus (Lyle and Wybar, 1967; Duke-Elder, 1973; Kervick, 1986). Squints may also appear after a childhood virus or infection such as a measles, mumps or fever. In such cases, the function of the extra-ocular muscles is normal and a lesion of the central nervous system is inferred (Lyle and Wybar, 1967).

As shown in Figure 6, non-accommodative squints may be either esotropic or exotropic. Esotropic squints fall into one of three categories; large angle squint, moderate angle squint and small angle (microtropic) squint. Exotropic deviations may be either primary, consecutive or microtropic in type.

1.2.2.1 *Large Angle Esotropia*

Large angle esotropia is an esotropia which, typically, arises within the first six months of life. The deviation is normally between 20 and 30 degrees, *i.e.* relatively huge and may be unilateral or alternating. A feature of this type of esotropia is a weakness of the lateral rectus muscle and therefore of abduction (Lyle and Wybar, 1967; Duke-Elder, 1973), which becomes apparent when the individual's ability to move the eyes horizontally is examined. For example, in a unilateral right esotropia, if the action of the right lateral rectus is reduced, when the eyes are moved to the right, the left eye will adduct normally but the right eye will not abduct fully. If the reduced abduction is due to an abnormality of the nerve supply to the muscle *i.e.* lesion of the sixth cranial nerve (the abducens) or of its nucleus, this is called a *true* weakness. Alternatively, if the weakness on abduction is due to lack of use of the muscle because of the nasal position of the eye, while the nerve supply is normal on account of the individual being reluctant to abduct into extreme gaze to the right, a *habitual* weakness of the lateral rectus is said to be present. This distinction between a *true* and *habitual* weakness is important as it helps to classify the squint and will affect the future management of the condition.

In cases of alternating large angle esotropia, *i.e.* the child fixates with the right eye and the left eye adducts then, at no set interval, the child fixates with the left eye and the right eye squints, the reduced abduction, either of a *true* or *habitual* nature, is typically bilateral. Normally, an alternating deviation is seen when fixating in the straight ahead position (the primary position). On looking to the right (dextro version), the left eye is used for fixation and when looking to the left (laevo version), the right eye fixates (Figure 7). This is called a tripartite field of fixation and is seen in cases of both a *true* and an *habitual* weakness of the lateral recti.

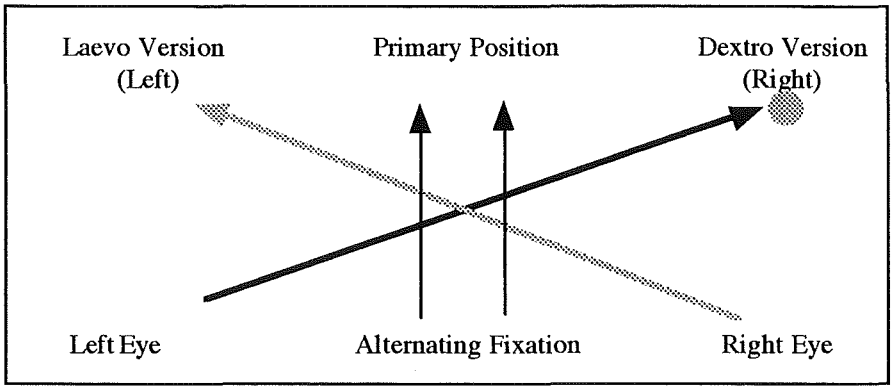


Figure 7. Tripartite Field of Fixation. The left eye is used (solid black line) when fixating an object (▒) situated to the right (dextro version) and the right eye (solid grey line) deviates (adducts) (in each case, movement of the companion eye has been omitted). On looking straight ahead both the right and left eyes may be used, *i.e.*, fixation will alternate between the eyes.

A further consideration arises in habitual weakness of abduction. Again, on looking to the right, the left eye fixates the object (and when looking to the left, the right eye is used). However, on extreme gaze to the right, the nose obstructs the line of sight in the left eye and, as a consequence, the right is forced to take up fixation and thus abducts fully (there is no lesion of the right sixth nerve). This is referred to as a quinquipartite field of fixation (Figure 8). (Likewise, on extreme gaze to the left, full abduction of the left eye occurs *i.e.* the lateral recti are acting normally).

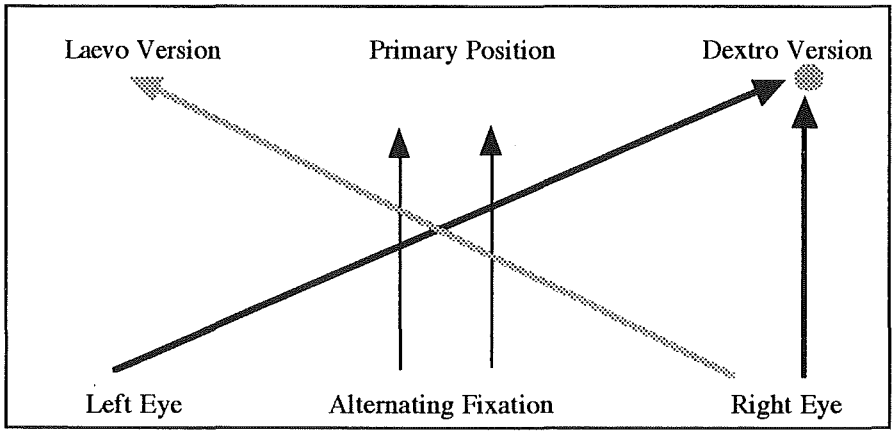


Figure 8. Quinquipartite Field of Fixation. Both eyes are used for fixation when looking in the straight ahead position, *i.e.* fixation alternates. The left eye is used when fixating an object situated to the right (▒) and the right eye adducts (solid grey line) until the line of sight in the left eye is obstructed by the nose. When this occurs, the right eye takes up fixation (denoted by the solid black line projecting from the right eye (the left eye will then adduct). (The opposite occurs when looking to the left - not shown in this figure).

A quinquipartite field of fixation will only be apparent in cases of *habitual* weakness of abduction. In cases of large angle strabismus of early onset (before the age of 2 years), normal BSV does not commonly develop, while visual acuity is, however, typically normal, (6/6 or better in each eye) because of the alternating nature of the strabismus and the presence of foveal fixation in each eye.

In addition, in early onset large angle esotropia, a condition known as dissociated vertical deviation (DVD) is often encountered (Mein and Harcourt, 1986; von Noorden, 1996).

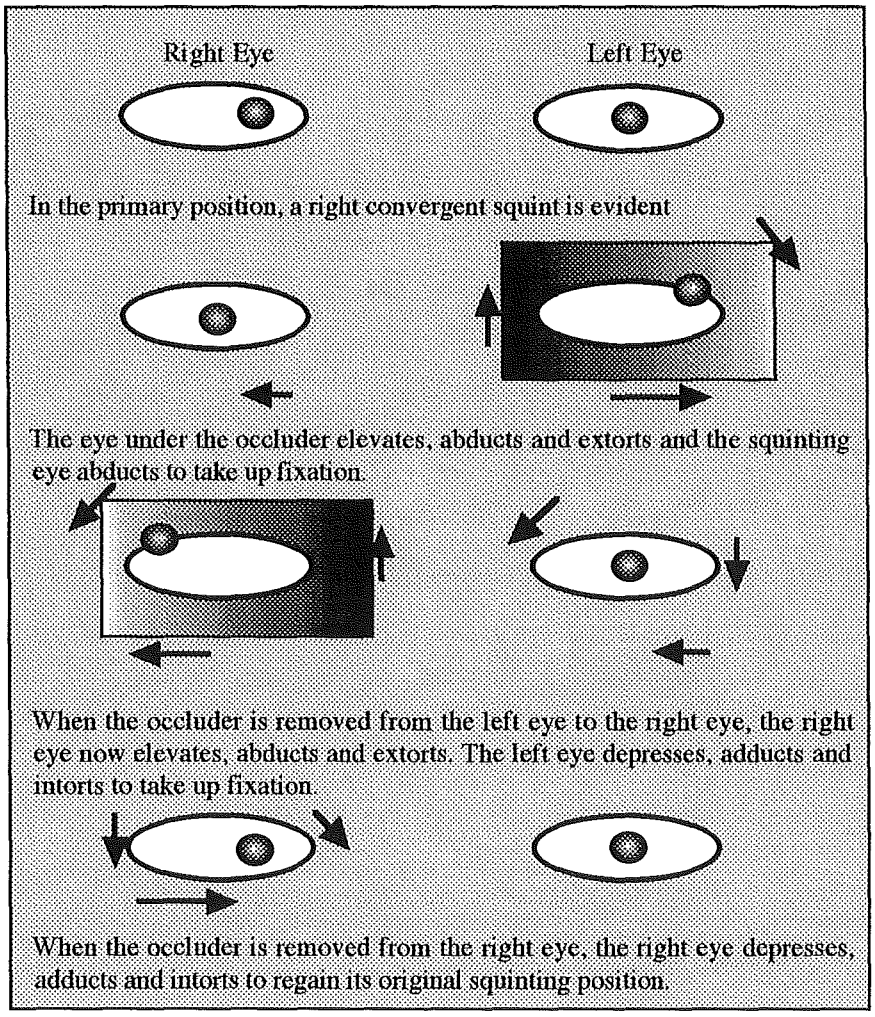


Figure 9 The phenomenon of dissociated vertical deviation (DVD). The occluder is represented by the shaded rectangle. Note the movements described in the text and in the diagram describe the movements which occur either as the occluder covers the eye or is removed from the eye.

This term is used to describe a bilateral phenomenon which is apparent when an occluder is placed over one eye. The eye under the occluder, elevates, abducts and excyclorotates (wheel rotation outwards) (Figure 9). This also occurs when the occluder is moved to the other eye with the difference that the elevation may be different *i.e.* asymmetrical (the elevation of the eyes under the occluder differs in magnitude). The elevation, abduction and extorsion is accompanied by nystagmus (small repetitive horizontal movement of both eyes) which, otherwise, is absent (von Noorden, 1996).

Large angle esotropia may also be found in conjunction with a condition known as nystagmus blocking syndrome (von Noorden, 1976). This is a bilateral condition in which congenital nystagmus is accompanied by esotropia. It is said to occur in between 4.8% and 10.2% of all squinting individuals (von Noorden, 1976). The oscillations may be so slight that they cannot be detected by the naked eye and thus are only evident when fixation is examined by ophthalmoscopy. Voluntary adduction of the non-squinting (fixating) eye reduces the nystagmus. The direction of fixation of the non-squinting eye after adduction is then maintained by turning the head by an equal and opposite amount. This is referred to as a blocking mechanism. Thus, individuals with this condition converge both eyes (Burian and von Noorden, 1981) in order to reduce the nystagmoid movements and thus restore visual acuity to the non-squinting eye. This effect of convergence is also enhanced on fixation of a near object. However, the convergence required is so great that the individual must bring the object very close to the eyes. Amblyopia is typically present in the squinting eye and BSV absent. In later childhood, the blocking mechanism ceases to be used but the constant esotropia with small amplitude manifest nystagmus remains.

1.2.2.2 *Moderate Angle Strabismus*

Moderate angle esotropes are also frequently encountered. They tend to develop at a later age than the larger angle squints. Typically, this type of strabismus

occurs suddenly and, frequently, no specific cause is apparent. Often, there is a report of fever or virus immediately prior to the onset of the deviation. It has also been known to develop after a period of upset, *e.g.* family bereavement, or a change of school, or family circumstance. It is normally unilateral in nature and moderate in magnitude measuring 10 to 20 degrees. If the squint is unilateral, amblyopia develops in the squinting eye. In alternating fixation, equal visual acuity is the rule rather than the exception. In both cases, binocular single vision is typically absent.

1.2.2.3 *Small Angle Strabismus*

This is also known as microtropia or microesotropia (Lang, 1974). Microesotropia is more commonly encountered in the strabismic population (40%) than microexotropia (3.6%). It is a small angle squint of five degrees (approximately ten prism dioptres) or less and, consequently, may be frequently missed in clinical examinations. Commonly, it is detected at three to four years of age during the preschool visual screening examination when reduced visual acuity in the affected eye first becomes apparent.

Microtropia can be divided into two types, microtropia with identity and microtropia without identity (Figure 6). It is important to distinguish between them as one, microtropia with identity, is frequently misdiagnosed as anisometropic amblyopia. This will be discussed more fully later.

Microtropia with Identity

In this condition, since the same parafoveal point is used for fixation under all conditions *i.e.* under uniocular and binocular conditions of viewing, the fovea is neglected. The parafoveal point serves as a pseudo-fovea and has correspondence with the fovea of the fixating eye (non-squinting eye). Consequently, the fovea of the squinting eye becomes amblyopic. The true fovea now essentially projects as temporal retina on account of it being temporal to the pseudo-fovea through which the visual axis passes (Figure 10). Hence,

on conventional testing of the visual acuity, the level of vision is determined by the acuity of the pseudo-fovea and is reduced compared with normal visual acuity. It remains an unanswered question as to what is the visual acuity subserved by the true fovea of the squinting eye.

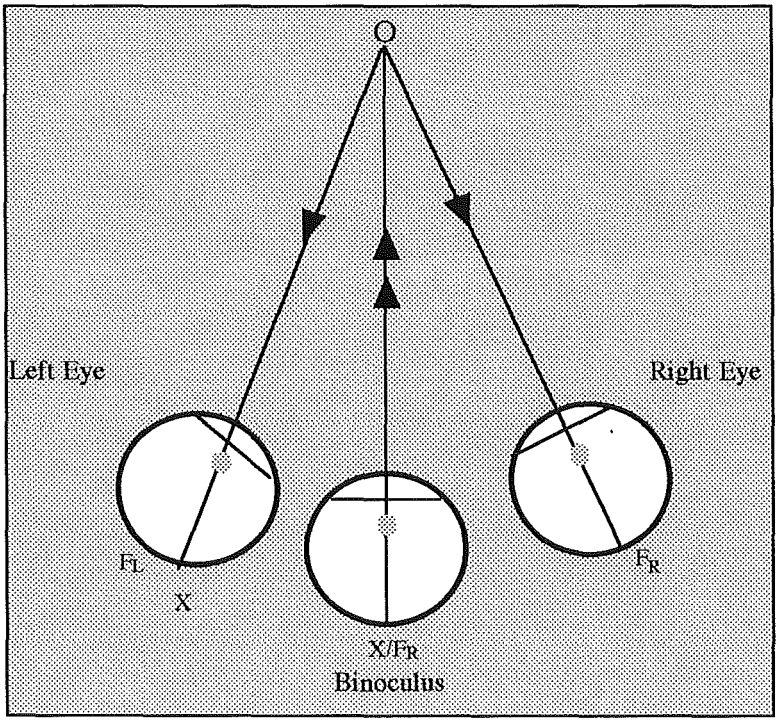


Figure 10 Abnormal projection in microtropia with identity. The fovea of the fixating eye (F_R) is used in conjunction with the pseudo-fovea in the squinting left eye (x) under all conditions, i.e, under both monocular and binocular conditions of viewing. The retina between the extra-macular point, x and the fovea of the left eye (F_L) is either suppressed or acts as temporal retina. (O represents the object of fixation).

On examination with the cover test no strabismus is detected (Methods p.80); instead an esophoria is evident. The squint is thus, particularly difficult to detect (Duke-Elder, 1973; Mein and Trimble, 1991). The initial clinical indication of microtropia is the presence of amblyopia in the squinting eye and it is ophthalmoscopy which is required to detect the microtropia (Methods p.78).

Microtropia Without Identity

The more commonly encountered type of microtropia is microtropia without identity. A small angle esotropia of 5 degrees or less is evident on examination

as the magnitude of microtropia changes with monocular and binocular viewing. It is thus detectable with the cover test. The other characteristics of this type of microtropia are the same as those manifested in microtropia with identity, *viz*. parafoveal fixation, amblyopia and anomalous BSV.

The cause of microstrabismus has been strongly debated. Three explanations for the development of this disorder have been offered. First, anisometropia, which is a difference in the magnitude or type of refractive error between the right and left eyes (see later) is frequently associated with microtropia and is considered to be the primary cause of this condition (Setrayish, Khodadoust and Daryani, 1978). The presence of anisometropia results in a defocused retinal image in what will become the squinting eye (the more ametropic eye). In the absence of a clearly defined foveal image, a parafoveal retinal point takes up fixation and eventually, this eccentric fixation becomes fixed; amblyopia in the microtropic eye and anomalous BSV thereafter develop. Second, microtropia is known in many cases to be inherited indicating a genetic predisposition. Third, in a minority of cases of microtropia, the presence of a foveal scotoma arising from a localised lesion, not detectable by ophthalmoscopy, is thought to be responsible for the parafoveal fixation, and thus microtropia (Lyle and Wybar, 1967; Duke-Elder, 1973).

1.2.3 *Exotropia*

Exotropia is less commonly encountered than esotropia. Exotropia is influenced by uncorrected refractive errors and disordered accommodation but unlike esotropia, is not, in the majority of cases, directly caused by them. The aetiology of exotropia is debatable. Duane (1896, 1897; cited in von Noorden, 1996) offered the view that exotropia was a result of an "innervational imbalance", an exotropia most evident for distance viewing, for example, he ascribed to "hypertonicity of divergence". Duane was thus of the opinion that divergence was an active process which in fact has been confirmed by

electromyographic studies (Breinin and Moldaver, 1955; Breinin, 1957; Blodi and Van Allen, 1962). On the other hand, Bielschowsky (1934) was of the view that several anatomical factors, including a wide inter-pupillary distance (IPD), or mis-insertion of the extra-ocular muscles, contributed to exotropia.

Divergent squints vary considerably in magnitude and therefore do not readily fall into the categories of large, moderate and microexotropia. Consequently exotropia is described as primary, secondary or consecutive. In the present study, only constant divergent strabismics were encountered, intermittent exotropes, which are the most common form of divergent squint, have therefore been excluded from the following description.

1.2.3.1 *Primary Exotropia*

Primary exotropia is commonly due to anatomical abnormalities such as abnormal development of the extra-ocular muscles, and abnormal insertion of the horizontal recti muscles; in addition, central and peripheral neurological abnormalities of the innervation of the medial or lateral rectus muscle have also been found (Breinin, 1957). An abnormally wide inter-pupillary distance (telecanthus) such as that encountered in cranial facial dysostosis and other conditions giving rise to various forms of abnormal head shape (Wesson, 1964; Lyle and Wybar, 1967; Duke-Elder, 1973; Burian and von Noorden, 1981; von Noorden, 1996) also contribute to the development of exotropia. The age of onset is commonly at or shortly after birth (Costenbader, 1950) or within the first two years of life (Hall, 1961; Krzystkowa and Pajakowa, 1972). Primary exotropia may be unilateral, in which case amblyopia will be present in the squinting eye, or it may be alternating, in which case equal visual acuity is typically present. In both cases BSV is absent. The angle of deviation is typically 15 degrees or more and increases with age. However, the most commonly encountered form of divergent squint is consecutive exotropia.

1.2.3.2 *Consecutive Exotropia*

This form of divergent squint occurs subsequent to esotropia and may be gradual or abrupt. In the former case, there may be a gradual evolution from esotropia into exotropia, in esotropes with amblyopia and an absence of BSV, the two main factors which predispose towards divergence. A gradual development of exotropia subsequent to an otherwise satisfactory surgical outcome *i.e.* a cosmetically acceptable small angle esotropia, post-operatively, may also occur. A rather more dramatic shift may then be seen in these individuals at around 40 years of age when presbyopia becomes problematic. In all cases, the individual continues to exhibit amblyopia and absence of BSV which characterised the initial esotropia (Duke-Elder, 1973; Mein and Harcourt, 1986).

In the context of this study, it becomes important to distinguish between primary and consecutive exotropes (see later).

1.3 Sequential Changes in Strabismus

In both esotropia and exotropia, the individual concerned may thus be amblyopic in one eye and may suffer from an absence or from anomalous BSV. These changes represent the end point of a series of alterations which occur as a consequence of the presence of the squint and/or refractive error. The sequence of these changes is now described starting with consideration of the consequences of the sudden occurrence of a convergent squint on an individual's binocular vision, as represented in Figure 11.

1.3.1 *Confusion and Diplopia*

In esotropes still exhibiting normal retinal correspondence, the image of the object of regard, *i.e.* the fixation object (O) stimulates the fovea of the fixating eye (denoted F_L in Figure 11) but, because of the presence of esotropia, the image of O also stimulates an extra-foveal point in the nasal retina of the squinting eye denoted X. The fovea of this eye (denoted F_R) is thus stimulated

by the image of a peripheral object (denoted P) which is perceived to be at the same point in space as O. As a result, two greatly dissimilar images are perceptually superimposed and the phenomenon of confusion is experienced.

Further, since the image of O stimulates an extra-foveal point on nasal retina of the squinting eye (X), two non-corresponding retinal points are stimulated simultaneously by the same image and diplopia (O and O') is appreciated. In the case of the right esotropia, shown in Figure 11, the diplopic image is perceived to the right of the object of regard (O) and the resultant diplopia is therefore designated as homonymous or uncrossed diplopia (Lyle and Wybar, 1967).

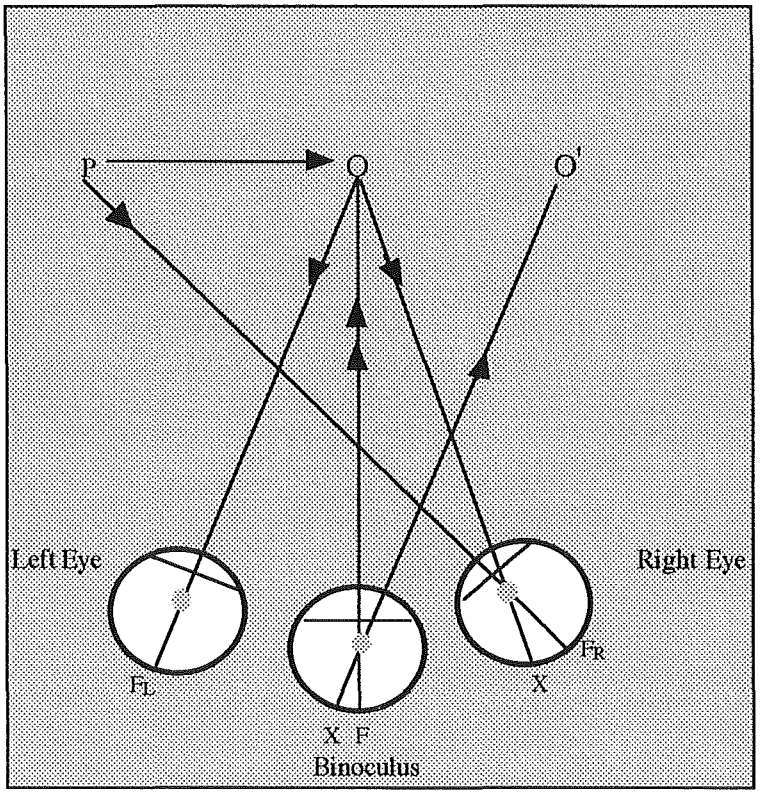


Figure 11 Diagram illustrating the phenomenon of confusion and diplopia in a right convergent squint. Perceptually, P is superimposed on O and confusion is appreciated. The double image (diplopic image) of the fixation object O is perceived to the right at O'.

In exotropia, the same principles apply except that point X now lies on the temporal retina of the squinting eye which is turned outwards (Figure 12).

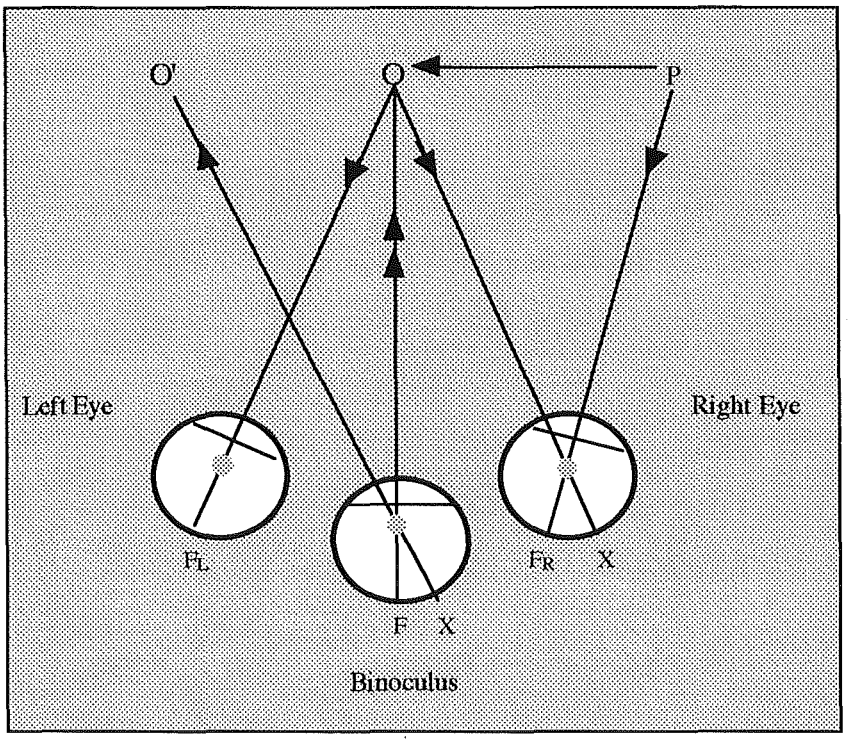


Figure 12 Diagram illustrating the phenomenon of confusion and diplopia in a right divergent squint. Perceptually, P is superimposed on O and confusion is appreciated. The diplopic image of the fixation object O is perceived to the left at O'.

Thus, in exotropes still exhibiting normal retinal correspondence, the image of the object of regard, *i.e.* the fixation object (O) stimulates the fovea of the fixating eye (denoted F_L in Figure 12) but, because of the presence of exotropia, the image of O also stimulates an extra-foveal point in the temporal retina of the squinting eye denoted X. The fovea of this eye (denoted F_R) is, thus, stimulated by the image of a peripheral object (denoted P) which is perceived to be at the same point in space as O. As a result, two greatly dissimilar images are perceptually superimposed and the phenomenon of confusion is experienced. Diplopia occurs because the image of the fixation object, O stimulates the fovea of the fixing left eye but, simultaneously, a temporal retinal

point, X in the squinting right eye. As the two retinal points are non-corresponding points, diplopia of the image of the fixation object, O, is appreciated. As the diplopic image is located to the left of the fixation object, the diplopia is designated as heteronymous or crossed horizontal diplopia (Figure 12).

Diplopia and confusion are, in early childhood, stimuli for suppression; consequently, the brain actively neglects the perception of the confused and diplopic images by a process which is referred to in ophthalmology as suppression (Lyle and Wybar, 1967; Duke-Elder, 1973). Thus, suppression is regarded as being the perceptual inhibition of images stimulating the retina of a squinting eye.

1.3.2 *Suppression*

1.3.2.1 *Suppression in Esotropes*

In binocular viewing confusion is eliminated as a result of suppression of the visual signal received from the fovea of the squinting eye (F_R), with the result that vision is subserved by the fovea of the normal eye (F_L) (Figure 10). Subsequently, diplopia is eliminated by suppression of the extra-foveal point, X, of the squinting eye.

Thus, initially, two discrete scotomata are evident in the squinting eye at F_R and X (Lyle and Wybar, 1967; Duke-Elder, 1973). In time, suppression in the squinting eye may extend from the fovea to encompass the entire retina between the fovea and the extra macular point (F_R-X) (Lyle and Wybar, 1967) thus forming a suppression area equal to the angle of strabismus (Figure 13). This type of suppression pattern is typically encountered in esotropes.

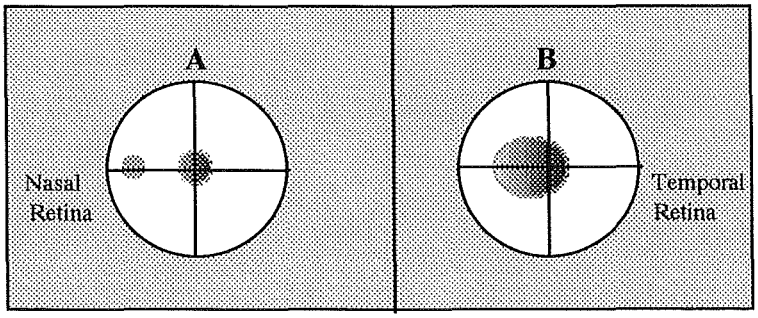


Figure 13 Diagrammatic representation of the retinal suppression pattern in esotropes showing the central retina represented by the circle and the position of the foveal suppression area (▒) at the intersection of the horizontal meridian (denoted by the horizontal line) and vertical meridian (denoted by the vertical line) (not to scale).
A: Two suppression scotomata initially occur at the fovea and the extra-foveal point in the squinting eye. The density of suppression is greatest at the fovea and reduces with eccentricity.
B: The suppression scotoma extends from the fovea to the extra-macular point of the squinting eye. The density is greater at the fovea and reduces with eccentricity .

1.3.2.2 *Suppression in Exotropes*

In exotropes, the diplopia occurs as a consequence of simultaneous stimulation of the fovea of the normal eye and a temporal retinal point in the exotropic eye. Confusion exists between the fovea of the aligned eye and the outwardly directed fovea of the exotropic eye (Figure 12). The suppression pattern, however, differs from that of esotropia in that the visual input from the entire temporal retina of the exotropic eye, including the fovea, is suppressed; this is referred to as a hemi-retinal suppression area (Jampolsky and Schlor, 1955; Pratt-Johnston and Wee, 1969) (Figure 14A). In some cases of large exotropia, the suppression scotoma often extends across the vertical meridian into the nasal retina (Pratt-Johnson and McDonald, 1976) (Figure 14B).

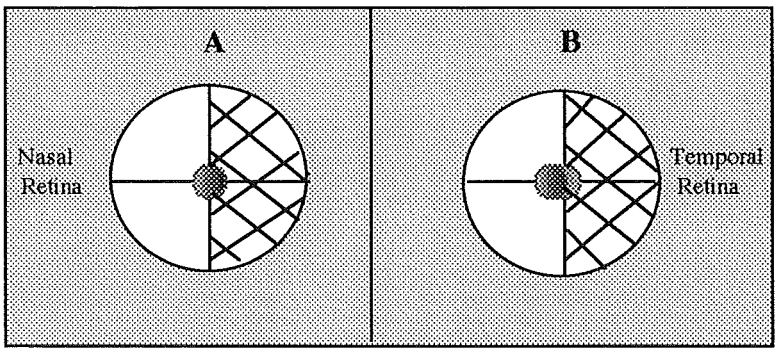


Figure 14 Diagrammatic representation of the hemi-retinal suppression pattern in exotropes.
A: The suppression scotoma (dark, shaded area) in the squinting eye extends continuously from the fovea over the entire temporal retinal area (cross hatched). The density is greater at the fovea and reduces with eccentricity.
B: The suppression scotoma in the squinting eye extends from fovea over the entire temporal retinal area (cross hatched) and also extends across the midline into nasal retina (darker, shaded area extending into nasal retina). The density is greater at the fovea and reduces with eccentricity.

Development of suppression in strabismus acquired in childhood eliminates diplopia and confusion in binocular viewing. Strabismic suppression is generally restricted to children under the age of eight years who thus do not experience confusion and diplopia. By contrast, acquisition of a squint above eight years, including adulthood, does not lead to suppression and diplopia is invariably experienced (Duke-Elder, 1973). Paradoxically, after the onset of childhood strabismus, the density and area of suppression frequently reduces during adulthood and may even disappear altogether. The result is the onset of diplopia which may be insidious or sudden (Wadell and Fells, 1980). Thus, a feature of suppression is its diminution during adulthood. In general usage, the term strabismic suppression is used synonymously with the generic term suppression.

So, whilst a prerequisite for the development of suppression is early onset strabismus, in terms of the area and depth of suppression, not withstanding this continued evolution of suppression, the depth of amblyopia remains invariant.

1.3.3 *Strabismic Amblyopia*

An explanation for the cause of strabismic amblyopia was first made by Worth (1903) (cited in Lyle and Wybar, 1967) who postulated that amblyopia represented an "arrest of development" of visual acuity due to the presence of a "sensory obstacle", *e.g.* unilateral strabismus with the result that the visual acuity in the esotropic eye, for example, remained at the level achieved at the age of onset of the obstacle. Thus, Worth considered it possible that it was the continued operation of suppression in binocular viewing which maintained the "arrest of development" thus resulting in amblyopia on monocular viewing. Worth extended this further and offered the opinion that if the amblyopia were treated during childhood, this "amblyopia of arrest" would be reversible whereas, if untreated, would develop into the irreversible form of "amblyopia of extinction".

It was further proposed that it was the presence of a confused and/or dissimilar image in binocular viewing which leads to the continuous suppression of the neural input from the fovea of the squinting eye and thus to amblyopia (Lyle and Wybar, 1967; Duke-Elder, 1973). von Noorden (1976) has offered the opinion that it was the degradation of the image falling on the fovea of the squinting eye, due to the difference in distance of the visual scene from the foveae of the two eyes, (*i.e.* in strabismus, the fovea of the squinting eye would require that the object be either further from, or nearer to, the object of fixation for in-focus stimulation) and that it was this difference which gave rise to continuous blur in binocular viewing. Thus, he proposed that it is the blur effect which leads to amblyopia.

However, the proposition that suppression inevitably leads to amblyopia requires qualification for the following reasons. In alternating and intermittent squints, the visual acuity is often normal in the strabismic eye. In these cases there is, nevertheless, considerable suppression of the visual input to the squinting eye but only during binocular viewing. Furthermore, it has been

shown that, in alternating and intermittent squints, there is an inverse relationship between the depth of suppression and the degree of visual loss in amblyopia (Holpigian, Blake and Greenwald, 1988). Suppression of the visual input from the squinting eye in these cases was not continuous due to the nature of the strabismus. Thus, it would appear that it is the persistence of the suppression in binocular viewing in unilateral strabismus which leads to amblyopia.

Subsequent to the occurrence of suppression and amblyopia, there may develop abnormal retinal correspondence *i.e.* the correspondence between the two retinae becomes realigned, and anomalous BSV results. Abnormal retinal correspondence and anomalous BSV often arise in small to moderate angle squints.

1.3.4 *Abnormal Retinal Correspondence and Anomalous BSV*

In strabismus, binocular viewing leads to stimulation of non-corresponding retinal points which leads to suppression of the visual input from the area of the retina encompassing the fovea and the extra-macular point of the squinting eye (Figure 13B). However, there may develop a correspondence between the fovea of the fixating eye and the extra-macular point of the squinting eye. This abnormal retinal correspondence develops frequently in small to moderate angle esotropes and always in microtropes. It is a rare occurrence in large angle esotropes and in exotropes with the exception of microexotropia (Lyle and Wybar, 1967; Duke-Elder, 1973; Burian and von Noorden, 1981).

Abnormal retinal correspondence (ARC) is defined as "a binocular condition in which the fovea of the fixating eye corresponds to, and has a common visual direction, with a point other than the fovea of the deviating eye" (BOS, 1980). The angular subtense between the extra-foveal point and the fovea equals the angle of squint. This type of abnormal retinal correspondence is called harmonious ARC (Figure 15).

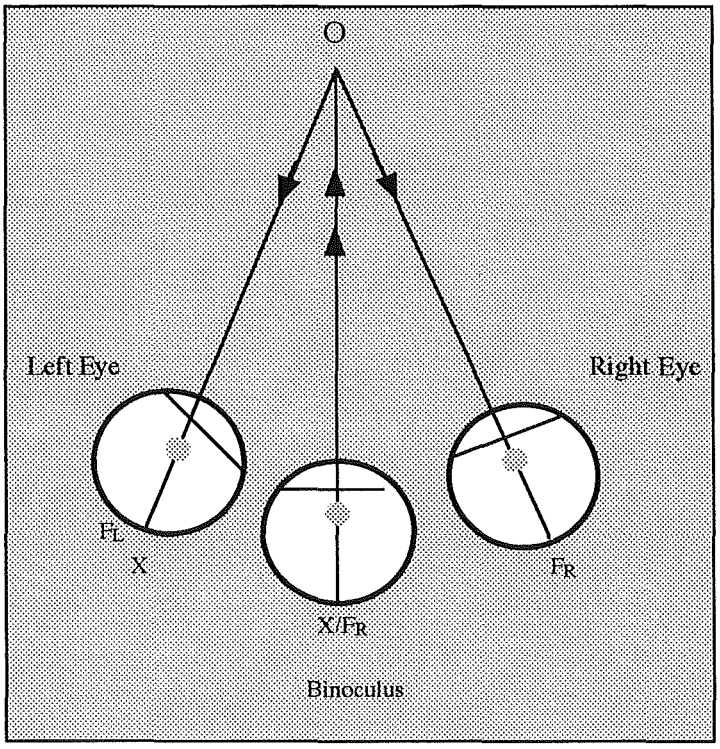


Figure 15 Diagram illustrating the phenomenon of harmonious abnormal retinal correspondence in a left convergent squint. The fixation object O stimulates the fovea of the fixating right eye and an extra-macular point, X, in the squinting left eye. As the fovea of the right eye and the extra-macular point in the left eye correspond, *i.e.* have an abnormal correspondence, O is perceived by both eyes to lie at the same point in space.

In harmonious ARC, there is a correspondence between the fovea of the fixating eye and the extra-macular point in the esotropic eye. In some cases, the ARC is extended so that the fovea of the esotropic eye projects as if it is a temporal retinal point. Suppression of the visual input from the fovea and the intervening retina (Figure 13) therefore disappears in ARC.

In other cases of esotropia with ARC, the visual input from the fovea and intervening retina between the fovea and extra-macular point in the squinting eye is suppressed but the correspondence between the fovea of the non-squinting eye and the extra-macular point of the esotropic eye remains.

BSV may then develop in the presence of ARC. This is known as anomalous or abnormal binocular single vision. This always develops in small angle deviations (microtropia) once ARC has been established.

In moderate angle squints however, ARC may exist without the subsequent development of anomalous BSV (Lyle and Wybar, 1967; Mein and Trimble, 1991). Anomalous BSV is an example of the visual system's ability to adapt to squint and is considered advantageous to the majority of strabismic individuals in whom it develops.

1.3.5 *Eccentric Fixation*

ARC and anomalous BSV thus occur under binocular viewing conditions in microtropia. The extra macular point may be used for fixation under both uniocular and binocular conditions as in microtropia with identity: this is referred to as eccentric fixation (Figure 10). Alternatively, the extra macular point may be used under binocular conditions only and another eccentric point used under uniocular conditions of viewing, as in microtropia without identity. The only way to diagnose the presence of eccentric fixation is to examine the fixation in the squinting eye with an ophthalmoscope (this is described more fully in the Methods, Chapter 2) (Lyle and Wybar, 1967; Duke-Elder, 1973). The point of eccentricity may thus be 5 degrees or less from the fovea. In cases where the microtropia is very small *i.e.* 1 degree or less, the visual acuity may still be relatively high at 6/9-6/12. By contrast, in cases of larger angle squint in which eccentric fixation is present, the resultant level of visual acuity is much lower, sometimes at the level of counting fingers as in the case of moderate angle esotropia.

Just how eccentric fixation develops is open to debate. Two suggestions have been made (Duke-Elder, 1973). The first is that eccentric fixation occurs because the fovea, for some reason, loses its principal visual direction (straight ahead projection) which is then adopted by the eccentric point. This point becomes established over time and eventually is used under both uniocular and binocular conditions of viewing such as in microtropia with identity.

The second proposal states that eccentric fixation occurs as a consequence of the presence of a sub ophthalmoscopic lesion at the fovea (*i.e.* not detectable by

ophthalmoscopy). The eccentrically fixating point adopts the principal visual direction and acts like a pseudo-fovea without the potential for foveal visual acuity (Lyle and Wybar,1967; Duke-Elder,1973; Burian and von Noorden, 1981).

1.4 Refractive Errors

1.4.1 Ametropia.

Amblyopia is, however, also commonly encountered in association with ametropia (uncorrected refractive error) and anisometropia (unequal refractive errors in the right and left eyes). These anomalies normally develop in childhood within the visually formative years.

The eye is known to change in the early years of life. These changes occur as a consequence of growth phases or "growth planes" in the development of the axial length of the eye. A relatively rapid increase in axial length occurs from birth to 1.5 years of age. A slower, second phase, lasting up to 8 years of age, followed by a third phase from 9.5 yrs to 11yrs is, thereafter evident (Sorsby, Benjamin, Davey and Sheridan, 1961). It is obviously difficult to predict the refractive development of any individual as much depends on the genetic predisposition for refractive errors and early visual experience.

The majority of infants, for example, are hypermetropic and astigmatic (Slataper, 1950; Ingram and Barr, 1979), the degree of which reduces as age progresses. Thus, at some point in childhood (normally before 5 years of age) "emmetropisation" (attainment of a state in which there is no refractive error) is expected to occur. It is the defocus of the retinal image which is thought to drive the mechanisms responsible for axial growth (O'Leary and Milldot, 1979; Hoyt, Stone, Fromer and Billdon, 1981) and thus the natural processes involved in attaining emmetropia. Therefore, it is possible that correction of hypermetropia and/or astigmatism in very young children may actually adversely affect the natural refractive development such that the hypermetropia is exacerbated

It is in the later years of childhood that the adult refractive errors (both hypermetropia and myopia) begin to develop, reaching their maximum extent in the late teens and early twenties. If the refractive development of each eye is sufficiently different, anisometropia may result (Lyle and Wybar, 1967).

1.4.2 *Anisometropia*

Anisometropia is defined as a condition in which there is a refractive difference between the right and left eyes of 1 dioptre or more in any meridian (Jampolsky, Flom, Weymouth and Moses, 1955; Ingram, 1977). It is estimated to occur in between 4.7% (de Vries, 1985) and 7.5% (Ingram, Traynor, Walker and Wilson, 1979) of children.

In hypermetropia in which in-focus distance viewing is achieved by an increase in accommodation, the amount of accommodation is determined by the eye with the lesser degree of refractive error. The companion eye thus still has a refractive error with a resultant blurred image for distance viewing. As a consequence of the presence of this blurred image, amblyopia may develop in this eye.

Myopia and anisometropic myopia, whilst common in adults, usually develop in late childhood, after the critical period for visual development, and do not normally give rise to amblyopia; however, in cases of congenital myopia which are characterised by a very large myopic error, amblyopia may develop. If the myopia is sufficiently severe that viewing for both near and distance is defocused, amblyopia may develop in that eye. Hence, the amblyopia may be bilateral for bilateral severe myopia and unilateral if one eye is either normal or is not so severely myopic that near viewing is in-focus, while the other eye is myopic with these viewing conditions.

The severity of visual deficit is, normally, greater in degree in anisometropic amblyopes than in symmetrical bilateral ametropic amblyopes. This is

presumed to be a consequence of an additional competitive factor which places the more ametropic eye at a disadvantage to the less ametropic eye (von Noorden, 1990). In addition, the prognosis for improving vision in the amblyopic eye in anisometropic individuals is also poorer than that in bilateral ametropes.

As well as the greater refractive error causing *per se* greater defocus of the image, another complicating factor is the image size difference, aniseikonia (Lyle and Wybar, 1967; Duke-Elder, 1969) which is considered to be amblyogenic (von Noorden, 1976). With greater degrees of anisometropia, and hence greater degrees of aniseikonia, the severity of amblyopia is increased (Duke-Elder, 1973). Furthermore, a 5% difference in image size has been reported to be the largest difference which can be tolerated and still permit fusion (Lyle and Wybar, 1967; Duke-Elder, 1969). Thus, the presence of a significant degree of aniseikonia prevents fusion with the consequence that strabismus, usually esotropia, develops (Lyle and Wybar, 1967; Duke-Elder, 1973).

An additional complication is the frequency with which anisometropia is found in association with microtropia which arises for reasons already described (Section 1.3.5 - eccentric fixation). It is important, clinically, to differentiate between the two conditions. All too often, the presence of microtropia is not taken into account as an additional complication as, for example, in Bradley and Freeman (1981). Anisometropic microtropes thus exhibit, in addition to amblyopia, parafoveal fixation in the squinting eye, anomalous BSV and central suppression. This is a very different clinical picture to that of simple anisometropic amblyopes who demonstrate normal BSV, and foveolar fixation in the more ametropic eye.

1.5 Management of Strabismus and Amblyopia

The management of strabismus and/or amblyopia in young children can be divided into two broad strategies. The first priority is to regain visual acuity in

the amblyopic eye. The objective is to achieve 6/6 vision which is possible only with foveal viewing. Thus, in cases of microtropia with eccentric fixation, this level of improvement cannot be attained. The second priority is to achieve BSV or anomalous BSV which may necessitate a surgical correction. If BSV is not attainable, a surgical correction may be undertaken for cosmetic reasons. The treatment of these two anomalies will now be considered.

1.5.1 *Treatment of Amblyopia*

The common treatment for amblyopia is occlusion therapy. This entails occluding (patching) the non-squinting eye for a certain period of time. The type of occlusion varies and several commercially available occlusive plasters are used. Occlusive plasters fall into two main categories, namely, "total to light" occlusive plasters and "total to form" plasters. In the former, no form is appreciated and the amount of light entering the eye is greatly reduced. In the latter case, the plaster occlusion permits light to enter the eye and reduces the appreciation of the form of the object. Improvement in visual acuity should occur provided the child complies with the treatment programme.

1.5.1.1 *Anisometropic Amblyopia*

As amblyopia is commonly associated with refractive error such as anisometropia, the first course of action is for the child to be refracted and the anisometropia corrected. Ideally, full correction should be prescribed. However, in some instances maximum correction is not possible. If the child is found to have a large degree of hypermetropia in one eye and a minimal amount in the other, for example +7.00DS in the right eye and + 1.25DS in the left eye, in the uncorrected state, the vision is likely to be reduced to 6/24 or less in the more ametropic eye. In order to achieve visual acuity of normal or near normal levels, the full amount of correction should be prescribed. Unfortunately, this may not be possible for the following reason. Convex lenses magnify an image. For every 0.25D an increase of 0.50% in the size of the image results (Duke-Elder, 1969). Thus, if a +7.00DS is required, the image perceived by

the left eye will be significantly greater compared with that in the less ametropic right eye which only requires a +1.25DS correction. There is therefore a trade-off between BSV and visual acuity. In these cases, a "balance correction" is normally prescribed, *i.e.* the hypermetropia in the more ametropic eye is only partially corrected. As a consequence of this, the visual acuity in the amblyopic eye is less likely to reach the normal level when treatment for the visual defect commences.

After the child has been refracted and the appropriate spectacle lenses have been prescribed, normally for constant wear, part-time occlusion of the non-amblyopic eye is prescribed for 3 hours each day. Part-time occlusion will avoid the development of occlusion amblyopia of the less ametropic eye (Burian, 1966). The period of occlusion per day and the duration of the occlusion period will depend on the severity of the amblyopia, and the age and co-operation of the child. It is not unusual for a child to be prescribed occlusion therapy which extends over a period of years. There is no hard and fast rule as when to stop occlusion therapy and in anisometropic amblyopes occlusion is frequently carried on to, or indeed commenced at, a much later age than in strabismic amblyopia.

1.5.1.2 *Strabismic Amblyopia*

Strabismic amblyopia, *i.e.* amblyopia due to the presence of squint, is more complicated to treat. Strabismic amblyopia is thought to arise as a direct consequence of the presence of a constant unilateral squint and therefore constant suppression (Worth, 1903). Suppression, as previously stated, occurs at the fovea of the squinting eye to overcome the phenomenon of confusion. As the fovea is the point on the retina responsible for maximum vision (6/6 or better), if it is constantly suppressed, visual acuity will be reduced. The severity of the amblyopia will depend on a number of factors: the age of the child when the strabismus occurred, the time lapse between the onset of the squint and commencement of occlusion therapy, and the compliance with

treatment. The complicating factor in the treatment of strabismic amblyopia is the risk of disrupting suppression in the squinting eye in older children, resulting in the appreciation of diplopia and, in rare cases, confusion (Lyle and Wybar, 1967). Thus, occlusion must be undertaken with great care.

Visual outcomes, however, will differ depending on the characteristics of the strabismus. For example, if foveal fixation in the squinting eye is present under uniocular conditions of viewing, then occlusion would be prescribed in an attempt to improve the vision to 6/6. If, however, eccentric fixation is present, the visual acuity in the squinting eye could never attain the level of 6/6; thus, occlusion treatment would aim to improve the visual acuity to the level of vision associated with the retinal point used for fixation such as in an individual with microtropia and parafoveal fixation where an acuity of 6/9 should be possible to achieve provided occlusion has been worn as instructed.

In infants and young children with a constant unilateral deviation, full-time occlusion (normally regarded as all waking hours) of the fixating eye is undertaken for days at a time.

Alternatively, full-time alternating occlusion whereby the fixating eye is occluded, for example, for 3 days and the occlusion is then switched to the amblyopic eye for one day, may be prescribed in those individuals in whom gross amblyopia is present. When the vision improves, the occlusion pattern is alternated so that eventually, the fixating eye is occluded on a full-time basis, for one day and the squinting eye is then occluded the next day (this is called alternate day occlusion). In infants and young children, alternate day occlusion is preferable to full-time occlusion of the fixating eye as it should prevent occlusion amblyopia in the fixating eye (amblyopia which occurs in an occluded eye due to the "stimulus deprivation" induced by the plaster occlusion) from developing.

In older children (*e.g.* 3 years and over) with severe amblyopia of 6/60 or worse, full-time occlusion is prescribed for a short period of time without the worry of inducing occlusion amblyopia. During the period of occlusion it is ensured that the occlusion therapy is not affecting the density and area of suppression in the squinting eye. As the visual acuity improves, the occlusion is altered to a part-time regime, for example, 3 hours per day. As age progresses and the child nears the end of the sensitive period occlusion therapy is discontinued.

Various patterns of occlusion therapy can be prescribed and the choice of occlusion, the daily period and the duration of occlusion depends on the preference of the orthoptist responsible for the child's treatment and the response of the child to occlusion therapy (Fielder, 1995).

1.5.2 *Surgical Correction of the Strabismus*

Once amblyopia has been reduced or eliminated in children with large squints, surgical correction may then be considered if restoration of BSV is possible or, in those cases where BSV is absent, to achieve a cosmetically satisfactory appearance.

In esotropic children in whom restoration of BSV is thought possible, the angle of squint is fully corrected, *i.e.* the angle of deviation is neutralised, in order to regain bifoveal fixation. In exotropic children, the angle of strabismus is purposely over-corrected to allow for postoperative re-divergence.

In cosmetic cases of esotropia the aim of surgery is normally to under-correct the deviation so a residual angle of squint of approximately 5 degrees (10^) is achieved. However, greater under-correction of the strabismus is purposely carried out in children with severe residual amblyopia and no BSV, as the absence of BSV predisposes the child to divergence of the visual axes in later life. Conversely, in cosmetic cases of exotropia, the angle of deviation is over-corrected. In this instance, some children experience post-operative diplopia

due to the presence of esotropia; normally, the diplopia disappears as the angle of post-operative esotropia reduces in the post-operative period.

In order to fully appreciate the changes in the visual system which must have occurred in order for sensory adaptations to have developed, an account of the mechanisms operating within the visual system is necessary. Thus, a brief overview of the visual pathway, its gross anatomy and physiology is now addressed.

1.6 The Visual Pathway

Much of our present knowledge and understanding of the visual system has derived from animal research. Initial studies have been undertaken on the cat while more recently these have been extended to the primate with a visual system which is much closer to that of man. The consequences to the human visual system of the presence of stimulus light deprivation, such as that caused by congenital cataract and stimulus form deprivation such as that caused by uncorrected refractive error and strabismus, during the neonatal period have been deduced from these studies. Accordingly, the following description of the characteristics of visual neurones, the pathways into which they are organized and the consequences of visual deprivation pertains mainly to the primate with reference to the cat where this is the only work available and with reference to the human condition when this has been investigated.

1.6.1 *Retinal Neurones*

Light passes through the refractive media of the eye and is transduced by the photoreceptors of the retina, the rods and cones, into electrical signals. These photoreceptors which comprise two types, rods and cones, possess a different morphology and different physiological characteristics.

The human retina contains 75-150 million rods which increase from the rod free area to a peak at 10 degrees, thereafter declining steadily towards the periphery

of the retina (Osterberg, 1935). They function under low levels of illumination (twilight) and are saturated at higher illuminances. Rods contain a single visual pigment (rhodopsin) with a peak absorbance of 498nm (Bowmaker and Dartnall, 1980). Cones are fewer in number, with 5-7 million in the human retina, 50% of which lie within ±18 degrees from the centre of the retina and decrease in number per unit area with eccentricity (Osterberg, 1935).

Synaptic transmission occurs between the photoreceptors and bipolar cells and then between bipolar cells and ganglion cells. In the primate, Kolb (1970) identified two types of midget bipolar cell, one forming invaginating contacts and the other forming flat contacts with the pedicle of the same cone cell; these bipolar cells are referred to as invaginating midget bipolar cells and flat midget bipolar cells, respectively and they, in their turn, each form synaptic connections with a single midget ganglion cell (Lee, 1996). This arrangement underlies the fidelity of transmission of information from the cone cells to the retinal output since there is an absence of convergence in these pathways. Within the central retina, the midget ganglion cells retain their connections with only one bipolar cell; however, by approximately 7 deg. eccentricity, the dendritic tree of the midget ganglion cell receives input from several midget bipolar cells (Lee, 1996). In addition, larger ganglion cells identified as parasol ganglion cells, with larger dendritic trees than the midget ganglion cells receive converging inputs from several diffuse or mop bipolar cells which, in turn, receive inputs from about 6 cone pedicles (Lee, 1996; Kolb, 1970, respectively).

1.6.1.1 *Cat Retinal Ganglion Cells*

With respect to the number of ganglion cells, there are about 1 million in the human retina with 50% located within ±13 degrees of the centre of the retina (Dawson and Maida, 1984). These fall mainly into two broad categories as shown by the work of Kuffler (1953) in the cat. ON retinal ganglion cells which generate action potentials in response to the presentation of illumination

and OFF retinal ganglion cells which generate action potentials in response to the termination of illumination (*i.e.* the onset of darkness). In the cat, the ON retinal ganglion cells receive inputs from the invaginating bipolar cells while the OFF retinal ganglion cells have been shown to receive their synaptic inputs from flat bipolar cells, thus constituting a segregation of these two pathways (Famiglietti and Kolb, 1976; Nelson, Famiglietti and Kolb, 1978).

The responses described above are effected when the stimulus is located at that part of the retina which is termed the receptive field centre. In the cat, this is invariably larger than the extent of the dendritic field of the ganglion cell (Peichl and Wassle, 1979). However, should that part of the retina surrounding the receptive field centre be stimulated, a response of opposite sign is evoked *viz.* an ON response in an OFF centre ganglion cell and an OFF response in an ON centre ganglion cell (Kuffler, 1953). The significance of the receptive field surround is that antagonism of the centre response occurs when both areas are stimulated. Thus, projection of a stimulus which extends over both the receptive field centre and the receptive field surround leads to a diminished response. It is thus by the operation of the surround mechanism that the ganglion cells are spatially tuned *i.e.* detect retinal images of a particular size.

In the cat, another classification cuts across the ON-centre/OFF-surround, OFF-centre/ON-surround classification of Kuffler. This arose from an investigation of the linearity of spatial summation in the ganglion cell (Enroth-Cugell and Robson, 1966; Cleland, Dubin and Levick, 1971). The basis of the method of investigation was the projection of approximately one cycle of a sine wave grating pattern onto the entire receptive field of the retinal ganglion cell. In one group of retinal ganglion cells, once this sine wave had been appropriately positioned, it could be instantaneously reversed without causing the generation of a response. This type of retinal ganglion cell which thus displayed linear spatial summation was termed an X cell while retinal ganglion cells for which it was not possible to reverse the grating sine wave pattern without evoking a

response were termed Y cells since they did not display linear spatial summation (Enroth-Cugell and Robson, 1966). A third group of cells, the W cells has also been identified (Stone and Hoffman, 1972). These do not have a clearly defined centre-surround arrangement but respond to specific trigger features and many project to the superior colliculus.

1.6.1.2 *Primate Retinal Ganglion Cells.*

The classification of primate retinal ganglion cells is based on the classification applied originally to the lateral geniculate nucleus (LGN) which consists of six laminae, the dorsal four of which contain small neurones and are thus referred to as the parvocellular layers, and the ventral two of which contain large neurones and are thus referred to as the magnocellular layers. Thus, the division into P (parvocellular) neurones and M (magnocellular) neurones was made. Wiesel and Hubel (1966) classified primate LGN neurones on the basis of their spectral sensitivity:

Type I consisted of concentric, single opponent cells, *e.g.* red ON-centre, green OFF surround. Type II consisted of single opponent cells with no clearly delineated receptive field surround, *e.g.* red ON, green OFF. Type III consisted of non-spectral, concentric neurones of the type described by Kuffler in the cat (1953); Type IV consisted of non-spectral ON or OFF cells which were inhibited by red light. Livingston and Hubel (1984) later showed that the parvocellular layers contain 80% Type I, 10% Type 2 and 10% Type III neurones, while the magnocellular layers contain entirely Type III and Type IV non-spectrally sensitive cells.

This classification has been translated to primate retinal ganglion cells where Type I comprised 57%, Type II, 2%, Type III 34%, Type IV, 9% (De Monasterio, 1978a and b). The single opponent Type I neurones, which have very small receptive field centres, are thought to correspond with midget ganglion cells on account of their very small dendritic field diameter (Lee,

1996). The non-spectrally tuned ganglion cells appear to correspond to the parasol ganglion cells (Lee, 1996).

1.6.2 *The Visual Pathway*

The retinal ganglion cell axons pass into the optic nerve to the optic chiasm where decussation occurs. Axons from nasal retina project contralaterally to layers 1, 4 and 6 of the LGN while axons from temporal retina project ipsilaterally to layers 2, 3, and 5 of the LGN. In addition, in a 1-2 degree vertical strip which passes through the centre of the retina, 50% of ganglion cells in the nasal retina project ipsilaterally and 50% of ganglion cells in the temporal retina project contralaterally, thus ensuring overlap of the central part of the visual field (Bunt, Minckler and Johanson, 1977).

In the LGN there is retained a separation of ocularity and, in addition, a separation into a P pathway projecting through the parvocellular layers of the LGN and the M pathway projecting through the magnocellular layers of the LGN. Behavioural evidence for a dichotomy into P and M pathways has been obtained by Merigan and colleagues (Merigan, Katz and Maunsell, 1991) who made lesions selectively to either the parvocellular or the magnocellular laminae of the LGN. These lesions were thus believed to cause specific ablation of either the P or M pathway so that the behavioural deficit could be taken to represent the normal function of that pathway.

Lesions of the parvocellular laminae effected by an oral dosage of acrylamide led to loss of contrast sensitivity at medium and high spatial frequencies, loss of visual acuity, loss of fine acuity stereopsis and loss of chromatic sensitivity (Merigan, 1989). By contrast, lesions of the magnocellular laminae which were effected by direct injection of ibotenic acid into layer 1 (driven by the contra-lateral eye) led to loss of contrast sensitivity at low spatial frequencies especially when the stimulus was temporally modulated, and loss of flicker sensitivity

without an effect on chromatic acuity or stereoacuity functions (Merigan, Katz and Maunsell, 1991). The functions of coarse stereopsis and luminance sensitivity were mediated by either pathway.

1.6.3 *The Visual Cortex*

In the human primary visual cortex, a precise topographical map of the contra-lateral hemi-field is found in area 17 (Holmes, 1918) with disproportionate coverage given to the foveal area, which was inferred to arise as a consequence of the increased number of retinal ganglion cells in the central retina (Wassle, Peichl, and Boycott, 1991). The foveal representation is located at the occipital pole, and the peripheral field represented on the medial surface of the cortex and is substantially located within the calcarine sulcus. The disproportionate foveal representation is shown by the "cortical magnification factor" which is 6mm across the cortex per degree of visual angle at the centre of the visual field and falls rapidly to 0.2mm per degree in the peripheral visual field (Daniel and Whitteridge, 1961).

The visual cortex of the primate, and in man comprises six layers, layer 4 being the broadest. In the primate, the major projection of afferents is to layer 4 which is divided into 4A, 4B, 4Cα, and 4Cβ. The neurones of the four parvocellular geniculate layers project to layer 4Cβ, while layer 4Cα receives afferents from the two magnocellular layers. More recently, there has been discussion of the significance of neurones located between the main layers of the lateral geniculate nucleus (Koniocellular neurones) which have been demonstrated to project to layers 2 and 3 of the visual cortex; however, the function of the K pathway remains unresolved (Casagrande, 1999).

1.6.3.1 Cat Visual Cortex

The receptive field characteristics and neuronal organisation of visual cortical

neurones of the cat were first described by Hubel and Wiesel (1962). The neurones were not responsive to spot stimuli but required a bar or edge of light which had to lie at a particular orientation in order to evoke a maximal response from the neurone. This is referred to as the "preferred" orientation and the neurones are said to be "orientation tuned". The cells are also effectively stimulated when the edge is swept across the receptive field at the preferred orientation.

1.6.3.2 *Classification of Neurones*

The simplest type of orientated neurone lies predominantly in layer 4 of the cat cortex and is called a "simple" cell. These cells are marked by a high specificity to the orientation of a stimulus and, in particular, to its position in the visual field (Hubel and Wiesel, 1962). It was proposed by Hubel and Wiesel (1962) that this type of receptive field arose from the convergence of geniculate afferents onto the simple cell such that the concentric receptive fields of these geniculate neurones were co-linear, thus resulting in an elongated receptive field for the simple cell. This constituted part of the "hierarchical theory". Subsequent experimental evidence identified intra-cortical neuronal circuits as being responsible for orientation specificity (Sillito, 1977). Recent research in which the orientation specificity of layer 4 simple cells was maintained after cooling of the upper layers of the cortex which would be expected to inactivate intra cortical neurones has essentially confirmed the hierarchical theory with respect to simple cell organisation (Ferster, Chung and Wheat, 1996). Complex cells are also orientation specific but not to the same extent as simple cells. They also respond to a visual stimulus presented over a more extended range of the visual field as if they were formed by several simple cells of the same orientation preference concatenated together. These cells have, accordingly, relatively large receptive fields. In some cases, if a stimulus is then increased in length the response of these neurones is inhibited. These cells are thus sensitive to the actual length of a stimulus and are called hypercomplex cells. Hypercomplex cells arise as if three complex cells are connected such

that stimulation of the two laterally located complex cells results in antagonism of the excitation generated by the centrally located complex cell. Originally, hypercomplex cells were found in areas 18 and 19 but then were later found in area 17 where they had very small receptive fields and are therefore thought to be end-stopped simple cells (Dreher, 1972).

Neurones in the visual cortex of the cat were additionally shown by Hubel and Wiesel (1962) to have a columnar organisation. On a vertical traverse down through the layers of the cortex, all the neurones encountered had the same orientation preference, thus constituting an orientation column. Thus, neurones with a orientation specificity of, for example, 90 degrees, are all found in register. On a tangential electrode traverse through the cortex, a regular step wise shift of orientation preference was recorded. Each orientation column was thought to represent a 15 degree step in orientation and was 50μm in width. Thus, 180 degrees of orientation change constituted an orientation hypercolumn 0.6mm in width. The existence of orientation columns has been confirmed morphologically by infusing the marker ^{3}H 2 deoxyglucose which is taken up by neurones actively responding to a particular visual stimulus. The 2 deoxyglucose, which is not metabolised, remains as a marker which is detectable by autoradiography. Schoppman and Stryker (1981) compared the stain density of the autoradiograph for the same stretch of cortex from which the orientation preferences had previously been recorded electrophysiologically. They confirmed that those neurones optimally stimulated during injection of 2 deoxyglucose had indeed the greatest uptake of 2 deoxyglucose while, in other neurones, staining was correlated with the degree of excitation of the neurones during presentation of the visual stimulus.

A further neuronal characteristic identified by Hubel and Wiesel (1962) was that of ocularity. For the first time, binocularly activated neurones were encountered in which neuronal responses were evoked by stimulation of either

eye or by both eyes. In the cat, both simple and complex cells exhibited this property. However, there was variation in the extent to which the neurones responded to either right eye or left eye stimulation. This gave rise to a 7 point ocular dominance classification (Figure 16).

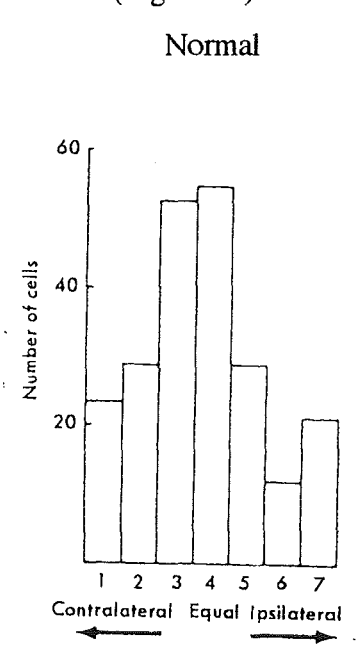


Figure 16 Ocular dominance distributions of single cells recorded from the striate cortex of cats (Hubel and Wiesel, 1962).

Category 1 is driven only by the contra-lateral eye, category 7 is driven by the ipsilateral eye (these are monocular cells) while category 4 shows equal responsiveness to left and right eye stimulation. In the cat, categories 3 to 5 predominate to the extent that 80%-84% of neurones are binocularly driven (ibid, 1962).

1.6.3.3 *Primate Visual Cortex*

Four types of neuronal responses have been identified in area 17. These are: concentric cells, which show no orientation preference, are always monocular and occur particularly in layer 4C; simple cells which occur infrequently in the primate, exhibit orientational specificity to a stimulus, are invariably monocular and occur mainly in layer 4B. Complex cells which are numerous occur in layers 2, 3, 5 and 6 and are orientation specific.

Hubel and Wiesel (1968) confirmed the presence of orientation columns in the primate cortex in that, on a vertical penetration, the orientation specificity extended through layers 2, 3, 5 and 6, while neurones of layer 4C showed no orientation preference, which corresponded to the presence of concentric neurones in this layer. Generally, the orientation columns were described as somewhat more narrow, at 20μm, than in the cat.

The distribution of ocular preferences was also markedly different from that of the cat (Figure 17). In layers 2, 3, 5 and 6, binocularly driven neurones were encountered although these did not show the same emphasis on true binocularity as cat neurones. The majority of neurones fell within categories 2/3 and 5/6 with relatively few neurones in category 4. A substantial number of monocular neurones, including complex cells, were also present throughout the cortex.

Normal

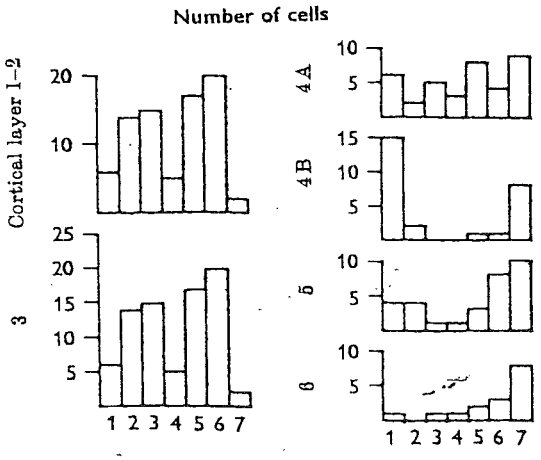


Figure 17 Ocular dominance distributions of single cells recorded from the striate cortex of monkeys (Hubel and Wiesel, 1968).

The neurones in layer 4C were organized such that on a horizontal traverse through layer 4C, all the neurones encountered in a 400μm stretch were driven

by one eye only, and then in the next 400μm stretch are driven by the other eye only and so on (Hubel and Wiesel, 1972). This ocular dominance arrangement has been viewed in 2 dimensions as a result of autoradiographic studies in which radioactive ^{3}H proline, injected into the vitreous of one eye, is taken up by the retinal ganglion cells and transported transneuronally through the lateral geniculate nucleus to layer 4C of the cortex where it was viewed by autoradiography. Autoradiographs of tangential sections through layer 4C revealed a "zebra-stripe" pattern of tracts which represented alternate left and right eye territories. The total left and right eye territories were equal to within 5% (Hubel, Wiesel and LeVay, 1977).

1.6.3.4 *Cytochrome Oxidase Organisation*

By staining fresh slices of visual cortex for the mitochondrial enzyme cytochrome oxidase, some areas of the cortex showed more intense stain than others. These areas, in tangential section, were in the shape of blobs or patches (Horton and Hubel, 1981). Each blob was elliptical in shape and approximately 150μm x 200μm in extent, spaced approximately 350μm apart (Horton and Hubel, 1981). At the point of foveal representation, the blobs were large and less thickly packed. They became smaller and more closely spaced, in parallel with the gradual shrinkage of the ocular dominance stripes. In the area which represents the temporal crescent of the retina, the blobs became more widely spaced again. In a vertical section through the visual cortex, the patches were revealed as having a columnar structure which extended through layers 2, 3, 5 and 6. Layer 4 was stained continuously, with the exception of layer 4B which was deficient in cytochrome oxidase staining. This pattern of staining is resilient to short term changes in neuronal activity and required rather draconian manipulation like enucleation of one eye before the continuous band of stain in layer 4 was disrupted (Carroll and Wong-Riley, 1984).

The surprising outcome of investigations in which neuronal characteristics were correlated with the location of the neurones with respect to the cytochrome oxidase patches was that the latter constituted a repository of spectrally tuned neurones (Livingston, and Hubel, 1984). The cytochrome oxidase patches contained monocular concentric neurones of which 70% were shown to be spectrally specific; the remaining 30% were classified as broad band. Ts'o and Gilbert (1988) later showed that the cytochrome oxidase patches contained neurones of either the red/green system or the blue/yellow system, with a ratio of 3:1. The inter-patch regions were shown to be the location of the orientated neurones, described previously by Hubel and Wiesel. Of these orientated neurones, which were predominantly complex cells, 61% were broad band while 39% were spectrally tuned. Neurones of layer 4Cβ were confirmed to be entirely concentric, monocular and spectrally tuned. They were described as being predominantly Type I single opponent neurones. Neurones of layer 4Cα were described as broad band neurones which were often orientation specific (Livingstone and Hubel, 1984).

There is some disagreement as to the nature of the spectrally coded neurones within the cytochrome oxidase patches. Livingstone and Hubel (1984) described the occurrence of double opponent concentric cells in which the excitatory centre was surrounded by an inhibitory zone of the same spectral specificity thus giving rise to spatial tuning as well as spectral tuning. Ts'o and Gilbert (1988) however, concluded that these cells had been misclassified and were in fact modified Type II neurones with a broad band inhibitory surround to the receptive field of the normal Type II cell.

Neurones of layer 4B, which are non spectral, have been shown to consist of monocular simple cells (Livingstone and Hubel, 1987) or complex cells (Ts'o and Gilbert, 1988), both of which may be directionally specific.

1.6.3.5 *Primate Cortical Organisation*

This may be viewed as basically similar to that of the cat, with layer 4C of the primate being taken to be analogous to layer 4 of the cat while layers 4B, 4A, 3 and 2 are taken to be analogous to layer 3 and 2 of the cat (Callaway, 1998).

Both the cytochrome oxidase patches and inter-patches in layer 2 and 3 are reported to receive their input from spiney stellate neurones of layer 4Cβ which is the destination of the LGN P neurones, while these also have a substantial projection into layer 6. From layers 2 and 3, the axonal projections of the small pyramidal cells constitute the main output of the cortex, while a projection is also sent to layer 5. This organisation may be considered to constitute the P pathway. By contrast, the M pathway consists of the projection of LGN M neurones into layer 4Cα. From there, projections are made into layer 4B from which the cortical output for this pathway arises (reviewed by Callaway, 1998). Finally, the K pathway consists of the projection of intercalated (koniocellular) neurones of the LGN directly into layers 2 and 3 of the visual cortex (Fitzpatrick, Itoh, and Diamond, 1983). This pathway appears to be superimposed upon the P cell pathway and may have a neuromodulatory function rather than constituting a major visual pathway *per se* (Casagrande, 1999).

1.6.3.6 *Stereoscopic Vision*

Each area 17 receives visual information from the contra-lateral hemi-field. Thus, in order for binocular vision to occur there must be a convergence onto the cortical neurone of visual inputs from the corresponding regions of the two retinae which, in the primate, occurs above the level of layer 4C which contains entirely monocular neurones. These binocularly driven neurones consist of complex cells in the primate..

When an object is located on the horopter (page 5), corresponding retinal points are stimulated so that optimal stimulation of binocular cortical neurones would be expected to occur, as it does in a large number of cases. However, many neurones have a misalignment of their receptive fields with respect to what should be corresponding retinal positions. The magnitude of the misalignment is referred to as a retinal disparity and for the neurone to be stimulated optimally binocularly would require the placement of the visual object either in front or behind the horopter thus requiring a positional disparity with respect to the horopter.

Barlow, Blakemore and Pettigrew (1967) were the first to report the existence of positional disparities in binocular cortical neurones of the cat. The mean values were considerable: 6.6±1.5 (S.D.) deg for disparity in the horizontal meridian and 2.2 ± 0.5 (S.D.) deg in the vertical meridian. In the primate, however, Hubel and Wiesel (1970) reported the presence of positional disparities for binocular neurones in area 18 but not in area 17 where there was apparently exact correspondence of the left and right receptive fields. Furthermore, in investigations in the cat, when the direction of gaze of each eye was monitored by long term recording of the receptive field position of a binocular simple cell, they reported that 93% of cortical neurones had no measurable disparity, 4% had questionable disparity and in 3% a measurable disparity of up to 0.75 deg was evident (Hubel and Wiesel, 1973). The positional disparities measured were thus more in keeping with those reported by Nikara, Bishop and and Pettigrew (1968), which ranged from 3 min arc up to ± 1.2 deg. Subsequently, Hubel and Wiesel's assertion of an absence of positional disparities in area 17 of the primate has undergone revision. Recording from implanted electrodes in conscious monkeys showed disparities within a range as small as ±0.25 to ±0.50 deg (Poggio and Fischer, 1977). This range of magnitude of positional disparities thus accords well with the extent of Panum's area which extends ±7-12 mins arc in front of and behind the horopter (Mitchell, 1966).

There is also the possibility that depth perception may be subserved by orientation disparities of binocular cortical neurones. In the cat, Blakemore, Fiorentini and Maffei (1972) recorded differences in orientation optima of ±28 deg.

Further studies in the primate (Poggio, 1984) has resulted in the formulation of a classification of disparity sensitive neurones which were reported to be located predominantly in layers 4B and 4Cα of area 17. These consisted of disparity tuned neurones and disparity selective neurones. The former category consisted of neurones tuned to respond to targets on the horopter, *i.e.* "tuned zero" and neurones with very narrow positional disparity tuning curves which were either "tuned near" *i.e.* located in front of the horopter or "tuned far" *i.e.* located behind the horopter. In addition, "tuned inhibitory" neurones were inhibited when the object fell on the horopter but were responsive when the stimulus moved away from the horopter. The implication of these results is that the neurones require a very precise alignment of the left eye and right eye receptive fields so that precise stimulation of these receptive fields will therefore give rise to either binocular facilitation or binocular inhibition. Other neurones which were also found to be disparity selective for near or far distances from the horopter were responsive whenever the object fell in front of or behind the horopter, respectively, and that inhibition ensued once the visual object was translated to the other side of the horopter.

A further important aspect of stereopsis is global stereopsis which will be dealt with later.

1.6.4 *Pre-striate Cortex*

The pre-striate cortex extends from the boundary with the striate cortex to the posterior bank of the superior temporal sulcus and contains areas 18 and 19 which are characterised, histologically, by a broad layer 3 and a narrow layer 4. The prestriate cortex of the primate was subdivided by Zeki into several discrete visual areas, based on the location of bands of degeneration taken to represent

the location of the vertical meridian after section of the corpus callosum (Zeki, 1969). These areas are known as V2 (broadly comparable to area 18), V3/V3A, V4 and V5, also known as MT (middle temporal area). Homologous areas have also been shown to exist in the human visual system by using functional MRI scanning. The striate cortex of the human is twice the area of that in the macaque monkey (Sereno, Dale, Reppas, Kwong, Belliveau, Brady, Rosen and Tootell, 1995). Of special interest is area V3/V3A which is disproportionately much larger in the human than in the primate (Tootell, Dale, Sereno and Malach, 1996).

In area V2, cytochrome oxidase staining of tangential sections showed a pattern of alternating thin stripes and thick stripes separated by cytochrome oxidase deficient regions (inter-stripes) (Horton and Hubel, 1981). By localised injection of HRP (horseradish peroxidase) into area V2, where it was taken up by neurones and transported retrogradely into area V1, Hubel and Livingstone (1983) showed that the cytochrome oxidase patches of V1 projected to the thin stripes of V2, while the inter-patch areas of V1 projected to the inter-stripe zones of V2. Later, they demonstrated that the thick stripes of V2 received a diffuse projection from layer 4B of V1 (Hubel and Livingstone, 1987). The result of these projections is that neurones of area V2 have specific response characteristics according to the location of these neurones.

Within the thin stripes, neurones have been demonstrated to be predominantly spectrally specific though some neurones were binocularly driven or were orientation specific (DeYoe and Van Essen, 1985). Inter-stripe neurones were shown also to be spectrally specific, though not with the frequency of thin stripe neurones, while binocularity and orientation specificity were also recorded. Neurones located in the thick stripes were shown to have the properties of directionality, binocularity and orientation sensitivity.

A more firmly demarcated separation of visual function was described by Hubel and Livingstone (1987). Thin stripe neurones were described as being

concentric neurones which were thus inferred to be spectrally sensitive; the inter-stripes contained orientation specific and end stopped neurones, while the thick stripes contained binocular neurones which showed positional disparities.

The projections from the different parts of area V2 are also specific. DeYoe and Van Essen (1985) demonstrated that the neurones of the thin stripes and inter-stripes projected to area V4, while the neurones of the thick stripes projected to area V3 and area V5, both of which also receive a direct projection from layer 4B of layer V1 (Livingstone and Hubel, 1987).

The higher prestriate areas have previously been described as being specific for different modalities of the visual stimulus so that area V3 was described as an area involved in the processing of visual form and binocularity, area V4 was described as a colour processing area and area V5 was described as an area for processing motion (Zeki, 1992). However, the functional characteristics of each specific region are now known to be more complicated than previously thought. In his original description of area V3, Zeki (1978) reported that a considerable number of neurones were orientation selective and had a requirement for binocular stimulation. This was later extended by Fellman and Van Essen (1987) who reported that neurones of V3 showed specificity for a wide range of modalities, in particular, to orientation, directionality and positional disparities, with a relatively low incidence of spectrally specific neurones. An area ventral to V3 and originally believed to be part of V3 has been described as a separate visual area denoted VP (Ventral Posterior). Its main difference from V3 was the relative paucity of directionality sensitive neurones and the high incidence of spectrally specific neurones (Burkhalter and Van Essen, 1986).

Area V4 is the most controversial of the prestriate visual areas. Originally denoted an area involved in colour processing (Zeki, 1977), this is now recognised as an area which is involved in the processing of the spatial form as well as the spectral content of the image (Desimone and Schein, 1987, 1989).

More recent studies have implicated area V4 as being involved in the detection of the "difficult to see" (*i.e.* lower contrast or smaller size) targets (Schiller and Lee, 1991), illusory contours, hyperbolic or polar contours (Gallant, Connor, Rakshit, Lewis and Van Essen, 1996), or in the direction of attention (Luck, Chelazzi, Hillyard, and Desimone, 1997).

Area V5 constitutes an area over which broad agreement exists as to its function *i.e.* the detection of the direction of motion, without reference to the colour of the target (Zeki, 1977; Albright, Desimone and Gross, 1984). Localised lesions of this area results in the reduction of the velocity of saccades generated in response to a moving target but not in response to a stationary target (Newsome and Wurtz, 1988). Associated with area V5 is area V5A which is located anteriorly to the superior temporal sulcus and which is involved in the generation of smooth pursuit eye movements (ibid, 1988).

Thus, there appears to be a relatively clear cut dichotomy of the visual pathway in terms of the type of visual information transmitted. The magnocellular or M pathway projects from the M laminae of the LGN to layers 4Cα and 4B of V1, to the thick stripes of V2. Both 4B of V1 and thick stripes of V2 project to V3 and V5. The parvocellular or P pathway is involved in the transmission of form and spectral information from the P laminae of the LGN to 4Cβ of V1, thence from layers 2 and 3 of V1 to the thin stripes (spectral) and inter-stripes (form) of V2. Both then project to V4.

However, in recent years this apparently clear cut dichotomy has become somewhat blurred. Within layer 4B of area V1, the dendritic field of the spiney stellate neurones remain localised to that layer and receive a specific input from the M laminae of the LGN. By contrast, pyramidal cells located in layer 4B receive inputs from the M pathway at the basal dendrites and cell body and from the P pathway at the apical dendrites which extend into layers 2 and 3 (Sawatari and Callaway, 1996). The stellate neurones thus relay a relatively uncontaminated M signal to their destination, area V5, while the pyramidal

neurones relay a mixed M and P signal to the thick stripes of area V2 (Callaway, 1998). Thus, inactivation of the P laminae of the LGN leads to a 36% reduction in V4 neurone responsiveness while inactivation of the M laminae leads to a 47% reduction. By contrast, V5 was affected only by M cell lesions and not by P cell lesions (Nealy and Maunsell, 1994).

1.6.4.1 *Global Stereopsis*

Global stereopsis is the appreciation of depth within a complex visual scene such as random dot stereogram (Julesz, 1960). Each eye views an apparently identical array of randomly positioned elements (sometimes dots are used). However, within a central area which defines a particular shape, for example, a square or diamond, between the two displays each element is shifted by a constant positional disparity which is undetected on monocular viewing. Thus, when fusion of the array of features occurs on viewing through a stereoscope, the central feature, due to the consistent positional disparity, is seen to rise up above the background. This appreciation of an object hidden in the random dot stereogram occurs very rapidly to the extent that it has been thought to be carried by parallel processing rather than by serial processing (Bergen and Julesz, 1983).

Behavioural studies in primates have implicated the infero-temporal cortex in the function of global stereopsis. Lesions of this area resulted in impaired discrimination of objects in complex visual scenes while the function of stereoacuity was unimpaired. The latter was shown to require the integrity of V1 (Cowey and Porter, 1979).

Of the neurones responsive to random dot stereograms, 90% consist of complex cells with large receptive fields, a necessary prerequisite for the appreciation of a stereogram stimulus. The "hidden object" which is seen in depth, is different from that detected by conventional means using a bar stimulus (Poggio, 1984). Contrasts as low as 1% are detectable within a random dot pattern. The incidence of neurones responsive to random dot

stereograms increases markedly beyond V1 of the macaque monkey where the frequency of occurrence is approximately 30%, increasing to 60% in V2, 70% in V3/V3A and 90% in V5A (MST).

1.6.4.2 *Stereopsis in Man*

Stereoscopic vision requires the fusion of images represented in each hemisphere. Stereopsis for a target situated, for example, 5 degrees to the right or left side from the object of regard which is lying in the vertical midline can be appreciated as the displaced target stimulates nasal retina in one eye and temporal retina in the other eye. Thus, these visual inputs from the contra-lateral nasal retina and ipsilateral temporal retina realign onto the same side of the visual pathway and converge within the cortex. However, stereopsis for a target located directly behind or in front of the object of regard situated in the vertical midline can only be appreciated if the visual inputs to each eye are combined through the corpus callosum as the inputs from the two eyes do not pass to same cortex. Therefore, in order to appreciate stereopsis, callosal transfer of information is required in this instance. Thus, in humans in whom the callosal fibres have been sectioned, stereopsis is absent for targets situated in the vertical midline (Mitchell and Blakemore, 1970).

1.7 Normal Development of the Visual System

1.7.1 *Humans and Primate*

The neonatal eye is considerably smaller than that of the adult. The axial length increases rapidly from 17mm at birth to 24mm at around 3 years of age. Thereafter, it slows down until 12-15 years when the adult length is normally attained. The increase in axial length is normally followed by a fall in the total dioptric power of the eye from 86D to 55D due to the decrease in corneal curvature and the decrease in refractive power of the lens. These changes result in an increase in the posterior nodal distance and, hence, in retinal subtense which is increased by 50%. As age progresses, there is an increase in the

packing of the foveal cones with a concomitant reduction in inter-cone spacing. The consequence of this is an increase in the theoretical maximum resolution (the Nyquist Limit) during maturity by a factor of 2. It has been estimated that the neonatal visual system can resolve 0.75c/deg (6/240) within the first few days of life. At one month this improves to between 1.0 to 2.0 c/deg (6/180-6/90) and at 2 to 3 months to 6.0 c/deg (6/36 approx) (Atkinson and Braddick, 1981). At approximately 3 years of age, visual acuity of between 6/9 and 6/6 should be attainable.

In a review by Jacobs and Blakemore (1988), the time course involved in attainment of maximum spatial resolution (Nyquist limit) as calculated by the inter-cone spacing and the resolution of cortical neurones was compared to the behavioural acuity achieved by the primate as age progressed. The neurophysiological performance was significantly poorer than the photoreceptor sampling limit during the first few months; however, up to approximately 10 weeks of age, there was a substantial improvement in cortical neuronal performance which beyond 10 weeks ran almost parallel to the Nyquist limit. Behavioural acuity was substantially lower than the cortical neuronal resolution but, again, at around 10 weeks of age, it reached the level of performance of the cortical neurones. Thus, considerable maturation of the primate visual system occurs particularly within the first 10 weeks after birth.

1.7.2 Cat

With respect to the properties of orientation specificity, directionality and binocularity, Hubel and Wiesel (1963) sought to determine if these were innate properties of visual neurones or if they required visual experience for their development. They showed in very young kittens that cortical neurones possessed all of these functional properties; they also described the existence of orientation columns in visually inexperienced kittens as young as two weeks of age. Albus and Wolf (1984) confirmed that orientation selectivity was present in approximately 15% of neurones at 6 to 7 days of age in the kitten, *i.e.* before

eye opening. These responses were generated by simple cells which were detected in layers 4 and 6 of the striate cortex at this time; however, orientation specificity in complex cells in layers 2 and 3 was not recorded until 15 days after birth, indicating that differential cortical maturation occurs.

With respect to neurones sensitive to positional disparity, these were not recorded until 5 weeks after birth. Furthermore, the development of these neurones was shown to be entirely dependent on normal visual experience (Pettigrew, 1974).

The cortical neuronal responses are, however, subject to modification dependent on early visual experience. Orientation specificity of neurones was investigated by the drum rearing experiments of Blakemore and Cooper (1970) who showed that selective viewing of vertical or horizontal stripes by neonatal kittens resulted in modification of cortical neuronal responses. Cortical neurones only responded to the orientation of the striped pattern to which they had previously been exposed. Hirsch and Spinelli (1971) applied striped goggles, in which one eye piece contained vertical stripes and the other eyepiece horizontal stripes to neonatal kittens. They showed that within the same animal, cortical neurones driven by the eye which had been exposed to vertical stripes were responsive only to vertical stimuli, while the cortical neurones driven by the eye which had been exposed to horizontal stripes were responsive only to horizontal stripes. Furthermore, the susceptibility of visual cortical neurones to modification of the visual experience in the neonatal period was shown to occur only in those cortical neurones which had the characteristics of Y cells, while those which had the characteristics of X cells were not modified (Hirsch, Leventhal, McCall, and Tieman, 1983). This accords with the delayed development of the Y pathway compared with the earlier development of the X pathway in neonatal kittens (Sur, Weller, and Sherman, 1984).

1.8 Effects of Abnormal Visual Experience

If the human visual system is deprived of an adequate visual stimulus, reduced visual acuity (amblyopia) frequently occurs if the deprivation is present within what is termed "the critical period" for visual development. Since there are several causes of amblyopia *viz*. occlusion, strabismus and anisometropia, the neural consequences of the presence of these deprivation factors have been investigated using animal studies. Experimentally, the most commonly employed form of deprivation has been monocular occlusion effected by lid suture early in the animal's life.

1.8.1 Monocular Occlusion

1.8.1.1 Physiological Studies in Cat

Much of the impetus for investigation into the effects of visual deprivation stem from the pioneering studies of Hubel and Wiesel, initially in the cat and thereafter in the monkey. They demonstrated that monocular deprivation, effected by suturing closed the eyelid of a kitten during the neonatal period, caused a shift in ocular dominance from the normal pattern in which there was a preponderance of binocular neurones (see Figure 16) with the result that the cortical cells were driven, almost entirely, by the open eye (Hubel and Wiesel, 1965). Monocular deprivation, however, was without effect if it was commenced later than three months after birth *i.e.* outside the critical period for neuronal plasticity which is regarded to be within the first 12 weeks of life. Reversal of the ocular dominance shift, so that normal binocularity was restored, could be effected if the previously deprived eye was opened within this critical period. The question arose as to whether the loss of responsiveness, as a result of monocular deprivation, was due to the absence of visual input to one eye *per se* or was due to a competitive imbalance between the two eyes. In order to answer this question, kittens were reared in total darkness for four to five months. Thereafter, when the ocular dominance pattern was examined it was shown to be essentially normal with the exception

that a higher than normal incidence of unresponsive neurones was recorded. An extension to this work was reported by Mower and Christen (1983) who showed that monocular deprivation implemented after four to five months of dark rearing still resulted in a shift of ocular dominance to the open eye, indicating that dark rearing had deferred the actual commencement of the critical period.

1.8.1.2 Physiological Studies in Primate

The ocular dominance histograms in the primate are markedly different from those of the cat, with neurones outside of layer 4 showing a much greater tendency to be driven either by one eye only or to be dominated by one eye, so that true binocular neurones were relatively rare (see Figure 17) (Hubel and Wiesel, 1968). In layer 4C, however, the neurones are entirely monocular, being driven by either the right or the left eye. Thus, the effect of monocular deprivation caused by eyelid suture in the neonatal period was to shift the ocular dominance pattern so that only the open eye drove the neurones of layer 4C. Again, there was the requirement that the deprivation had to be implemented during the critical period which in the primate extended to some six months. Occlusion outside of this period was without effect on the responsiveness of neurones to stimulation through what, at that time, was the closed eye. There were, however, some very marked differences from the cat. First, simply opening the occluded eye during the critical period was insufficient to restore the responsiveness to stimulation through that eye. Furthermore, a period of closure as short as a few days was sufficient to cause a profound shift in the ocular dominance pattern which was not restored to normal even if the closed eye was reopened for as long as several years. An important finding was that responsiveness through a previously closed eye could be restored, provided the hitherto open eye was now occluded (*i.e.* reverse suturing), if the reverse suturing occurred within the critical period.

The optimal time period for reverse suturing was determined by Blakemore,

Vital-Durand and Garey (1981). Monkeys which had one eyelid sutured until 24 days after birth were subjected to varying periods of reverse suturing. It was shown that the normal balance of ocularity for both layer 4 and non-layer 4 neurones occurred at 3 days and 6 days of reverse suturing, but for longer periods, reverse suturing resulted in an imbalance in favour of the now open eye.

1.8.1.3 Morphological and Histological Studies

Hubel, Wiesel and LeVay (1977) also visualised, morphologically, the results of monocular occlusion on layer 4C of the primate cortex. After an injection of ^{3}H proline into one eye during the course of the eyelid suture experiments, they were able to examine the ocular dominance organisation of layer 4C using autoradiography of tangential sections. The eyelids of a 2 week old monkey had been sutured for a period of 18 months when the injection of ^{3}H proline was made. There occurred a marked shrinkage of the territories driven by the deprived eye with a corresponding expansion of the territories driven by the non deprived eye so that the combined width of the left and right eye columns remained at 800μm, which is the width in the normal animal. This indicated that the ocular dominance column width changes had arisen as a result of competition between open and closed eye inputs.

The changes in layer 4C of the visual cortex were also accompanied by changes in the lateral geniculate nucleus. Previously, Hubel and Wiesel (1965) had shown in the cat that the layer of the lateral geniculate nucleus driven by the occluded eye was markedly shrunken compared with the layer driven by the open eye. This was confirmed in the primate in which all the layers driven by the deprived eye were shrunken in appearance (Hubel, Wiesel and Le Vay, 1977). Generally, the shrinkage of the layers was associated with the shrinkage of neurone size in these layers; both parvocellular and magnocellular neurones were affected. As a result of more detailed studies of the time course of the

changes in cell size in the lateral geniculate nucleus, it has been established that the shrinkage occurred over a more extended time course than the changes in neuronal responses in the cortex *i.e.* the inference is that shrinkage of LGN neurones was not a causal factor in the ocular dominance shift in the cortex but may represent the result of deprivation disuse (von Noorden and Crawford, 1978).

A further insight into the LGN changes during monocular deprivation was provided by Blakemore and Vital Durand (1986) who reported that the responses of neurones of the deprived laminae, in terms of their spatial resolution, were unaffected by the deprivation. They thus inferred that the cortical abnormalities arose centrally within the cortex and were not as the result of changes in the lower visual pathway.

1.8.2 Strabismus

There are two aspects to the effects of strabismus: first, the degree to which the neuronal responses driven by the strabismic eye are adversely affected and, second, the extent to which binocularity is deranged.

1.8.2.1 Physiological Studies in Cat

Reduced spatial resolution of the X cells of the central visual field representation of the LGN (Ikeda and Wright, 1976) and the retina (Ikeda and Tremain, 1979) were recorded in response to visual stimulation through the esotropic eye. Physiologically and behaviourally, spatial resolution was lowest for kittens reared with strabismus from three weeks of age while in animals in which the squint was induced at twelve weeks, there was no significant difference between the strabismic and the normal eyes, again highlighting the importance of the critical period.

By contrast, in a kitten in which exotropia had been induced experimentally, the cortical neurones remained responsive to stimulation through either of the two

eyes (Wiesel and Hubel, 1965). However, in this animal there was a complete absence of binocularly activated neurones which indicated an absence of binocular vision.

The difference between the outcomes of the two sets of experiments may be attributed to the occurrence of alternating fixation in the exotropic animal which was not possible in animals with marked esotropia. However, derangement of binocularity, nonetheless, occurred in the exotropic animal (as it would have occurred in the esotropic animals).

1.8.2.2 Physiological Studies in Primate

In the experiments of von Noorden and Crawford (1977), the normal ocular dominance histogram showed a high proportion of binocularly activated neurones in the manner shown in Figure 16. However, experimentally-induced esotropia in the neonatal period caused a significant shift in ocular dominance so that the majority of cells were driven by the normal eye, and virtually no neurones were binocularly driven. Responsiveness through the esotropic eye was restored by subsequent surgical realignment within the critical period, though there was no restoration of binocularly driven cells. Furthermore, in other animals, eyelid suturing of the normal eye led to the restoration of responsiveness of cortical neurones driven through the esotropic eye, though this was at the expense of the number of cortical neurones driven by the normally aligned eye.

A link between the results of neurophysiological studies and behaviour has been provided by the work of Crawford, Harwerth, Chino, and Smith, (1996). When esotropia was induced prismatically in neonatal primates, the marked loss of binocularly driven cortical neurones was confirmed in animals in which acute experiments were undertaken. In another set of animals, the prisms were removed after 12 weeks which resulted in the normal alignment of the eyes being regained. However, in these animals, contrast sensitivities determined

behaviourally did not show the normal enhancement on binocular viewing compared with the monocular contrast sensitivities present in control animals. Furthermore, the prism reared monkeys were unable to detect the target feature in random dot stereograms. These results thus confirmed an absence of BSV in these animals, with the inference that BSV was dependent upon the normal function of binocular cortical neurones.

1.8.3 Anisometropia

1.8.3.1 Physiological Studies in Primate

In cases of anisometropia, a similar finding to the changes found in esotropia was evident in that experimentally induced anisometropia resulted in a shift in ocular dominance to the normal eye (von Noorden and Crawford, 1977). Anisometropia, induced by atropinisation of one eye, also resulted in a marked reduction in the spatial resolution of both simple and complex cortical cells driven by the atropinised eye (Movshon, Eggers, Gizzi, Hendrickson, Kiorpes and Boothe, 1987). Further studies showed that the ocular dominance columns, determined by autoradiography, corresponding to the normal eye were wider than those served by the deprived eye (Hendrickson, Movshon, Eggers, Gizzi, Boothe and Kiorpes, 1987), the inference being that the more ametropic eye was placed at a competitive disadvantage compared with the less ametropic eye.

1.9 Amblyopia

1.9.1 Physiological Studies

Electrophysiological studies have, for some time, been utilised in the diagnosis of amblyopia. The electrodiagnostic tests commonly used consist of recording the visually evoked response (VER) and the electroretinogram (ERG). The former reflects cortical activity and the latter retinal activity. In each case, the stimulus presented may comprise a flash of light or a patterned display of constant overall luminance. Normally, in non-amblyopic subjects, the

amplitude of the VER in response to stimulation of each eye is different by no more than 10% (Arden, Barnard and Mushin, 1974). In amblyopia, however, the differences between the normal eye and the amblyopic eye may be considerable. Arden *et al* (1974) demonstrated that the amplitude of response for stimulation through the amblyopic eye was reduced, and the recorded wave form showed a considerable delay compared with the response from the normal eye. These changes in response were reported to occur in anisometropic amblyopes, esotropic amblyopes and occlusion amblyopes.

The use of the flash ERG, which elicits responses from the photoreceptors and the inner nuclear layer of the retina, has shown there to be normal responses in amblyopia (Burian and Lawwill, 1966). The pattern ERG (PERG) however, which is said to represent ganglion cell function generated in response to temporal modulation of a grating pattern has shown anomalies in amblyopia. Sokol and Nadler (1979) showed that the amplitude, but not the latency, of the waveform in the PERG was reduced in the amblyopic eyes of three adults compared with the responses from the normal eye. In addition, in this limited sample, it appeared that the greater the depth of amblyopia, the greater was the attenuation in the amplitude of the waveform. However, Hess and Baker (1984), on the basis of the distribution of the inter-ocular variation in normal subjects, adopted a criterion of a reduction of 50% in the amplitude of the PERG in the amblyopic eye compared with the normal eye before classifying it as abnormal. As a consequence of this, they concluded that the PERG was not abnormal in amblyopia, though their records do show a reduction in many amblyopes. Had this criterion of a 50% reduction been used by Arden, Vaegen, Hogg, Powell and Carter (1980), the reductions in the PERG reported in their study would not have been classified as abnormal. Devlin, Jay and Morrison (1989) showed that in kittens with surgically induced esotropia, in which amblyopia was confirmed by behavioural testing, the amplitude of the PVER was consistently reduced for stimulation through the squinting eye. Furthermore, there was a delay in the implicit time, but not in amplitude, of the

PERG in the squinting eye, suggesting that the retina was implicated in the mechanisms responsible for amblyopia at least in the cat.

1.9.2 Morphological Studies

Understandably, there is a dearth of morphological information regarding the effects of stimulus deprivation amblyopia in humans. However, structural changes in the human visual pathway in anisometropic amblyopia have actually been documented. von Noorden, Crawford and Levacy (1983) found, at post mortem, that the parvocellular neurones in the lateral geniculate nucleus of the human were 18% smaller in the more ametropic eye compared with those in the less ametropic eye. This finding suggested that the consequences of the presence of a stimulus deprivation factor such as anisometropia may give rise to similar changes in the visual pathway as those encountered in animal studies as a result of monocular occlusion (see Section 1.8.1).

1.9.3 Clinical Studies

It has long been accepted that the earlier the age of onset of the deprivation factor, the greater the depth of amblyopia (Duke-Elder, 1973). Furthermore, the later the onset of the treatment, the less successful is the restoration of vision. Maurer and Lewis (1993) found that 90% of infants, in whom bilateral congenital cataracts were removed within the first year of life, achieved normal visual acuity, while this success rate reduced to 45% at 2 years and 22% at 3 years of age. In addition, the majority of clinical studies have shown that the greater the severity of the stimulus deprivation, the greater the severity of the visual loss. In anisometropic amblyopes, for example, the level of amblyopia typically increased with the magnitude of the refractive error (Ingram, 1977). Tanlamai and Goss (1979) showed that the prevalence of amblyopia was 50% for hypermetropes with 2.5DS refractive difference between the eyes and for myopes with 4.0DS of a refractive difference, while Kivlin and Flynn (1981) reported a 100% incidence of amblyopia in hypermetropes with 4.0DS of anisometropia and in myopes with 6.0DS.

In 1974, Ikeda and Wright, on the basis of experimental work in kittens, proposed that the visual deprivation occurring in strabismus was the result of stimulation of the central retina of the deviated eye by a low contrast, detailed, defocused image. Bagolini (1974), when discussing Ikeda and Wright's suggestion, argued that if their theory were correct then it would be reasonable to expect mild amblyopia in small angled strabismus and severe amblyopia in large angled strabismus. Later, von Noorden and Frank (1976) investigated this possibility but they found no correlation between the magnitude of the strabismus and the depth of amblyopia; mild and severe amblyopia occurred in strabismics of all angle sizes. Thus, defocus of the retinal image, *per se,* is insufficient to account for the depth of amblyopia in human esotropia.

Instead, according to von Noorden, (1976), the depth of amblyopia, and by inference, the prognosis for restoration of vision, depends on the number of "amblyopiogenic factors" (also called amblyogenic factors) which is determined by the nature of the deprivation. These factors are light deprivation of the entire retina, form deprivation of the fovea and abnormal interaction between dissimilar contours presented to the retinae, the latter being a consequence of light or form deprivation. Conditions which give rise to light deprivation would be dense cataract, complete ptosis, and severe corneal scarring. Form deprivation would occur as the result of refractive error and/or strabismus, while abnormal binocular interaction would occur if the image perceived by each eye differed in clarity or size. A case of unilateral congenital cataract, for example, would result in light deprivation, form deprivation and "abnormal binocular interaction". Thus, the presence of three "amblyopiogenic factors would give rise to a more severe depth of amblyopia. Bilateral cataracts of equal density would not, on the other hand, result in such deep amblyopia as only light and form deprivation are present. In strabismic amblyopes and anisometropic amblyopes only two amblyogenic factors are present (form deprivation and abnormal binocular interaction), and therefore the severity of

amblyopia would be expected to be less in these cases compared to that encountered in unilateral congenital cataract. Thus, successful restoration of visual function depends on the number of amblyogenic factors. Furthermore, there is also a dependence on the duration of the stimulus deprivation within the critical period before treatment is commenced (Ingram, Walker, Billingham, Lucas and Dally, 1990) and subsequent compliance with therapy (Lithander and Sjostrand, 1991).

The clinical diagnosis of amblyopia is normally determined by measurement of an individual's Snellen acuity, the accepted visual norm being 6/6 (with refractive correction where applicable). Frequently, amblyopes experience crowding in which a line of letters is read with greater difficulty than single optotypes. Hence, in cases of mild amblyopia in which a Snellen acuity of 6/9 or 6/12 is recorded, this value will have been contributed to by crowding as well as by reduction in the visual acuity, *per se*. Of importance is that the Snellen test records a single end point which represents the highest level of acuity for letters of fixed contrast. There is, thus, the possibility of a lack of precision in the test due to the individual's ability to estimate or guess the identity of the letters. Furthermore, no information may be gained about how well the individual detects larger letters, the importance of which is that much of the visual information requiring to be processed by the visual system is rarely of the finest detail. Thus, in order to ensure a more objective and complete measurement of visual function, a "formless" stimulus of variable size and variable contrast should ideally be employed in the clinical diagnosis of amblyopia. Such a stimulus is employed in the measurement of contrast thresholds from which the contrast sensitivity function is derived (Schade, 1956; Campbell and Green, 1965).

1.10 Contrast Sensitivity

Contrast is a dimensionless value which expresses the difference in luminance between an object and its background. Since, as will be described later, the

contrast threshold for just being able to detect this object depends on the dimensions of the object, an experimentally convenient method of determining contrast threshold involves the viewing of a vertical sinusoidal grating pattern generated by an oscilloscope or television monitor (Figure 18). The utility of the sinusoidal grating pattern is that, first, in mathematical terms it represents the simplest wave form which can be used to generate a stimulus display. Furthermore, by adjustment of the spatial frequency *i.e.* the number of cycles of the sine wave per degree of visual angle, a change in object size is effected. Third, when the contrast is adjusted by increasing the maximum contrast and reducing the minimum contrast of the sine wave, the overall space averaged luminance remains constant. Under normal circumstances, the results are expressed in terms of contrast sensitivity *i.e.* the reciprocal of contrast threshold which gives a measure of the ability with which a particular grating pattern is detectable. Since the spatial frequency of the sinusoidal grating pattern is readily variable, the contrast sensitivities can be measured over a range of spatial frequencies with the result that the contrast sensitivity function (CSF), which is essentially the modulation transfer function of the visual system, is obtained.

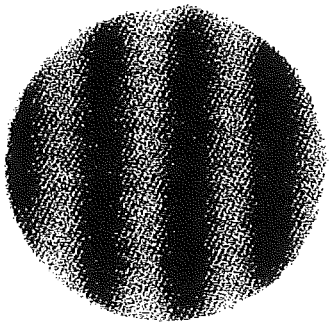


Figure 18. A sinusoidal grating pattern.

CSF has three main features; peak contrast sensitivity which is normally, in the adult, between three and five cycles per degree, attenuation of CSF

characterised by a gradual fall-off at low spatial frequencies, and the steep fall-off of the higher limb of the contrast sensitivity curve. The human visual system can discriminate grating patterns up to 45 c/deg (approximately) although the limit of resolution is 56 c/deg, as predicted by the Nyquist limit for inter cone spacing, and can normally only be attained by application of laser interferometry. Thus, both the monocular and the binocular contrast sensitivity curves resemble an inverted V. The attenuation at low spatial frequencies is thought to reflect the lateral inhibitory processes, while the decline at high spatial frequencies is contributed to by optical and neural factors of which the neural factor constitutes the limiting factor (Campbell and Green, 1965).

In 1968, Campbell and Robson, investigated whether the contrast sensitivity function arose from the responsiveness of a homogeneous population of neurones working over the entire spatial frequency range or from different populations of neurones subserving different spatial frequencies. Contrast thresholds were measured, first, in response to the detection of a sine wave grating pattern and, then, in response to the discrimination of a square wave grating pattern from the sine wave grating pattern of the same fundamental frequency. Hence, the difference between the two displays consisted of the higher harmonics present in the square wave grating pattern. Campbell and Robson showed that the third harmonic was detectable with normal sensitivity even in the presence of the fundamental harmonic. If spatial frequencies were detected by the same population of neurones then the ability to detect this third harmonic would have been impaired due to the presence of the fundamental which would have caused adaptation of neurones thus, reducing their sensitivity. They therefore showed that the visual system was made up of spatial filters, or channels, which were tuned to detect bands of spatial frequencies.

The characteristics of the channels were determined by Blakemore and Campbell (1969) who determined the contrast threshold elevation in response to

adaptation to a range of different spatial frequencies. They demonstrated the operation of an indeterminate number of channels each with a band pass of an octave at half amplitude of the channel's sensitivity. The channels were then shown to comprise a dichotomy since, at low spatial frequencies (up to 5 c/deg), there was a marked increment in contrast sensitivity in response to temporal modulation compared with stationary grating patterns (Tolhurst, 1973). This gave rise to the analogy that the temporally sensitive channels were related to the Y system of the cat and the stationary channels were related to the X system of the cat. Subsequently, a finite number of channels has been identified. Wilson, McFarlane and Philips (1983) proposed the existence of six channels with peak band passes at 0.75, 1.5, 2.8, 4.4, 8.0, and 16.0 c/deg (the former two being transient and the latter four sustained channels). Watson and Robson (1981) identified seven channels with the highest peak band pass at 32c/deg. More recently the concept that the visual system analyses visual information in terms of spatial frequency has undergone modification in that a more appropriate form of analysis may be in terms of Gabor functions. In these, the sinusoidal grating pattern is circumscribed in space by a superimposed Gaussian function which determines the rate of variation of contrast with distance (De Valois and De Valois, 1988). This leads to the possibility of an essentially limitless range of functions which vary in spatial frequency and in the number of cycles contained within the function.

1.10.1 Amblyopia and Contrast Sensitivity Function

For both anisometropic and strabismic amblyopia, there are characteristic contrast sensitivity deficits.

Levi and Harwerth (1977) demonstrated a depression of contrast sensitivities at both low and high spatial frequencies in a limited sample of anisometropes. By application of fogging spherical lenses in front of the normal eye in which the contrast sensitivity at the lowest spatial frequencies was minimally affected, they concluded that the low spatial frequency loss in amblyopia was neural in origin.

Bradley and Freeman (1981) demonstrated that the low spatial frequency loss in anisometropic amblyopes was attributable to the magnification difference present in the more ametropic eye and that anisometropes were fundamentally different from other types of amblyopes. Their conclusion was, however, complicated by the fact that 40% of their subjects had an additional strabismus.

Hess and Howell (1977) classified strabismic amblyopia on the basis of the contrast sensitivity deficit. They found that contrast sensitivity loss in esotropes and exotropes consisted of a spectrum of deficits ranging from a specific high spatial frequency loss which they termed Type I loss, to an overall depression of the contrast sensitivity function which they called Type II loss.

It has since been established that strabismic and anisometropic amblyopes may show either Type I or Type II loss. Lequire, Rogers, Bremer and Wali (1989) attributed the Type category to the severity of the amblyopia irrespective of its cause so that Type I deficits represent cases of mild amblyopia with Snellen acuity of 6/12 while Type II deficits represent more severe amblyopia of 6/24 or worse.

Contrast sensitivities are known to decrease with increasing eccentricity from the fovea. At higher spatial frequencies, the decline with eccentricity is rapid while at lower spatial frequencies contrast sensitivity falls gently at first with eccentricity and then starts to decline rapidly (Hilz and Cavonius, 1974). The effect of retinal eccentricity was, thus, to cause a progressive left wards shift, together with a downwards shift of the contrast sensitivity function. This was accounted for in terms of the cortical magnification factor in which progressively more peripheral regions of the visual field are subserved by disproportionately smaller regions of the visual cortex (Rovamo, Virsu, and Nasanen, 1978).

For normal eye viewing of relatively low spatial frequency grating patterns,

Hess and Pointer (1985) showed that logarithm contrast sensitivity with eccentricity displayed an inverted V profile with the peak value at the fovea and a progressive fall off towards 25 degrees nasal and 25 degrees temporal retina which was asymmetrical in appearance (apart from the blind spot). This inverted V profile of log contrast sensitivity against eccentricity was shifted uniformly downwards in anisometropes. By contrast, in strabismics, the nasal and temporal limbs of the logarithm contrast sensitivity were affected differently in that one limb gradually attained normal contrast sensitivity values as eccentricity increased while the other limb showed the downwards shift characteristic of anisometropes.

These results were taken to indicate a fundamental difference between anisometropia, in which vision was depressed uniformly across the retina, and strabismics in which there was a localised loss, the nasal retina (temporal field) being normal.

The loss of contrast sensitivity is normally encountered in the more ametropic and/or squinting eye, while the other eye has been described as normal (Hess and Pointer, 1985). However, reduced contrast sensitivities have also been found in the companion eye of anisometropic and strabismic amblyopes when compared to normal controls (Wali, Leguire, Rogers and Bremer, 1991). The latter suggested that the difference in contrast sensitivities between the eyes in amblyopes leads to an inter-ocular transfer in which vision through the companion eye is adversely affected. This effect endures such, that on subsequent monocular viewing the companion eye itself becomes subnormal.

From the studies of von Noorden (1976), Hess and Pointer (1985) and Wali *et al*, (1991), the operation of binocular interaction appears to play an important role in the aetiology of amblyopia. Hence, Hess and Pointer attribute the depression of contrast sensitivity in anisometropia to the consequences of binocular competition, though such a mechanism is unable to account for the

localised asymmetrical loss in strabismus. However, in the different forms of amblyopia, several binocular states exist. Thus, in anisometropes, BSV in terms of retinal correspondence is normal. However, in strabismics, BSV may be completely absent or may still be present but in an anomalous form which arises from the consequence of the presence of a pseudo fovea in the strabismic eye, with the result an abnormal retinal correspondence exists (see Section 1.3.4).

1.10.2 Binocular Interactions in Amblyopia

In normal subjects, the binocular interaction is facilitatory. Campbell and Green (1965b) showed that contrast sensitivities obtained for binocular viewing compared with those for monocular viewing increased by 41% while Ross, Clark and Bron (1985) showed an average increase of 37%. The question of what happens in amblyopes is not clear. Blake, Martens, and DeGianfillipo (1980) have assumed that that the amblyopic eye will make no contribution so that binocular contrast sensitivities would be equal to those for the normal eye alone. However, this is not the expectation on the basis of VER results in amblyopes with anomalous BSV, in which the VER response showed binocular summation (Campos and Chiesi, 1983). Furthermore, no distinction has been made with respect to the different states of BSV in amblyopes.

Thus, the present study has been undertaken to determine what effects, if any, binocular viewing has on contrast sensitivities over a range of spatial frequencies compared with monocular contrast sensitivities, in normal subjects and in different categories of amblyopes. The study is directed towards specifically, simple anisometropic amblyopes with normal BSV, micro-esotropes with anomalous BSV, esotropic amblyopes with anomalous BSV, and strabismics (esotropes and exotropes) without BSV. As well as comparison of binocular contrast sensitivities to monocular contrast sensitivities, the effects of neutralisation of the strabismus have also been investigated.

2.0 METHODS

An ophthalmic assessment was carried out on all individuals participating in the study. The examination procedures undertaken comprised determination of the visual acuity, subjective refraction (investigation of the presence, type and magnitude of refractive error) which was confirmed by retinoscopy (an objective assessment of the refractive error present), and assessment of the uniocular fixation pattern. The state of BSV, the direction and magnitude of the angle of deviation of the eyes, the amplitude of accommodation and the pupil diameter were also determined in each case. The main part of the study consisted of the measurement of uniocular and binocular contrast sensitivities in response to stationary vertical sinusoidal grating patterns.

2.1 Subjective Refraction

The subject was seated in a normally lit room, 6m from an illuminated Snellen test type chart which comprised letters of standard sizes ranging from 60 to 4. One eye was occluded and appropriate lenses (convex or concave spherical lenses (power is denoted DS - dioptres sphere), and/or cylindrical lenses (power is denoted DC - dioptres cylindrical with the power in one meridian) were placed in a trial frame in front of the eye under examination. The power of the lens was adjusted until best visual acuity was achieved and the accuracy of this correction was checked using the duochrome test. In cases of astigmatism, the axis of the cylinder was confirmed using an astigmatic fan. The corrected visual acuity was then determined. This procedure was repeated for the companion eye. Finally, the best acuity for binocular viewing was determined.

2.2 Retinoscopy

2.2.1 Confirmation of Refraction

Retinoscopy, which is an objective method of measuring the refractive power of the eye, was carried out using a streak retinoscope in all subjects. The participant was seated in a darkened room at eye level to the examiner who was in front and to the side of the individual. The examiner's working distance was, in the majority of cases, one metre. Thus, a spherical lens of +1.00DS was placed in front of the eyes to ensure that the rays of light from the retinoscope were parallel when striking the eyes, thus simulating infinity.

The subject was instructed to look into the distance and a vertical streak of light from the retinoscope was shone into the eye under test. The retinoscope was moved perpendicular to the axis of the reflected light and the direction of movement of the fundus reflex observed. In myopia, an "against" movement is observed and in the case of hypermetropia a "with" movement is seen (Figure 19A and B, respectively). A concave spherical lens in the former case, or a convex spherical lens in the latter case, was then placed before the eye and the test repeated. The lens was increased in power until neutralisation occurred, that is, no relative movement of the streak of light was observed (Figure 19C). The lens at which this occurred is a measure of the subject's refractive error in that meridian. Horizontal and diagonal meridia were examined in the same way, with appropriate alteration in the axis of the streak, and note was taken of any differences in the refractive power between meridians. A difference between meridia indicated that astigmatism was present. This was then corrected with the appropriate power of cylindrical lens positioned at the appropriate axis. Optimal visual acuity was then confirmed using the Snellen chart.

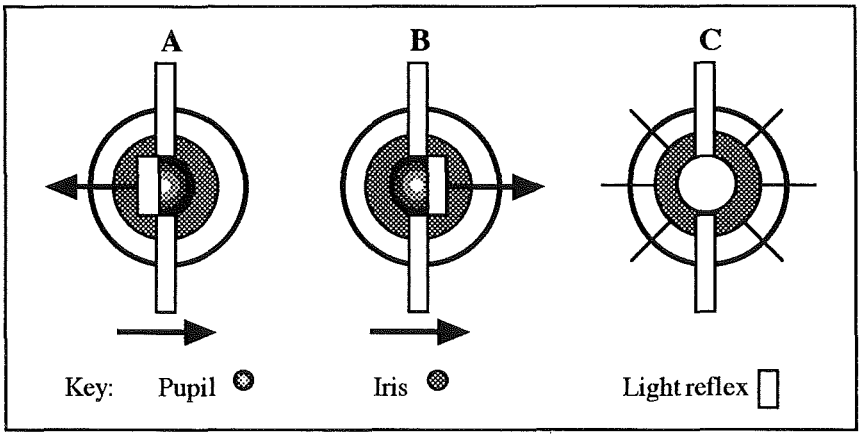


Figure 19. Diagrammatic representation of the movement of the light reflex in retinoscopy. The direction of movement of the light from the retinoscope is indicated by the arrows at the bottom of the diagram. The direction of movement of the light reflex in the eye is indicated by the arrows at pupil level.
A: Represents the "against" movement seen in myopia. The light reflex is seen to move in the direction opposite to the direction of movement of the retinoscope .
B: The "with" movement seen in hypermetropia:
C: When the refractive error has been neutralised the light fills the pupil and no movement in either direction is seen.

2.3 Assessment of Uniocular Fixation Patterns

This was undertaken to determine whether foveal or non-foveal fixation was present in amblyopes and/or strabismics. The participant was seated in a darkened room, one eye was occluded, and the graticule of the ophthalmoscope was projected into the non-occluded eye. The examiner noted the very small glinting spot on the retina at the centre of the fovea, the foveola, which is surrounded by a darker area, the macula region. The subject was instructed to fixate the central circle of the graticule and note was taken of the position of the fovea relative to the graticule. If foveal fixation was present, the centre of the fovea was seen in the centre of the graticule. The extent of eccentric fixation (measured in degrees) was determined by the position of the centre of the fovea relative to the graticule circles. (Figure 20).

In addition, it was necessary to record the characteristics of the eccentric fixation, *i.e.* whether it was steady, unsteady or wandering (Duke Elder, 1973). This gives an indication as to the stability of the eccentric point. Steady fixation

indicates a well established point, unsteady fixation indicates a less established point and wandering fixation indicates that no one retinal point is preferred for fixation.

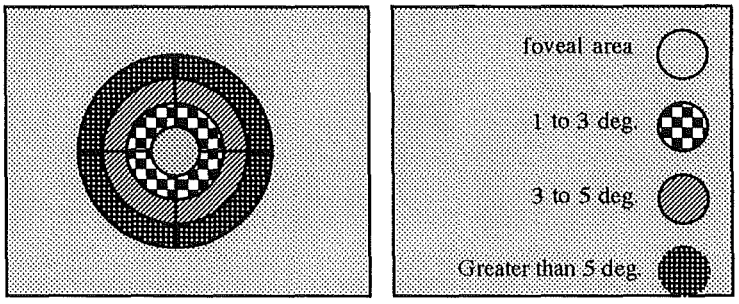


Figure 20. The Star Graticule of the Ophthalmoscope. The numbers indicate the degrees of eccentricity from the centre of the fovea (the central stippled area). 1 to 3 degrees is considered to fall into the category of para-foveola fixation, 3 to 5 degrees foveal fixation, and greater than 5 degrees macular fixation (not to scale).

The subject's perception as to the location of the graticule was also noted. If the graticule was perceived to be in the straight ahead position, this indicated that the eccentric point had adopted a straight ahead projection *i.e.* it had adopted the projection usually associated with the fovea (Lyle and Wybar, 1967). If, when the subject fixated the star graticule, it was perceived to the side, then the eccentric point had not adopted a new projectional value, ie. the eccentric point had maintained its original projection.

2.4 Assessment of the State of BSV in Heterophoria and Heterotropia

The presence or absence of BSV was determined in all cases. The investigative procedures are described.

1. The Cover Test.
2. Bagolini Striated Lornette.
3. Worth's Lights (macular)
4. The Four Dioptre Prism Test.

2.4.1 The Cover Test

Two types of cover test were employed; the cover/uncover test and the alternate (alternating) cover test. Both are objective, completely dissociative tests used in the course of determination of the presence of a deviation of the visual axis, in the former case, and the maximum angle of deviation, in the latter (see later). In order to diagnose the presenting condition, the subject fixated a target at the conventional distances of 0.3m and 6.0m, and at the additional distances of 2.86m and 2.43m, the viewing distances of the oscilloscope display, whilst seated in a normally illuminated room. The cover test was then performed. Spectacles were worn, if appropriate.

2.4.1.1 The Cover/Uncover Test

The cover/uncover test (Marshall, 1967) was carried out initially to determine the presence of a heterophoria, a normal condition which exists in the majority of the population. An explanation of heterophoria is contained in the Introduction (pages 6 and 7; Figure 5).

The subject was seated in a normally lit room at eye level to the examiner and was instructed to fixate the target situated at the appropriate distance. In order to determine the presence of heterophoria, the subject fixated the object of regard and an occluder was placed in front of one eye. The eye under the occluder was observed for movement when the occluder was removed (Figure 5). The previously uncovered eye was then occluded and that eye observed for movement as the occluder was removed. If the eye under the occluder was seen to move out as the occluder was removed, an esophoria or latent convergence was present; if it was seen to move inwards, an exophoria or latent divergence was evident. The presence of a vertical phoria was noted if the eye was seen to move upwards (hypophoria) or downwards (hyperphoria) on removal of the occluder.

The cover/uncover test was also employed to determine the presence and type of

strabismus (heterotropia). This test is of particular use in cases of non-eccentric fixation by the amblyopic eye on monocular viewing. In this instance, an occluder was placed in front of the suspected fixating eye and the uncovered eye was observed for movement. If movement of the uncovered eye was seen, strabismus was present (Figure 21).

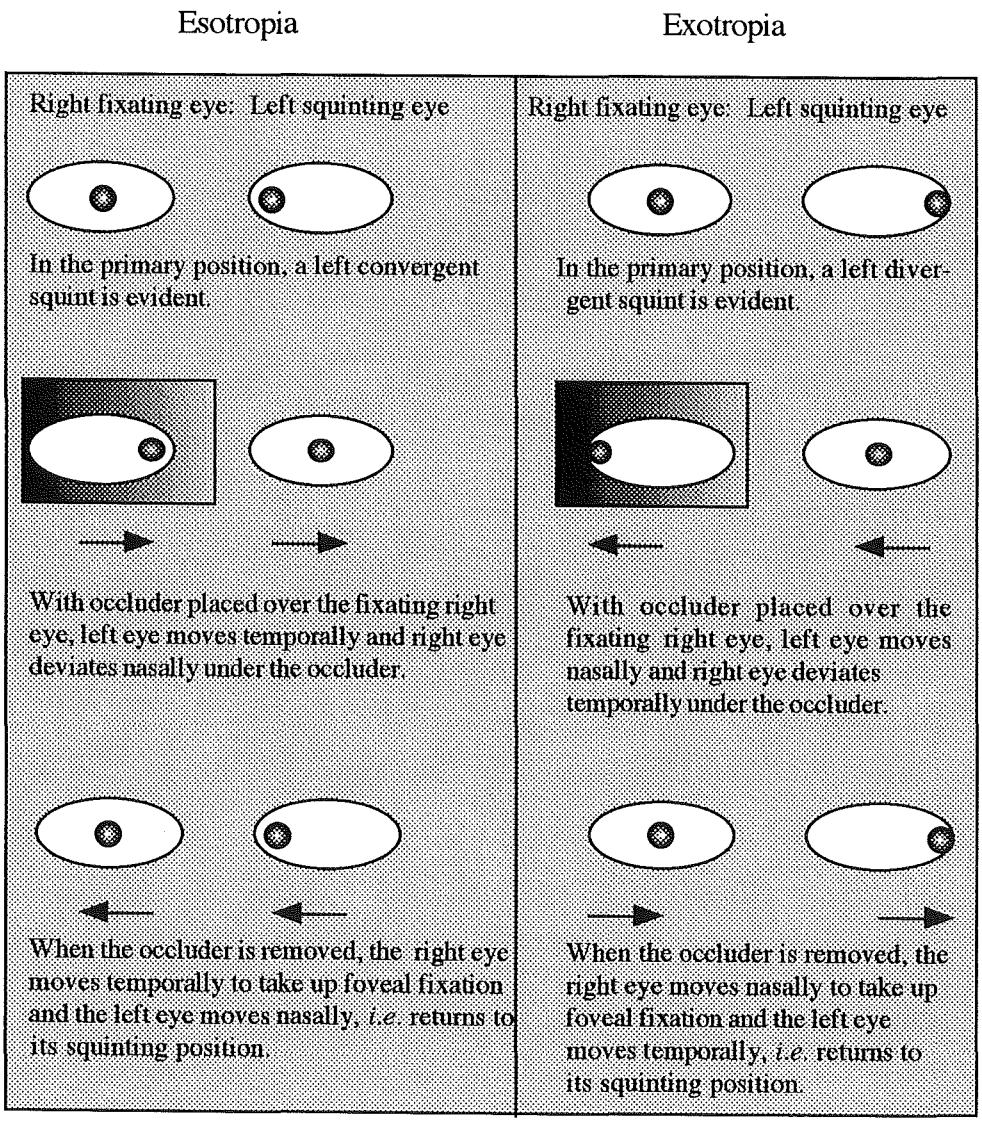


Figure 21. Diagrammatic representation of the Cover/Uncover Test in Heterotropia: Esotropia (left panel): Exotropia (right panel) (an explanation of the graphics is contained in the legend to Figure 5, page 7).

The type of squint was dependent on the direction of misalignment. If the uncovered eye was seen to move outwards, a convergent deviation or esotropia was present; if the eye was seen to move inwards, a divergent deviation or exotropia was evident. The presence of a vertical deviation was noted when the uncovered eye moved up (hypotropia) or down (hypertropia) to take up fixation. Horizontal and vertical deviation of the visual axes could exist in isolation or combination. Large deviations are readily detectable; however, small deviations may be readily missed. Thus, if a deviation was not detected by cover/uncover test, an alternate cover test was carried out as it has the advantage of making small squints more readily identifiable.

2.4.1.2 The Alternate (Alternating) Cover Test

This test is undertaken in the determination of the maximum angle of deviation *i.e.* the angle of heterotropia plus the angle of heterophoria, if present. The subject was instructed to fixate an appropriate target at the designated distance. Spectacles were worn, if appropriate. An occluder was placed over one eye and, when the examiner was satisfied that steady fixation of the target had been achieved by the uncovered eye, the occluder was then placed over this eye (Figure 22). Care was taken not to permit momentary fixation of the target by the previously occluded eye. Note was taken of the direction of the movement to take up fixation. Thereafter a rapid, alternating cover test, that is, covering one eye and then the other in quick succession, was performed ensuring that time was allowed for the uncovered eye to fixate on the target. Both eyes were never permitted to fixate at the same time. Normally, as the alternating cover test was continued, the angle of deviation was seen to slowly increase. Thus, the alternating cover test was continued until the examiner was satisfied that "complete dissociation" had been attained *i.e.* that the magnitude of movement was not increasing further. At this point, the maximum angle of deviation had been achieved *i.e.* the angle of heterophoria and heterotropia.

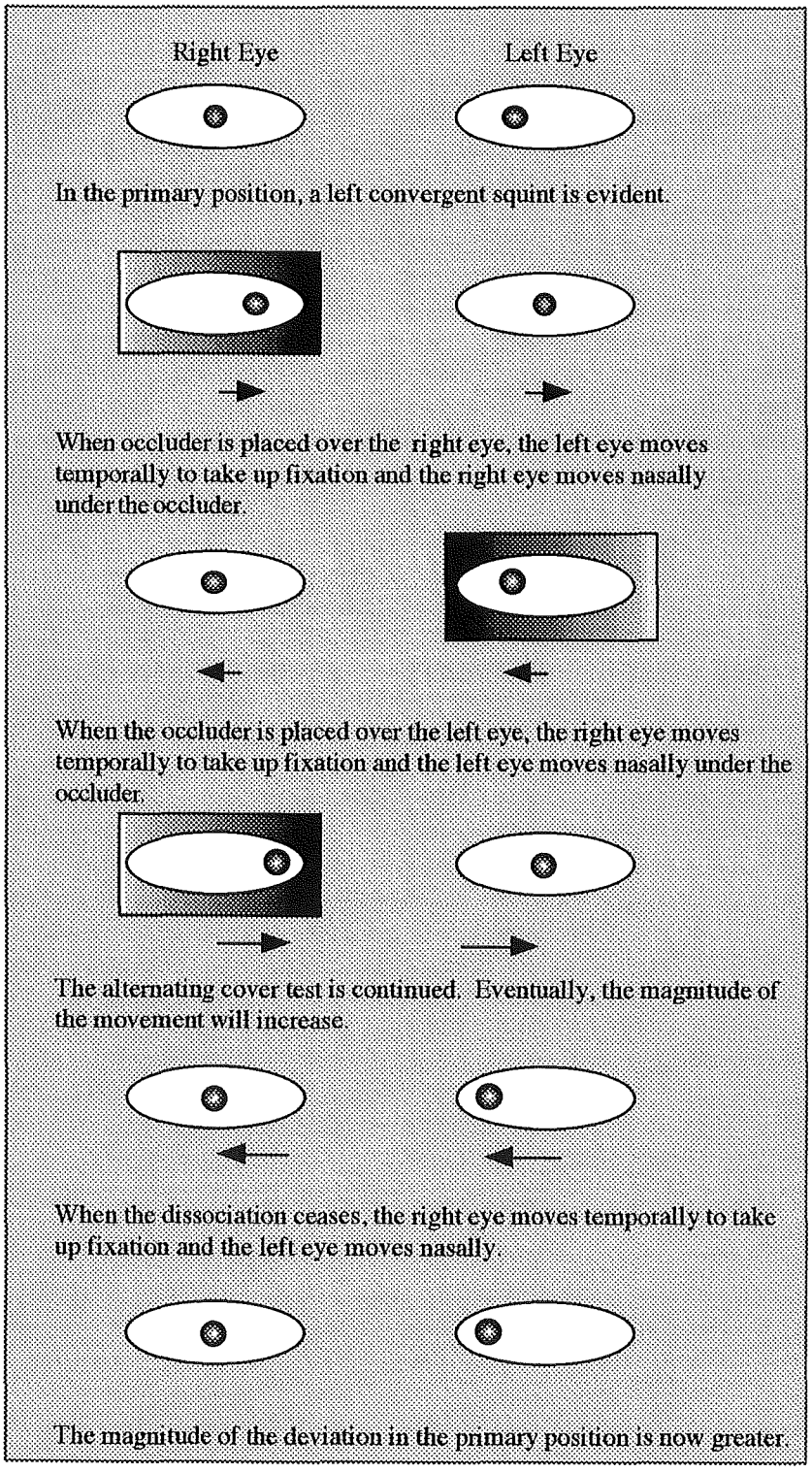


Figure 22. Diagrammatic representation of the Alternating Cover Test in Left Esotropia with non-eccentric fixation. (An explanation of the graphics is contained in the legend to Figure 5, page 7).

2.4.2 Bagolini Striated Lornette

The Bagolini Lornette consists of perspex eyepieces mounted in a frame. The eyepieces have fine striations etched on them at 45 degrees in one eyepiece and 135 degrees in the other eyepiece. These striations are so fine that they do not significantly affect visual acuity. The Bagolini Lornette converts a spot of light into a line of light 90 degrees to the direction of the striations which are composed of plano cylinders (Figure 23). This is a subjective, partially dissociative test used to determine the presence and type of binocular single vision under as near normal conditions as possible (Lyle and Wybar, 1967). The Lornette thus determines the projection of the retinal points used for fixation under binocular conditions of viewing.

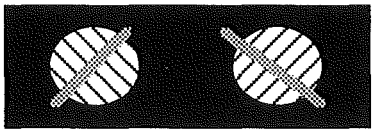


Figure 23. The Bagolini Lornette. The plano cylinders, denoted by the thin black lines, are parallel to each other and are at right angles to those of the other eye piece. The image of the spotlight is converted into a line of light (denoted by the light grey stippled line) seen at right angle to the plano cylinders

The Lornette is placed in front of eyes, the direction of striations in front of each eye (*i.e.* at 45 degrees and 135 degrees as shown in Figure 23) and the participant asked to state what he or she observes. In the presence of normal binocular single vision *i.e.* bifoveal fixation, a symmetrical cross in the form of a saltire is reported (Figure 24).

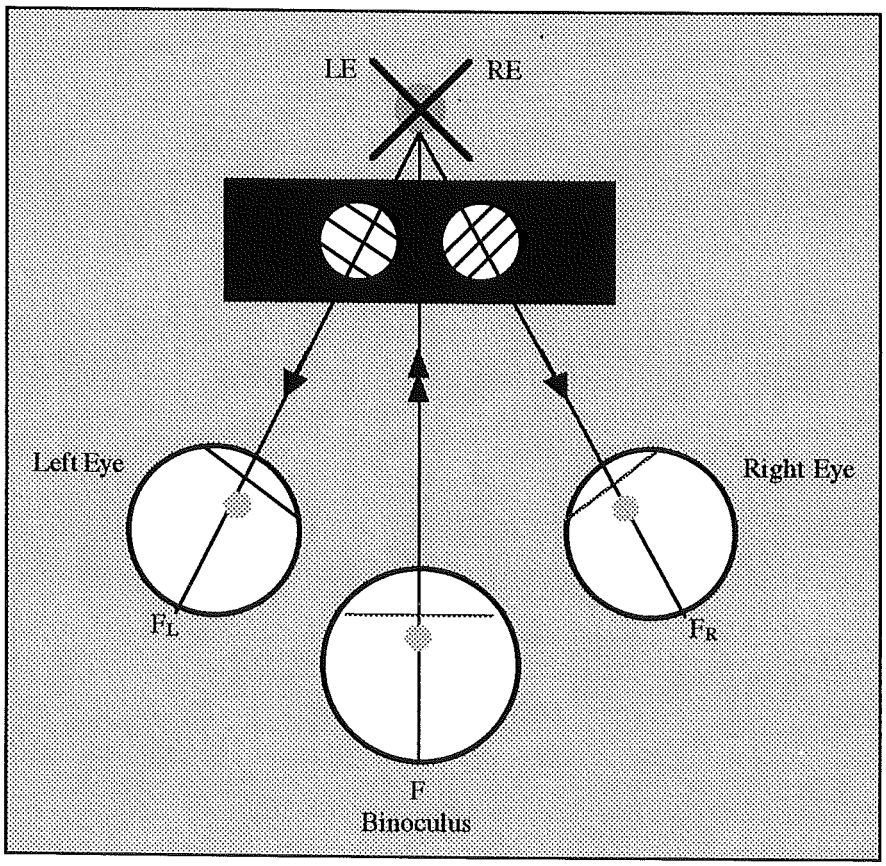


Figure 24. Illustration of the Bagolini Lornette. The retinal points in each eye, used for fixation under binocular conditions of viewing (the fovea of the left eye (F_L), the fovea of the right eye (F_R)) are stimulated by the fixation object, the spotlight. As the foveae project to the same point in space (represented by the foveae on the binoculus (F); the images of the lines of light are perceived to be emanating from the fixation object, the spotlight. (Incident rays are denoted by single arrows, and outward arrows mark the projection of the direction of gaze from the binoculus).

In esotropia, the fixation object falls on the fovea of the fixating eye but on a nasal retinal point in the squinting eye (Figure 25). However, if ARC has developed, the fovea of the fixating eye (FL) and a nasal point (X) in the squinting eye correspond under binocular conditions of viewing. Consequently, a saltire is perceived (Figure 25). Anomalous BSV is always encountered in individuals with small angled squints, called microtropias, and may also be present in some individuals with larger angled squints. However, not all strabismics exhibit BSV.

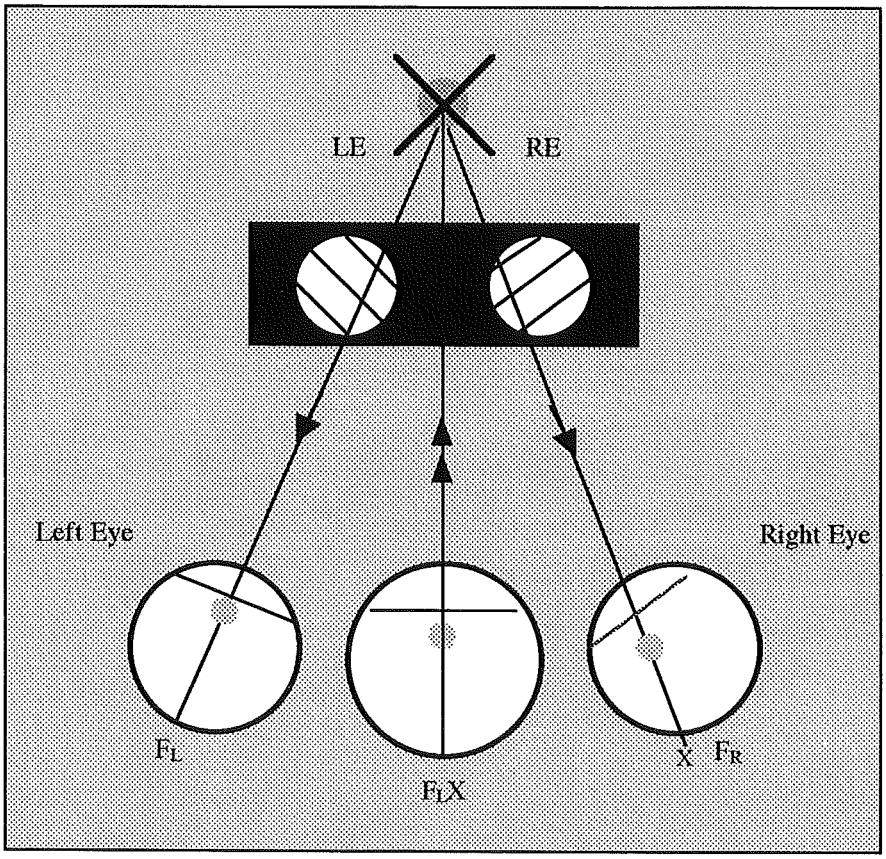


Figure 25. The Bagolini Lornette. A BSV response occurring in a right esotropia with anomalous BSV. The fixation object, the light, stimulates the fovea of the fixating left eye (F_L) and a nasal point, X, in the squinting right eye. X in the squinting eye corresponds to and has a common visual direction with the fovea of the fixating eye. Consequently, a saltire is perceived.

Strabismic individuals without BSV demonstrate suppression which is the non-perception of images of objects situated in a particular part of the visual field by the squinting eye. Suppression may be of two types, central suppression and peripheral suppression. In cases of larger angle esotropia, suppression occurs at the fovea of the squinting eye, at the extra-macular point and at the intervening retina (Figure 12B). Therefore, on examination with Bagolini Lornette, the visual input from the striation falling on the retina of the squinting eye is totally suppressed and only the visual input from the striation falling on the fixating eye is seen (Figure 26A). Thus, what is termed a peripheral suppression response is reported. In microtropia, since suppression of the image falling in the foveal region of the squinting eye occurs while the extra-

macular point is used as a pseudo fovea, only central suppression is evident and the outer parts of the striation are still perceived. (Figure 26B).

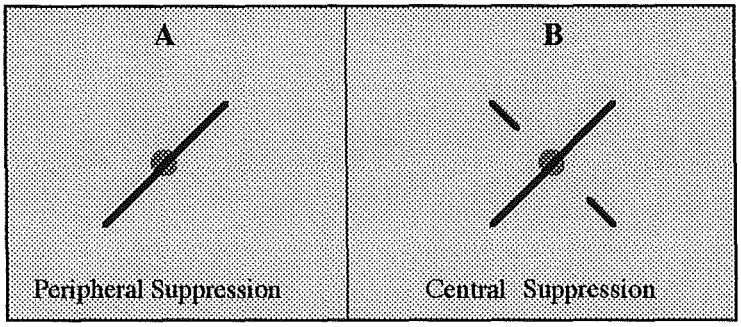


Figure 26. Illustration of suppression response in strabismus with Bagolini Lornette.
A: Peripheral suppression, *i.e.* complete suppression of one eye, typically exhibited in moderate angle right esotropia. Only the striation seen by the left eye is reported.
B: Central suppression response encountered in microtropia. Both striations are seen but the striation perceived by the right eye is incomplete because of the presence of suppression in the foveal region.

2.4.3 Worth's Lights (Macular)

This test, which is a partially dissociative test based on colour dissociation, was undertaken to confirm the presence of bifoveal fixation in heterophoria or, alternatively, central suppression in micro-strabismus. The macular Worth's Lights comprise a sleeve containing four small apertures. Each aperture is covered with a filter (one red, one white and 2 green filters). The filters are arranged like the cardinal points of a clock face (red-12 o'clock; the two green filters - 9 o'clock and 3 o'clock; white filter - 6 o'clock (Figure 27).

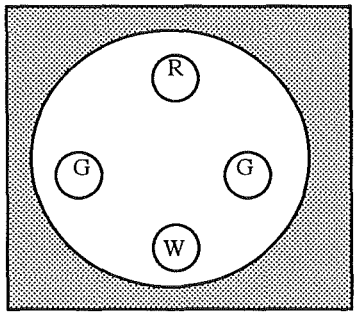


Figure 27. Diagrammatic representation of Worth's Four Lights (Macular) with the right eye viewing through the red filter and the left eye viewing through the green filter. The red light is seen by the right eye, the two green lights are seen by the left eye and the filtered version of the white light is seen by both eyes.

The sleeve is slipped over a pen torch and the stimulus is then fixated by the individual. The angular subtense of each of the coloured lights is so small that the image of the entire display falls within the foveal region. They can therefore only be used to determine the presence of central suppression and not peripheral suppression.

Red and green filter glasses were placed in front of the subject's eyes (a red filter in front of the right eye and green filter in front of the left eye), and the subject was then instructed to fixate Worth's Lights held at 0.3m in a darkened room (Figure 27). The red light is perceived by the right eye, the green lights by the left eye and the filtered version of the white light by both eyes. In the presence of normal BSV, when the foveae project to the same point in space, the four lights in their correct formation are perceived (Figure 27). In the presence of central suppression in a right micro-esotropia, for example, the visual input to the fovea of the squinting eye is normally suppressed; thus, if the red filter is in front of the right eye, only three green lights will be seen.

2.4.4 The Four Dioptre Prism Reflex Test

The four dioptre prism reflex test was used to confirm the presence of normal BSV (Irvine, 1944) or central suppression (Romano, 1969). This test is based on the response of the eye to a prism placed in front of it (Figure 28). A prism deviates light towards its base and thus, the image of the object of regard is deviated toward the apex of the prism. A four dioptre prism, base-out for esophoria and base-in for exophoria, was placed in front of one eye whilst the subject fixated a target at 0.3m. In the presence of normal BSV, when the 4^ prism (equivalent to 2 degrees), with the base appropriately placed, was placed in front of one eye, a conjugate movement of both eyes, 2 degrees in the direction of the apex of the prism was seen. Non-corresponding retinal points were therefore stimulated and diplopia was momentarily appreciated. Diplopia is a stimulus for fusion and thus, a subsequent fusional movement of the uncovered eye to regain bifoveal fixation was observed.

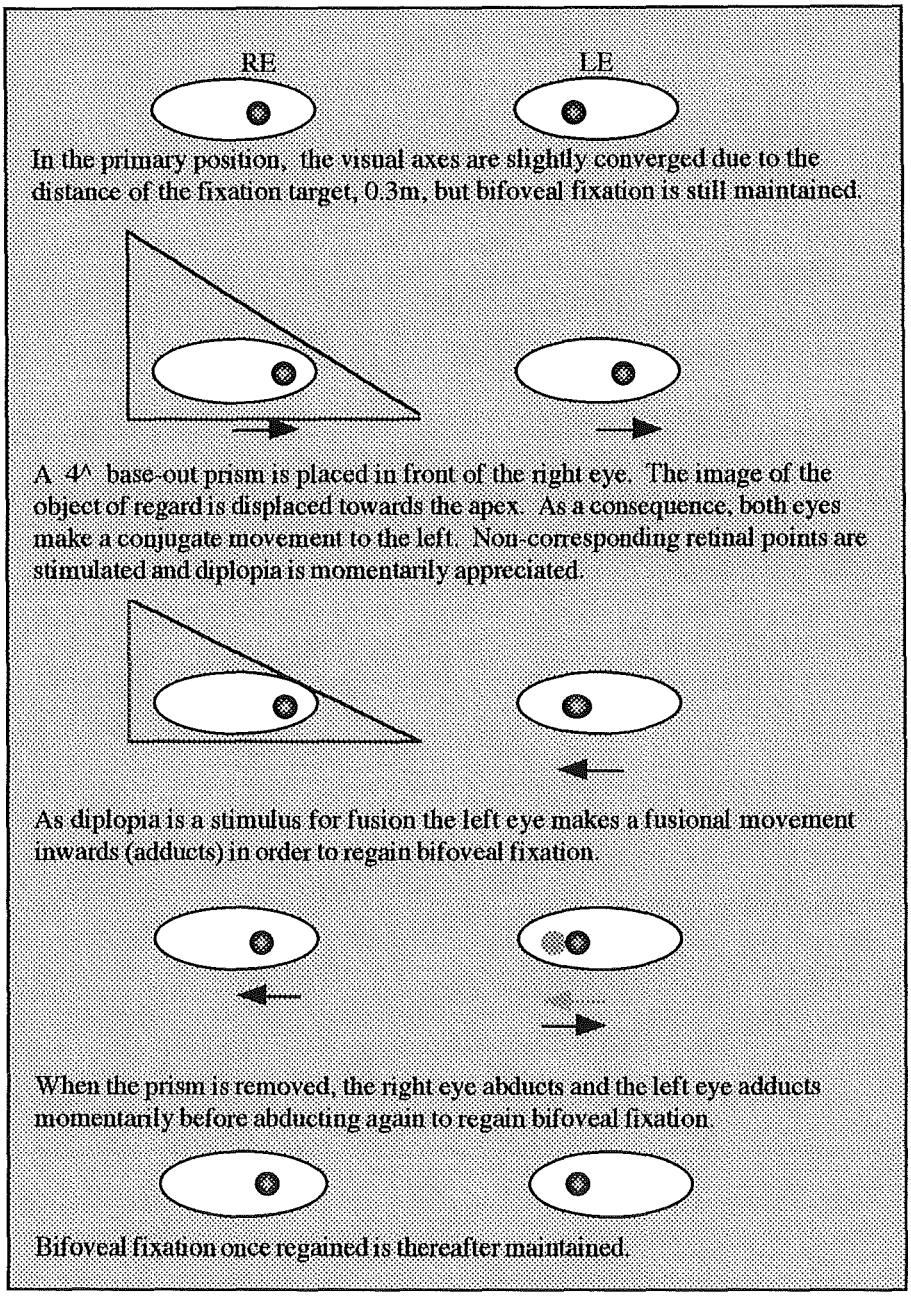


Figure 28. Diagram illustrating the response of the 4^ prism test in the presence of bifoveal fixation at 0.3m.

In the presence of central suppression in a left microtropia, the following is observed (Figure 29). When the base-out prism is placed in front of the fixating right eye, a conjugate movement of both eyes in the direction of the apex of the prism is seen. At this point, non-corresponding retinal points are stimulated. However, because of the presence of microtropia, the image of the

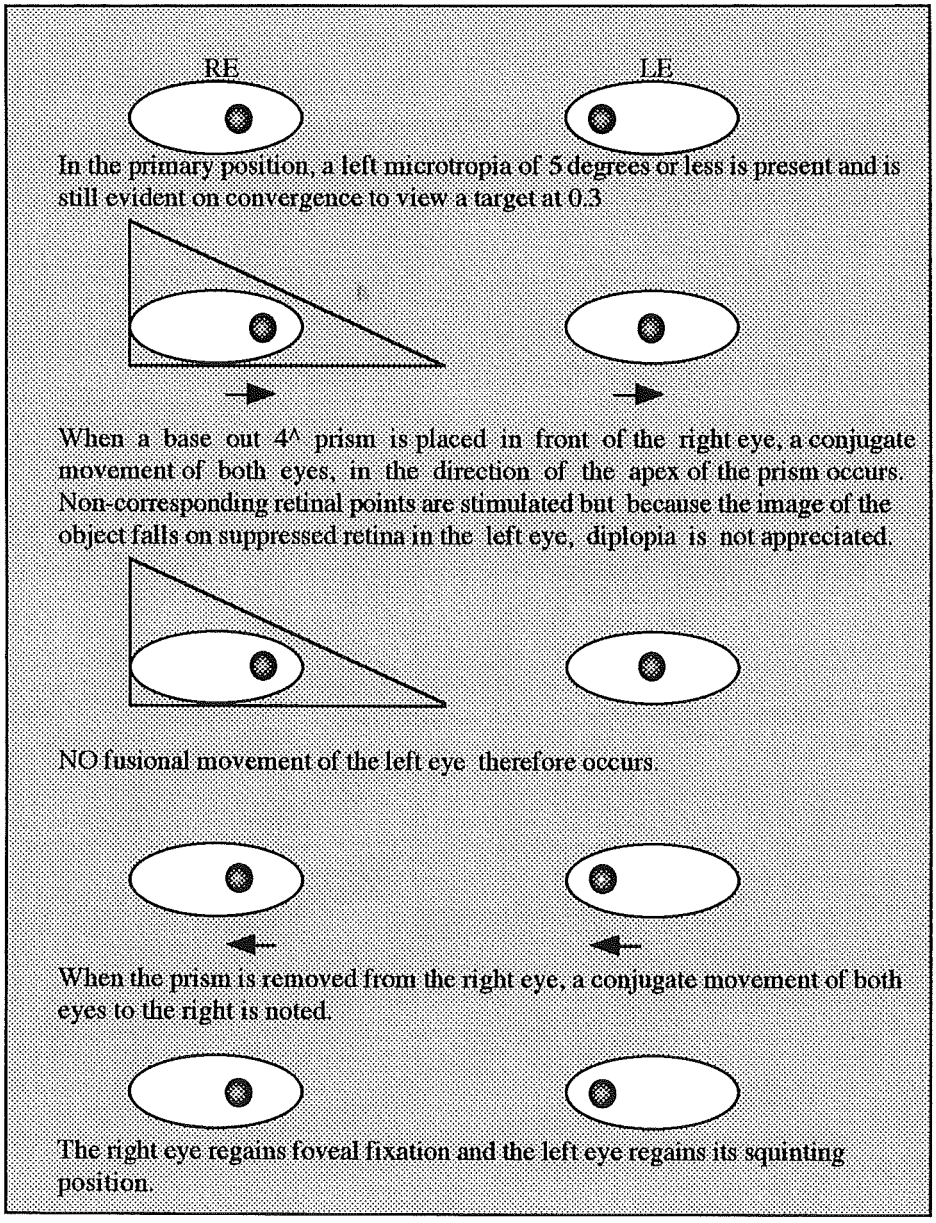


Figure 29. Diagram illustrating the Response of the 4^ prism test in the presence of central suppression in left microtropia.

object of fixation falls on suppressed retina in the squinting left eye and therefore no diplopia is appreciated. As a consequence, no fusional movement of the left eye is noted (Figure 29). To confirm this, the 4^ prism is placed base-out, in front of the squinting left eye. The image of the object of regard stimulates suppressed nasal retina therefore no movement of the left eye occurs

and thus no movement of the right eye is observed. This response confirms the presence of central suppression.

2.5 Measurement of the Angle of Heterophoria and Heterotropia

The prism and cover test is, in fact, the prism and alternate cover test. It measures the combined angular deviations arising from heterophoria and heterotropia (each of which may be present in varying magnitude) and the resultant value is the total angle of deviation. The simultaneous prism and cover test is only used in microtropia without identity and the resultant value is the angle of heterotropia in these cases.

2.5.1 The Prism and Cover Test

The prism and cover test is an objective, completely dissociative test used to determine the total angle of deviation (heterophoria and heterotropia) and is carried out while the subject is fixating a target at 2.43m and at 2.86m, when appropriate, the distances used in this study. The measurements at 2.43m and 2.86m were not undertaken on the same day. Initially, an alternating cover test was carried out and the direction of deviation of the eyes was noted (Figure 22). A prism of the appropriate base direction (base-out for eso deviations, base-in for exo deviation, base-down and base-up in hyper and hypo deviations, respectively) was placed in front of the dominant or non-amblyopic eye. The test was repeated and observations made of the prism power which was increased until no movement of either eye, to take up fixation, was observed. At this point, neutralisation of the total angle of deviation had been achieved. Reversal of the deviation occurred with a further increase in the prism strength. Thereafter, the strength of the prism was decreased until, once again, no movement was seen. The strength of the prism with which no movement occurred represented the total angle of deviation.

2.5.2 The Simultaneous Prism and Cover Test

In cases of microtropia without identity, a simultaneous prism and cover test

(SPCT) (Dale, 1982) was undertaken in order to determine specifically the angle of heterotropia.

The subject was instructed to fixate a target at test distance (either 2.86m or 2.43m). Once steady fixation was obtained, a prism of the appropriate base direction was placed in front of the squinting eye. At the same time, an occluder was held in front of the fixating eye. Movement of the eye under the prism was noted. The prism power was gradually increased and the process repeated. Neutralisation of the angle of microtropia was deemed to have occurred when no movement of the eye under the prism was seen on covering the fixating eye.

2.6 Measurement of the Amplitude of Accommodation

In order to determine if sufficient accommodation was available for the purposes of the test, and therefore ensure clarity of the visual stimulus at the testing distances, (2.86m and 2.43m), measurement of amplitude of accommodation was undertaken, the minimum requirement being about 0.4D for the viewing distances. Thus, accommodation was measured in all participants. The amplitude of accommodation was quantified using convex and concave spherical lenses and the Snellen test type at 6m. After the smallest line which could be clearly seen was fixated by the subject, increasing powers of concave lenses were placed in front of this eye while the companion eye was occluded. Time was allowed for the subject to alter the accommodative effort and then the subject was asked to state whether the line of letters on the Snellen test type was clear or if they remained blurred. The measure of accommodative effort was taken as the strength of the lens just less than that with which blurred vision was experienced. In order to ensure that the subject did not have an small, uncorrected amount of hypermetropia, convex lenses were then placed in front of the eye and the examination repeated. The companion eye was then tested in the same way. The amplitude of accommodation was the total power of the lenses, in dioptres, with which clear acuity was maintained. Thus, the

maximum accommodative effort available was the accommodation exerted with concave lenses plus the strength of any small convex lens required for clarity of the Snellen test type when read at 6m. This was recorded without regard to toleration of defocus blur which amounts to some 0.25D (Campbell, Robson, and Westheimer, 1959). This method of assessing the amplitude of accommodation was deemed preferable to that of the RAF near point rule as it eliminated the effects of proximal convergence and fusional vergence which could influence the findings, albeit not greatly (Lyle and Wybar, 1967).

The horizontal diameter of the pupils was also measured using the millimetre rule on the handle of the Romanes occluder, the instrument used to perform the cover tests.

2.7 Measurement of Contrast Sensitivity Function

2.7.1 Apparatus

A vertical sinusoidal grating pattern was generated on a Tektronix 606B monitor. The time base of the monitor was provided by the ramp output of the time base amplifier of a Tektronix 5103 oscilloscope running at 0.5ms/div, which was fed into the X input of the monitor. A uniform green raster was generated by feeding a 770 KHz triangular wave into the Y input of the monitor. Sinusoidal modulation of this uniform green raster in the horizontal direction was achieved by feeding the output of a Farnell LFP1 oscillator into the Z input of the monitor. The grating pattern was held stationary by feeding the trigger output of the oscillator into one of the vertical amplifiers of the Tektronix 5103 oscilloscope which was set to internal trigger mode *i.e.*. it was thus triggered by the signal from the oscillator. Therefore, the ramp output of the Tektronix 5103 oscilloscope was generated at the same point on the sine wave cycle fed into the Z input of the monitor. The Z modulation sine wave was displayed on a separate Tektronix 5103 oscilloscope which allowed the frequency of the Z modulation sine wave to be set to an accuracy of within 1%, and which allowed the peak to peak Z modulation voltage to be measured to an

accuracy of within 2.5%. The screen dimensions subtended 2 degrees horizontally and 1.5 degrees vertically when viewed from 2.86m, the distance of the first set of experiments. The display luminance, measured with a UDT S370 Optometer, was relatively stable during the period of experimentation, varying slightly between 8.3cd/m^2. and 8.5cd/m^2, with a mean of 8.4cd/m^2.

2.7.2 Calibration

The contrast of the vertical sinusoidal grating pattern was expressed as the Michelson Contrast Ratio (Lmax - Lmin /Lmax + Lmin). The calibration graph between contrast and sine wave amplitude was determined psychophysically by the method of Campbell and Green (1965), in order to relate the contrast of the sinusoidal grating pattern on the monitor to the pattern Z modulation voltage.

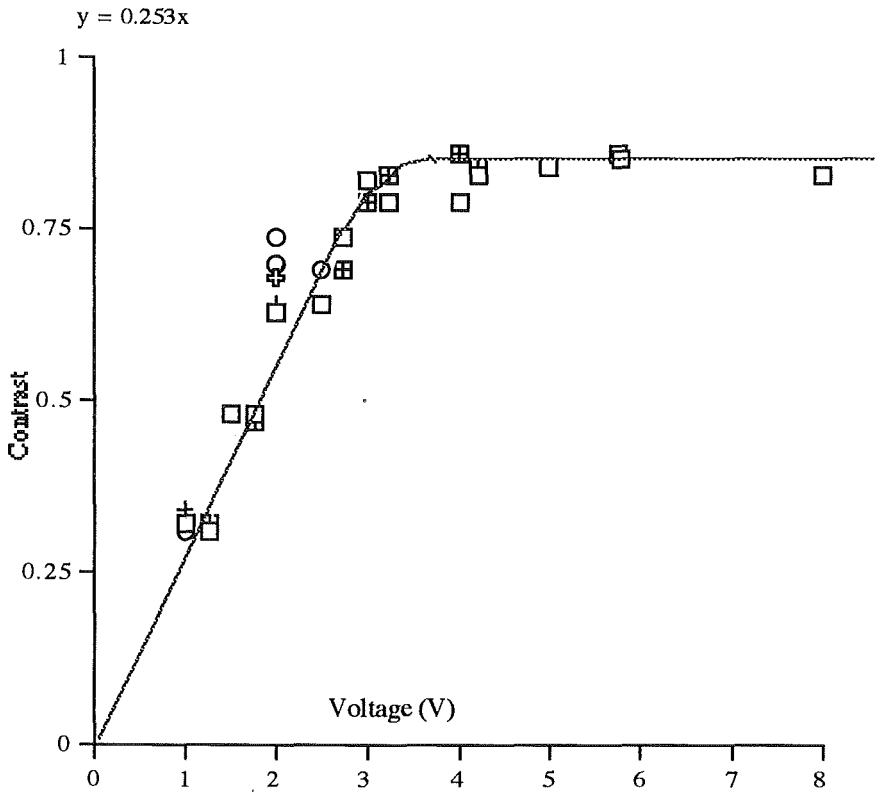


Figure 30. Calibration Graph of contrast against Z modulation voltage for the 606B Monitor. The symbols represent the readings obtained for three subjects examined on two occasions. Each subject is represented by a different symbol.

One cycle of a very low frequency square wave grating display was viewed through a vertical rectangular window. In one half of the window, on the side overlying the brighter half of the square wave cycle, was placed a calibrated neutral density filter while the other half cycle was unattenuated. The Z modulation voltage was adjusted so that the two halves of the window were judged to be of equal luminance. At this point, L_{min} of the Z modulation voltage was equal to L_{max} multiplied by the transmissivity of the neutral density filter from which the contrast was calculated. This was repeated for 0.1 logarithmic unit steps of neutral density filter for 3 subjects, and the results are shown in Figure 30. The resultant graph was a straight line with a slope of 0.253 contrast units/V peak to peak voltage up to a contrast of 0.75 above which saturation occurred. For voltages below 3v, contrast was determined by calculation (the mean voltage was multiplied by the calibration factor 0.253) while for 3v and above, the contrast was read directly from the calibration graph.

2.7.3 Experimental Procedure

Subjects wore the appropriate spectacle correction: the experiment was conducted in a darkened room with no natural illumination, and instructions were standardised for all subjects. The subject operated a control unit which, by a ten turn potentiometer, allowed fine control of the Z modulation voltage and hence of contrast. After the initial presentation of the grating pattern at high contrast to acquaint the subject with the stimulus to be detected, the subject was instructed to turn the potentiometer down, so that the CRT presented a uniform screen, and thereafter increase it until the grating pattern was just visible. The subject verbally indicated when the grating pattern was just discernible and the Z modulation voltage was recorded. At the end of each determination, the participant was instructed to look away from the display screen for a short time in order to reduce the possibility of adaptation at the spatial frequency under test (Blakemore and Campbell, 1969).

This was repeated to obtain six measurements from which the mean contrast threshold was calculated. In order that subjects could not relate the number of turns of the potentiometer to the perception of a grating pattern, the output of the oscillator was altered after each presentation by the researcher. Complete practice runs were undertaken at 10, 20 and 30 c/deg in order to allow the subject to become familiar to the task in hand; the main determinations were then undertaken. These were required to be completed in a single session as repeatability has been shown to occur if measurements are carried out in the same session, but a step shift in contrast threshold levels may arise if the sessions are split (Kay and Morrison, 1987).

Subjects comprising the normal group were examined first of all. Stationary vertical sinusoidal grating patterns with spatial frequencies of between 10c/deg and 40c/deg, (10, 15, 20, 25, 30, 35, and 40 cycles per degree) in order to examine the high spatial frequency limb of the contrast sensitivity function, were presented in random order. The contrast thresholds were measured for the right eye while the left eye was occluded, and then for the left eye while the right eye was occluded, at the same spatial frequencies, presented in the same order. When measurement of the monocular contrast thresholds had been completed, the occlusion was removed and the experiment was carried out under binocular conditions of viewing. The total experimental time was between 3 to 4 hours and breaks of 10 to 20 min were taken, as appropriate. All readings were obtained with natural pupils.

When the investigation of the normal group was completed, the amblyopic and/or strabismic subjects were then examined. In these cases, the non-amblyopic or fixating eye was always examined first whilst the companion eye was occluded. The amblyopic and/or squinting eye was then investigated. Since the amblyopic and/or squinting eye could not discern the higher spatial frequencies thus truncating the range of spatial frequencies, an additional spatial frequency at 8c/deg was tested in these subjects. Binocular contrast thresholds

were then measured. The time taken to complete the experiments in the amblyopic and/or squinting individuals varied considerably and this group of subjects required more short breaks than those individuals comprising the normal group.

2.8 Neutralisation of the Angle of Strabismus in Squinting Subjects.

Once the monocular and binocular experiments were completed in the amblyopic and/or strabismic individuals, an additional experiment was undertaken whereby the angle of strabismus was neutralised and the contrast thresholds measured. This experiment was carried out on the same day as the monocular and binocular measurements of contrast threshold just described.

Esotropes (both with BSV and without BSV) and exotropes (without BSV) constitute a single group with respect to the correction of the angle of heterotropia. Under binocular conditions of viewing, the object of regard stimulates an eccentric retinal point displaced from the fovea by the angle of heterotropia. Under monocular conditions of viewing, the fovea takes up fixation when the fixating eye is occluded. Thus, in these strabismic subjects, contrast thresholds for binocular viewing were measured after correction of the squint with a prism of appropriate strength and orientation, in order to determine if the contrast thresholds differed when enforced stimulation of a point, other than the eccentric point used under binocular conditions of viewing, occurred. The power of the prism required to fully correct the strabismus and effect bifoveal stimulation, was determined by the prism and cover test (see Methods, page 91). Thus, bifoveal stimulation was effected in strabismic subjects in whom only one eye normally viewed foveally while the other, strabismic eye, normally viewed non-foveally or was suppressed, and the contrast sensitivity for binocular viewing was obtained.

The power of the prisms required to neutralise the angle of deviation was divided between the eyes in order to minimise possible degradation due to the

presence of the prism (see later); the prism (s) was placed in a trial frame or attached to the existing spectacle correction. In the majority of cases, as the angle of deviation did not exceed 16^, the power of the prism in front of each eye was seldom greater than 8^.

A different procedure was necessary with respect to microtropes. First, microtropes with identity use the same eccentric fixation point under binocular and monocular viewing conditions and thus do not have a measurable angle of squint. However, no subjects fell into this category. The subjects in the present study were microtropes without identity. In these cases, an eccentric point is used for fixation under monocular conditions of viewing; when viewing binocularly the eye deviates to a greater angle and a different eccentric point is used for fixation thus, these microtropes have a measurable angle of squint. A glass prism equal to the angle between the eccentric point used under binocular conditions and the eccentric point used under monocular conditions of viewing was placed in front of the deviating eye and the contrast thresholds measured. A similar procedure was undertaken in the one strabismic subject with a moderate angle squint in whom eccentric fixation was also present.

2.9 Control Experiment on Prismatic Correction

In order to determine if the glass prism *per se* optically degraded the image and, therefore, adversely affected the contrast threshold, contrast thresholds were measured uniocularly, with prism powers ranging from 2^ to 12^ in four normal subjects. The companion eye was occluded and the prisms were either placed in a trial frame or attached to the spectacle lens directly. Contrast sensitivities at spatial frequencies of between 8c/deg and 40c/deg, viewed at 2.86m, with each power of prism appropriately placed (base-out with esophoria and base-in with exophoria) (2^, 4^, 6^, 8^, 10^, 12^) were measured and compared to the contrast sensitivities obtained without the prism. The duration of the experiment ranged between 2 and 3 hours and all readings were obtained in the same session.

2.10 Dichoptic Viewing Experiments

In non-squinting individuals *viz.* those comprising the normal group and the simple anisometropic amblyopes, it was not possible to use a prismatic correction to investigate the effect of stimulation of non-corresponding retinal areas on binocular contrast sensitivity. While the prism would initially disrupt normal BSV and result in the appreciation of diplopia due to stimulation of non-corresponding retinal points, the fusional mechanism would subsequently be exercised and fusion would occur, rendering the prism experiment ineffective. Thus, in order to effect stimulation of non-corresponding retinal points to determine the effect on binocular contrast sensitivity in these normal and non-strabismic amblyopes, the grating displays had to be presented under dichoptic conditions of viewing. The dichoptic experiments also provided an opportunity to validate the experiments in strabismic subjects using a prismatic correction.

2.10.1 Apparatus

The stimulus display consisted of a Tektronix 606B cathode ray tube (CRT) and a green light emitting diode (Led), 2mm in diameter, which was located 2 degrees to the left of the centre of the CRT, on the horizontal axis through the centre of the CRT (*e.g* Figure 32B). The CRT generated a vertical sinusoidal grating pattern which subtended 2 degrees by 2 degrees at a distance of 2.43m from the subject. This CRT was different from that used in the previous experiments and had a contrast-voltage relationship of 0.391 contrast units/V peak to peak voltage up to 1.5v above which it was curvilinear. Readings above 1.5 volts were thus read directly from the calibration curve. The Led provided a method by which steady fixation could be achieved and thus allow the grating pattern to be projected onto extra-foveal retina of non-strabismic subjects.

The images of the sinusoidal grating pattern and Led were divided by a beam splitter (BS) and two light paths for the sinusoidal grating pattern and the Led were created (Figure 31). The beam reflected by the beam splitter (BS) was then reflected 90 degrees by a rotatable front silvered mirror (M*) so that it was viewable by the right eye of the subject (all mirrors were $\lambda/20$ flatness).

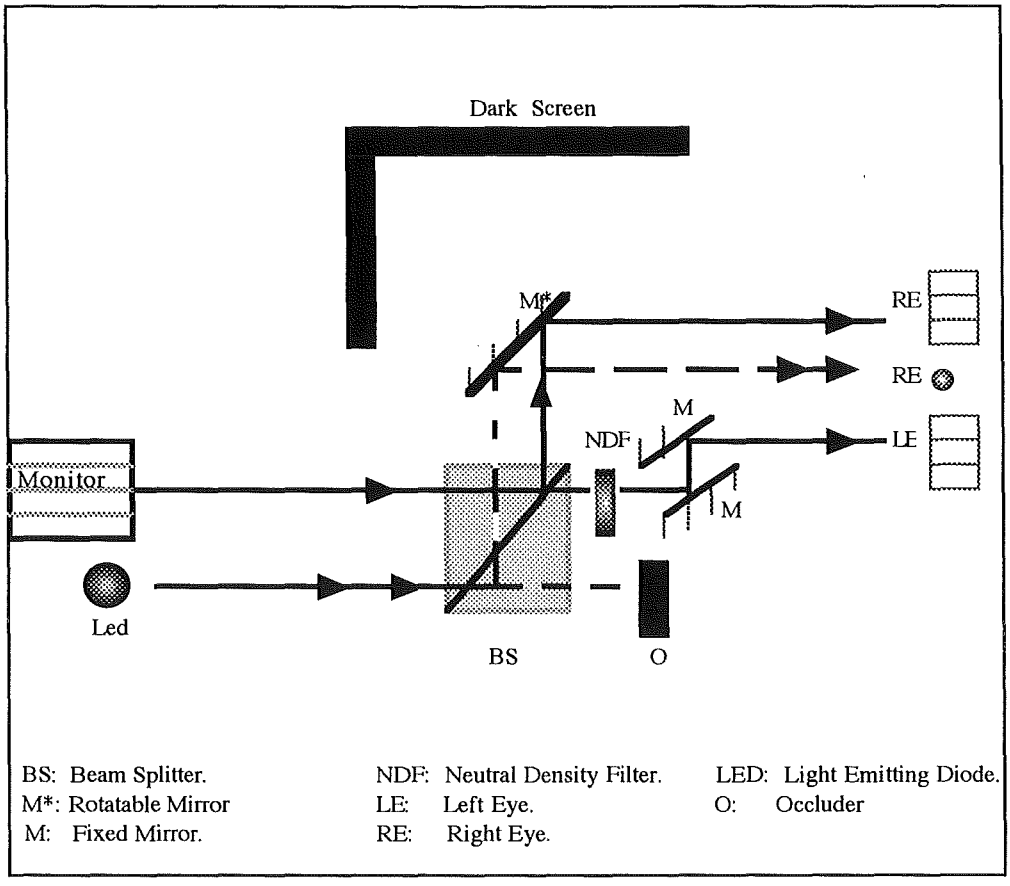


Figure 31. Diagram illustrating the dichoptic viewing apparatus used for normal subjects. The left eye viewed the grating pattern without the Led while the right eye viewed the grating pattern and the Led. For further details see text.

The beam transmitted by the beam splitter (BS) was then reflected at 90 degrees by each of the two fixed front silvered mirrors so that it was viewable by the left eye of the subject. This beam was attenuated with respect to the right eye beam

with a neutral density filter (NDF) in order to equalise the intensities of the two beams. Thus, each beam carried the images of the CRT and the Led (positioned to the left of the CRT). In the first instance, both images were permitted to pass into the right eye. In the case of the left eye, the image of the Led was occluded by the occluder (O) so that this eye received only the image of the CRT. This arrangement was changed for the experiments on strabismics (see later).

2.10.2 Experimental Procedure for Normal Subjects and Simple Anisometropic Amblyopes.

The subject viewed the stimulus with the head stabilised in a chin rest. This was arranged so that the left eye readily viewed the image of the CRT alone, but not of the Led, which had been occluded. Adjustments of the other beam were made with the rotatable mirror (M*) so that both the CRT display and the Led were visible to the right eye. In the experiments to be described, the contrast sensitivities at between 5c/deg and 35c/deg were presented in random order.

First, contrast thresholds were measured for left eye monocular viewing of the grating pattern alone. Thus, the grating pattern was presented to the left eye, which was viewed by the fovea of that eye, and the right eye was occluded as shown schematically in Figure 32A.

Second, it was necessary to determine the effect of the superimposition of the Led (seen by the right eye) on the contrast sensitivities of the left eye. Therefore, the grating pattern was presented to the left eye as before, and the Led was presented to the right eye. As both foveae are stimulated, the Led which stimulated the fovea of the right eye is superimposed on the grating pattern viewed by the fovea of the left eye. A grating pattern with a green Led superimposed in its centre was therefore appreciated (Figure 32B).

Third, in order to simulate the presence of a small esotropia, it was necessary to carry out the experiment with the image of the CRT display positioned

eccentrically in the right eye (Figure 32C). The grating pattern was therefore arranged to stimulate the right eye at 2 degrees from the centre of the fovea. This was achieved by fixation of the Led by the right eye which also viewed the eccentrically positioned grating pattern. The left eye viewed the grating pattern as before. Thus, the perceived images consisted of the grating pattern (seen by the left eye) superimposed on which was the Led (seen by the right eye) together with the nasally located grating pattern, 2 degrees from the fovea of the right eye (Figure 32C). Fixation of the Led was important to the success of this experiment and this required considerable concentration on the part of the subject, since a lapse at any time would result in foveation of the CRT display by the right eye and thus fusion of the two images. If this occurred, the subject restored the two images of the CRT by rotating the mirror (M*) to move the images of the CRT apart and then to readjust the alignment so that the Led seen by the right eye was once again seen to fall in the centre of the CRT seen by the left eye. This experiment would thus allow the determination of the effect of a nasally located grating pattern seen by the right eye on the monocular contrast sensitivities of the left eye.

In the case of the two simple anisometropic amblyopes who carried out this experiment, the monocular grating pattern was arranged to be presented to the non-amblyopic eye and the eccentrically placed grating pattern arranged to stimulate the nasal retina of the amblyopic eye.

All readings were obtained with natural pupils. The duration of these dichoptic viewing experiments varied between 1.5 and 3 hours and all readings were obtained in the same session.

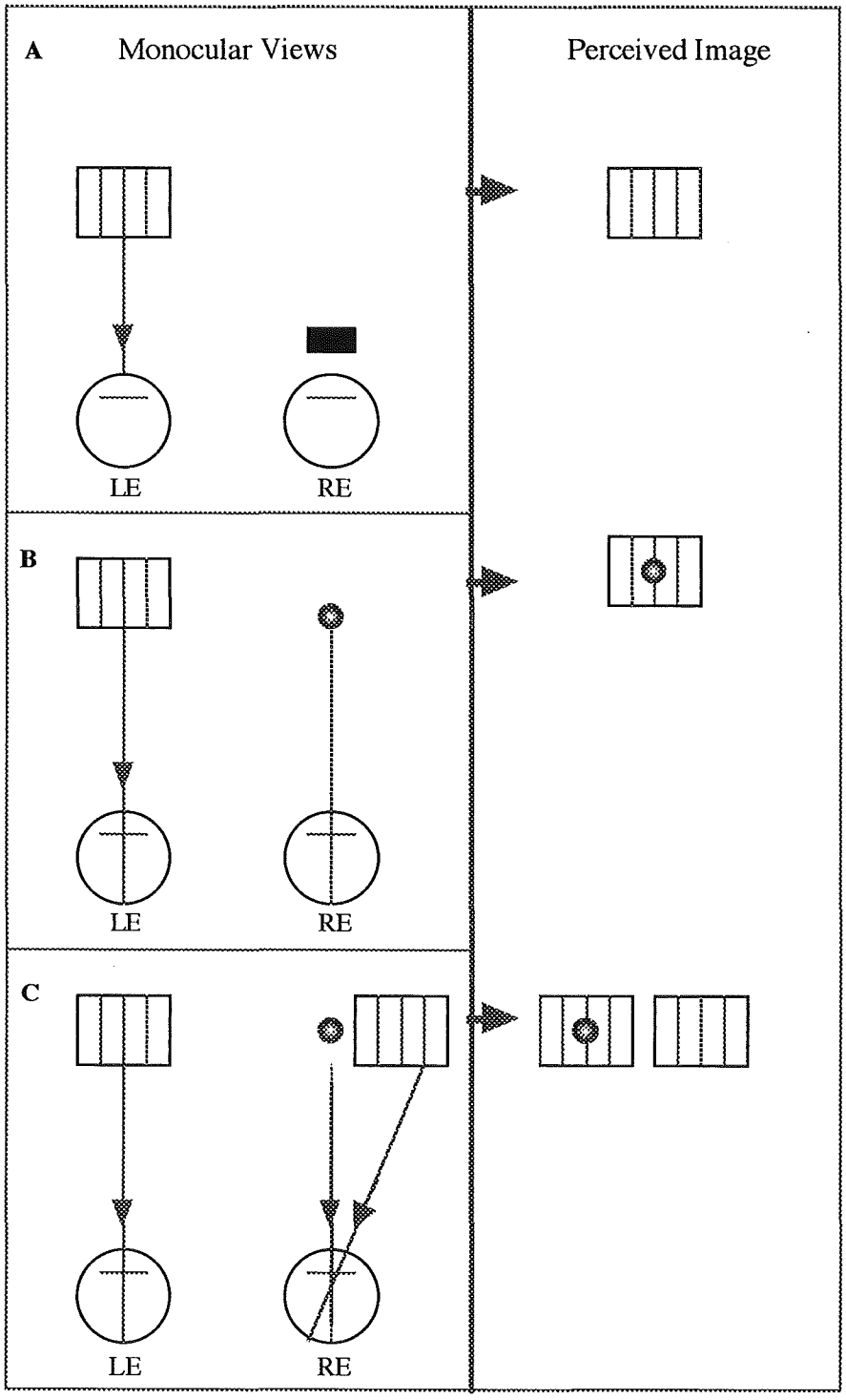


Figure 32. Diagrammatic representation of the dichoptic viewing experiment for individuals comprising the normal group. A further explanation is contained within the text.

2.10.3 Strabismic Subjects

The dichoptic viewing experiments in squinting individuals provided an opportunity to test the results of the prism experiments (Methods, page 97) *i.e.* it provided a second method of investigating the effects of neutralisation of the angle of strabismus on binocular contrast sensitivity.

The protocol for each of the strabismic subjects examined under dichoptic conditions of viewing required to be tailored for each individual. The monocular contrast thresholds of the better eye (fixating eye) and the poorer eye (squinting eye) were determined for spatial frequencies between 5c/deg and 35c/deg, whenever possible. In all cases, use of the Led to direct fixation in the strabismic eye caused enormous confusion in these participants. Thus, in these participants "free fixation" had to be permitted. The participants were therefore instructed to fixate the centre of the grating pattern with the fixating eye. With respect to the strabismic eye, the position of the grating pattern was so arranged that it stimulated the centre of the fovea of this eye. Thus, this required the measurement of the angle of heterotropia by the prism and cover test to allow the appropriate setting of the apparatus which was initially set up for bifoveal viewing of the grating patterns in normal subjects. In the strabismic subjects, the left or right beam, depending on which was the squinting eye, was translated in the appropriate direction by an angle equal to the angle of heterotropia, to effect stimulation of the fovea of the normally squinting eye (or the pseudo fovea in the case of microtropes without identity). In subjects with anomalous BSV, fusion of the two images of the grating pattern was still a problem. This was overcome, as before, by rotation of the mirror (M*), as described for normal subjects.

The dichoptic viewing experiments in these squinting individuals was, from the subjects' point of view, more difficult compared with the experience of individuals comprising the normal group. Strabismics required more re-assurance that they were performing well, a greater number of breaks were

taken and although the range of spatial frequencies examined was generally truncated, compared with the normal group, the same length of time, if not longer was taken to complete the experiment.

2.11 Group Composition and Characteristics

2.11.1 Selection

The participants in this study were recruited from staff and students at Glasgow Caledonian University, the University of Glasgow and the general public. Individuals with reported history of ocular pathology or those suffering from migraine and/or epilepsy were excluded from the study. A total of forty two individuals were examined. The age of the participants ranged from 18 years to 48 years and comprised 27 females and 15 males. Subjects comprising the normal group achieved a visual acuity of 6/6 or better in each eye. The visual acuity of those subjects comprising the amblyopic groups was 6/9 or less in the amblyopic eye. The participants were divided into one of eight groups based on the stated selection criteria.

2.11.2 The Normal Group

The normal group comprised individuals, the general criteria for selection for inclusion into this group were age, general and ocular health. The age distribution of the subjects ranged from 20 years to 45 years with a mean age of 35 years. The age range studied was below the point above which Snellen acuity and contrast sensitivity declined (Morrison and McGrath, 1985). It was important that participants had no previous history of strabismus, anisometropia or reduced visual acuity, even if it had been successfully treated, as a residual deficit in contrast sensitivity may have existed.

2.11.3 Simple Anisometropic Amblyopes

The specific criteria for selection were at least 1.00 dioptre of difference in the refractive power between the eyes in any meridian. Normal BSV and uniocular foveal fixation in both eyes on ophthalmoscopic examination were also pre-requisites.

2.11.4 Micro-esotropic Amblyopes

Individuals comprising this group of subjects exhibited a microtropia of 5 degrees (10^) or less, amblyopia in the squinting eye, central suppression at the fovea of the squinting eye, and well established anomalous BSV.

2.11.5 Esotropic Amblyopes with Anomalous BSV

A constant esotropia with associated amblyopia and anomalous BSV were the main criteria for inclusion into this group. Small and moderate angled squinters were included in this group. No individual exhibited eccentric fixation on uniocular examination of the amblyopic eye.

2.11.6 Esotropic Amblyopes without BSV

The criteria for inclusion in this group were constant strabismus, amblyopia in the squinting eye and no clinical evidence of BSV, *i.e.* the presence of constant central and peripheral suppression. The state of fixation, *i.e.* foveal (central) or eccentric uniocular fixation was not critical and, therefore, either type was included in this group.

2.11. 7 Non-Amblyopic Esotropes without BSV

This group consisted of non-amblyopic esotropes who possessed constant strabismus and no clinical evidence of BSV, *i.e.* the presence of constant central and peripheral suppression.

2.11.8 Exotropic Amblyopes without BSV

The criteria for inclusion in these cases were constant strabismus, amblyopia in the squinting eye and no clinical evidence of binocular single vision, *i.e.* the

presence of constant central and peripheral suppression. The state of fixation, *i.e.* foveal (central) or eccentric uniocular fixation was not critical and therefore individuals with or without foveal fixation were included in this population.

2.11.9 Non-Amblyopic Exotropes without BSV

The non-amblyopic exotropes in this group exhibited a constant exotropia and no clinically demonstrable binocular single vision.

2.12 Statistical Analysis

For the purposes of supporting claims of differences and establishing relationships between measurements, a range of statistical methods have been used. In particular, the paired t-test, the one sample and the two (independent) sample t-tests have been used as the data have been sufficiently continuous and normally distributed to meet the test validity criteria.

The paired t-test was employed within subject, between eye analysis; the one sample t-test was undertaken in the within group analysis and the two-sample t-test was carried out in the between group analysis.

A three factor anova was also used to investigate differences between eyes and conditions of viewing, taking account of the range of spatial frequencies and sample variation arising among different subjects.

Spearman's rank correlation test was undertaken to determine if a correlation existed between non-continuous data such as decimal acuity and angle of deviation.

All test procedures have been carried out using a 5% significance level or less and implemented using the proprietary statistical software package Minitab Version 10.

3.0 RESULTS

3.1 Investigation of Monocular and Binocular Contrast Sensitivities

3.1.1 The Normal Group

The normal group comprised 11 individuals, 2 males and 9 female participants. The age range was from 20 years to 45 years old, with a mean age of 35 years. All participants exhibited normal BSV and a visual acuity level of 6/5 or better in each eye (aided where applicable) (Table 1).

Table 1 Clinical Data for Control Group

Subject	Visual Acuity	Refractive Error	Angle of Deviation	Accommodation (Amplitude)
1	RE 6/4 LE 6/4	RE -3.25DS LE -3.25DS	N BI 4^ : D BI 4^	RE 9.5D LE 8.5D
2	RE 6/5 LE 6/5	Nil Nil	N BI 4^ : D BI 4^	RE 6.75D LE 6.75D
3	RE 6/4 LE 6/4	RE -0.75DS LE -1.50DS	N BO 4^ : D BO 2^	RE 6.25D LE 7.25D
4	RE 6/5 LE 6/5	RE -0.75DS LE -0.50DS	N BO 2^ : D BO 1^	RE 6.50D LE 5.75D
5	RE 6/5 LE 6/5	Nil Nil	N BI 4^ : D BI 4^	RE 4.25D LE 5.25D
6	RE 6/5 LE 6/5	Nil Nil	N BO 4^ : D BO 4^	RE 10.25D LE 10.25D
7	RE 6/4 LE 6/4	Nil Nil	N BI 4^ : D BI 4^	RE 4.75D LE 4.75D
8	RE 6/4 LE 6/4	RE +0.50DS LE +1.00DS	N BO 14^ : D BO 6^	RE 5.25D LE 5.00D
9	RE 6/4 LE 6/5	RE -4.75DS LE -5.50DS	N BI 4^ : D BI 2^	RE 1.75D LE 3.00D
10	RE 6/5 LE 6/5	RE -7.50DS LE -8.25DS	N BO 6^ : D BI 4^	RE 0.75D LE 0.75D
11	RE 6/4 LE 6/5	RE +1.75DS LE +2.00DS	N BI 2^ : D BI 1^	RE 1.50D LE 1.00D

Key: RE: Right Eye LE: Left Eye N: Near D: Distant BI: Base In BO: Base Out D: Dioptres of Accommodation: DS: Dioptre Sphere DC: Dioptre Cylinder ^: Prism Dioptres -: Concave Lens +: Convex Lens

3.1.1.1 Ocular Status

In 4 individuals, no refractive correction was required. The remainder exhibited, in isolation or combination, varying degrees of hypermetropia or myopia. In individuals in whom astigmatism was present this has been documented as a spherical equivalent. A cylindrical correction of 0.25 has been ignored and spherical equivalents have been rounded up or down. The refractive error ranged between +2.00DS and -8.00DS (Table 1). The amplitude of accommodation in individuals comprising this group ranged from 0.75D to 10.25D. The lowest value of 0.75D represents the available accommodation in subject 10, a high myope of 40 years of age, which was adequate for the viewing distance of the test (see Methods, page 92). The pupil diameter varied from 3mm to 5mm under room light, and in no case was there a discernible difference in pupil size between the eyes. Heterophoria was present in all cases. In 6 participants an exophoria (prism base in - BI), ranging from 1^ to 4^, was evident, and the remaining 5 participants exhibited an esophoria (prism base out - BO), the largest of which measured 14^ and the smallest 1^.

3.1.1.2 Contrast Sensitivity: Individual Data

In each subject, logarithm contrast sensitivity declined linearly over the spatial frequency range, 10-40c/deg for each of the viewing conditions *viz.* monocular and binocular. In each subject, linear regression analysis confirmed the inverse linear relationship ($R^2 > 87\%$, $P < 0.02$). The results for the subject with the most marked separation in logarithm contrast sensitivity for the three viewing conditions (Subject 2) are shown in Figure 33. For monocular viewing, logarithm contrast sensitivity for one eye, denoted the better eye or Be (right eye in Figure 33A), consistently exceeded those of the companion eye, denoted the poorer eye or Pe (left eye in Figure 33A). Binocular viewing resulted in a consistent increase over the spatial frequency range studied when compared with better eye viewing (Figure 33B). In Subject 2, the mean increase between the better eye and poorer eye in logarithm contrast sensitivity, averaged over the spatial frequencies, was 0.133 log units which is equivalent to an increase of

36% (P <0.05, paired t-test). The increase between binocular viewing and monocular viewing through the better eye was 0.173 log units, equivalent to an increase of 49% (P<0.01, paired t-test). In both cases, the increase was statistically significant.

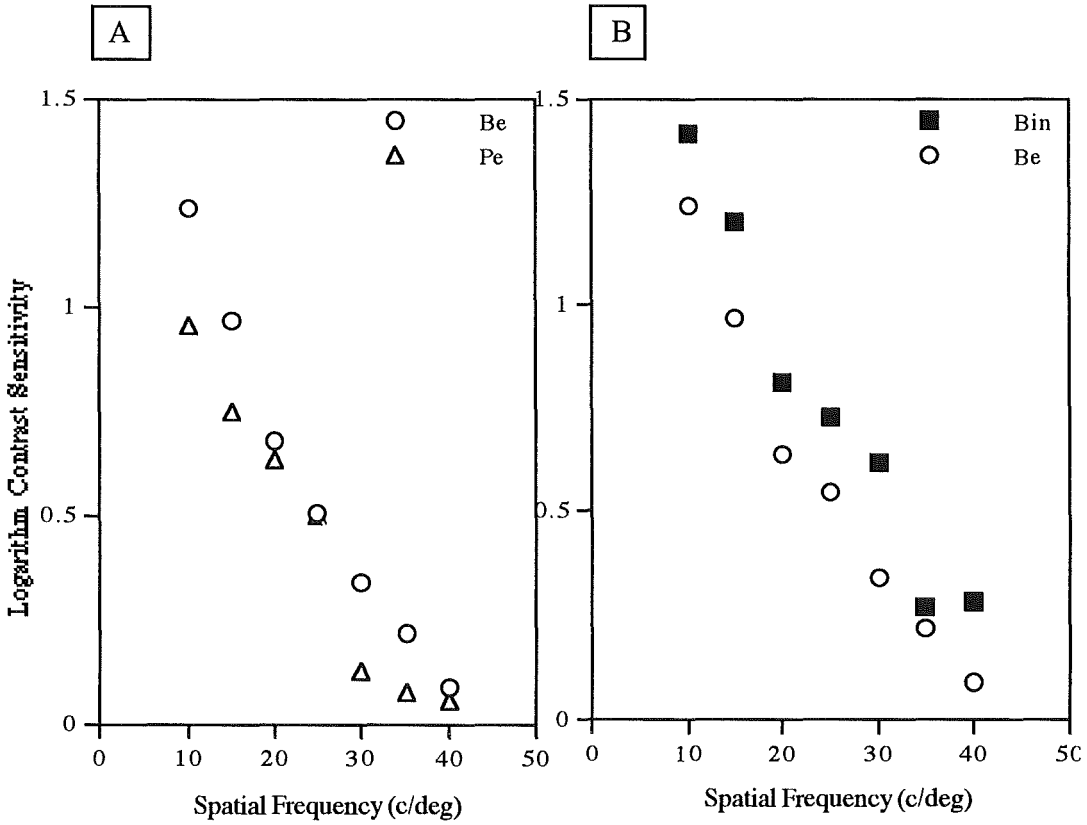


Figure 33. Logarithm contrast sensitivity against increasing spatial frequency for Normal Group Subject 2. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Monocular viewing through the better eye (Be) and the poorer eye (Pe). The best fitting regression lines were y=1.52-0.037x for the better eye (Be) (R^2 = 97%) and y=1.26-0.032x for the poorer eye (Pe) (R^2 = 95%). The slopes were statistically significant (P<0.01).
B. Monocular viewing through the better eye (Be) (same data as in **A**) and binocular viewing (Bin). The best fitting regression lines for binocular viewing (Bin) was y=1.73-0.039x (R^2 = 95%; P<0.001).

3.1.1.3 Contrast Sensitivity: Group Data

The mean contrast sensitivity functions over 10c/deg to 40c/deg for the group of 11 subjects for the three conditions of viewing are shown in Figure 34, in which the pattern shown for Subject 2 is confirmed. (The group mean logarithm contrast sensitivity at each spatial frequency was obtained by calculating the mean logarithm contrast sensitivity of the six replicates at each spatial frequency

for each subject and thereafter calculating the mean logarithm contrast sensitivity for the group at each of the spatial frequencies examined).

In this normal group of eleven subjects, there was a consistent increment of the logarithm contrast sensitivity for the better eye over the poorer eye, and for binocular viewing over monocular viewing through the better eye (Figure 34 A and B respectively). At each spatial frequency, with the exception of 10c/deg, when the better eye (Be) was compared to the poorer eye (Pe), the difference was statistically significant ($P<0.01$, paired t-test) (Figure 34A). There was also a significant difference at each spatial frequency, with the exception of 35c/deg, for binocular viewing over monocular viewing with the better eye ($P< 0.01$, paired t-test) (Figure 34B).

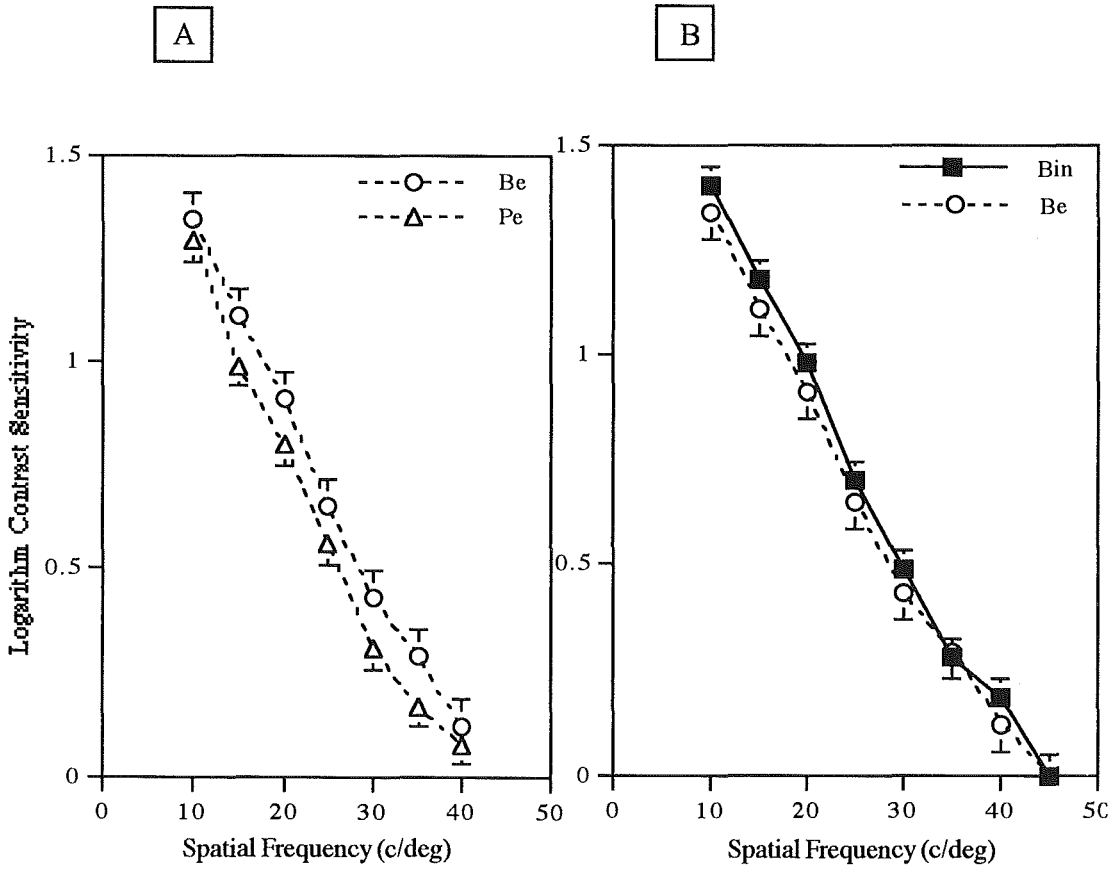


Figure 34. Logarithm contrast sensitivity against increasing spatial frequency for the normal group (n=11). Points shown represent the mean ± the pooled standard error of values for each of 11 subjects. Each of these values was itself the mean of 6 determinations.

A. Monocular viewing through the better eye (Be) and the poorer eye (Pe).

B. Monocular viewing through the better eye (Be) (same data as in **A**) and binocular viewing (Bin).

Within the mean data shown in Figure 34, there was a range of differences in contrast sensitivity between the data for the 11 subjects for each of the three viewing conditions. For each subject, the mean increase in linear contrast sensitivity averaged over the spatial frequencies studied in that subject is shown in Table 2 for monocular viewing *i.e.* better eye compared with poorer eye, and for binocular viewing *i.e.* binocular viewing compared with monocular viewing through the better eye.

Table 2 Increase in linear contrast sensitivities averaged over spatial frequencies studied between better and poorer eye and between binocular viewing and better eye in normal group subjects.

Subject	Better Eye vs Poorer Eye $\frac{(Be - Pe)}{Pe} \times 100\%$	Binocular vs Better Eye $\frac{(Bin - Be)}{Be} \times 100\%$
1	+40% ± 14% *	+16% ± 3% **
2	+36% ± 13% *	+49% ± 10% **
3	+28% ± 9% *	+ 7% ± 7% ns
4	+21% ± 9% *	+11% ± 4% *
5	+75% ± 33% ns	+11% ± 4% *
6	+23% ± 8% **	+ 6% ± 3% ns
7	+ 6% ± 4% ns	+19% ± 7% *
8	+ 7% ± 4% ns	+ 3% ± 2% ns
9	+12% ± 4% *	+ 7% ± 3% *
10	+66% ± 20% *	+32% ± 17% ns
11	+30% ± 9% *	+ 3% ± 7% ns
Mean	**+31% ****	**+15% ****

Each value is mean ± SE over the spatial frequencies tested in each subject.
Be - Better Eye; Pe - Poorer Eye; Bin - Binocular Viewing;
ns - $P>0.05$; * $P<0.05$; ** $P<0.01$.

The increase with the monocular viewing condition ranged from 6% ± 4%SE up to 75% ± 33%SE, (the difference of 75% for subject 5 was obtained even though the Snellen acuity through both eyes in that subject was 6/5). The mean differences in contrast sensitivity for the comparison between better eye and poorer eye viewing, with the exception of Subjects 5, 7 and 8, were statistically significantly different. A group mean increase of 31% ± 7%SE (n = 11; t =

4.64; P = 0.001; one sample t-test) was recorded (Table 2) .

A further more detailed analysis was undertaken using a 3-factor analysis of variance (ANOVA). This provided F-tests for significant differences among subjects, among spatial frequencies and between eyes, taking account of other factors. There was evidence of significant variation among subjects (F = 148.78; P <0.001). The between eye analysis indicated a significant difference between the better and the poorer eyes with the better eye exhibiting greater logarithm contrast sensitivity values compared with the poorer eye (F = 154.83; P< 0.001). The logarithm contrast sensitivity across the range of spatial frequencies was also significantly different (F=1873.99; P <0.001) and inspection of the means indicated that the logarithm contrast sensitivity reduced, relatively uniformly, with increasing spatial frequency.

The increase with binocular viewing ranged from 3% ± 2%SE to 49% ± 10%SE. The mean percentage differences for binocular and better eye viewing, with the exception of Subjects 3, 6, 8, 10 and 11, were statistically significantly different as was the mean of the differences for the group as a whole. The group mean binocular percentage contrast sensitivity was 15% ± 4%SE (n = 11; t = 3.5; P = 0.006; one sample t-test) greater than that of the better eye (Table 2).

A 3-factor ANOVA confirmed significant differences amongst subjects comprising this group (F = 186.45; P < 0.001). The binocular contrast sensitivity for the group was greater than that obtained with the better eye (F = 81.64; P <0.001) and the mean logarithm contrast sensitivity was again, significantly different across the range of spatial frequencies (F = 2942.85; P < 0.001).

The data shown in Figure 34 have been replotted in linear form to show the differences between the better eye and the poorer eye, and between binocular viewing and monocular viewing with the better eye at each spatial frequency, with the contrast sensitivities for the better eye expressed in each case as 100%.

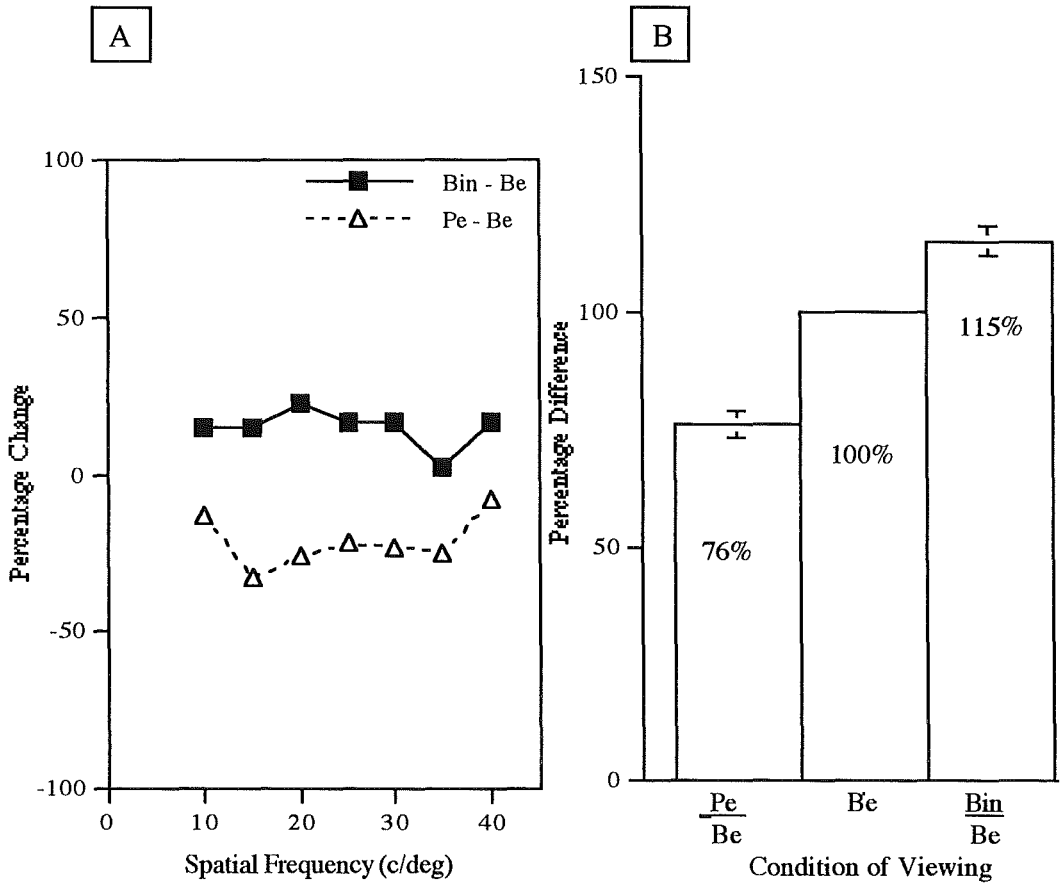


Figure 35. Contrast sensitivity changes in the normal group (n=11).
A: Percentage reduction in contrast sensitivity for poorer eye (Pe) and percentage increase for binocular viewing (Bin) each referenced to the better eye (Be) taken as 100%, at different spatial frequencies, averaged over the group of 11 normal subjects.
B: The same data as in **A** but additionally averaged over spatial frequencies to give a single mean value ± SE.

The results show that the deficits for the poorer eye remains broadly constant with respect to those for the better eye over 15c/deg to 35c/deg (Figure 35A). Likewise, there is a constant percentage increase for binocular viewing compared to the better eye, with the possible exception of 35c/deg. When the differences in the contrast sensitivities at the different spatial frequencies are averaged, the mean value (shown in the histogram on the right) shows a reduction in the poorer eye contrast sensitivity of 24% ± 5%SE and an increase in binocular contrast sensitivity of 15% ± 4%SE, compared with the better eye (Figure 35B).

3.1.2 Simple Anisometropic Amblyopes

This group was composed of 9 individuals, 6 females and 3 males, ranging in age from 27 to 48 years (mean age of 38 years). The prerequisites for inclusion into this group were the presence of amblyopia, anisometropia, and bifoveal fixation on ophthalmoscopy. Normal BSV was present in all cases. The magnitude of heterophoria was relatively small and ranged from 2^ to 6^ base-out and 1^ to 8^ base-in. Pupil diameter ranged from 3mm to 4mm under room light and, in all cases, the pupil size was the same in the right and left eyes. The amplitude of accommodation varied between 1.00D to 8.00D (Table 3).

3.1.2.1 Ocular Status

The visual acuity in the amblyopic eye ranged from 6/9 to 6/36, and broadly fell into two groups: slight amblyopes (6/9 to 6/12) and moderate amblyopes (6/18-6/36). The refractive difference between the two eyes ranged from 1.25DS to 5.00DS. Astigmatic corrections have been shown as spherical equivalents.

3.1.2.2 Contrast Sensitivity: Individual Data

For each subject, the contrast sensitivities expressed in logarithmic form at spatial frequencies 8, 10, 15, 20, 25, 30 and 35 c/deg were obtained for left and right eye viewing, and then for binocular viewing. In all subjects, the logarithm contrast sensitivities declined monotonically over the spatial frequency range examined.

The contrast sensitivities for one simple anisometropic amblyope (Subject 7), which are representative of the group as a whole, are shown in Figure 36. The results show a mean difference in logarithm contrast sensitivity between the better (Be) and poorer eye (Pe), over the range of spatial frequencies, of 0.30 log units which represented a mean attenuation of 50% ± 8%SE (Figure 36A). This was significant ($P<0.01$, paired t-test). When the logarithm contrast sensitivities for binocular viewing (Bin) were compared to those of the better eye, there was a consistent increase at all the spatial frequencies (Figure 36B).

The mean increase was 0.19 log units which represented an overall increase of 55% ± 9%SE. Again, this was statistically significant (P<0.01, paired t-test).

Table 3 Clinical Data for Simple Anisometropic Amblyopes

Subject	Visual Acuity	Refractive Error	Angle of Deviation	Accommodation (Amplitude)
1	RE 6/4 LE 6/36	RE -0.25DS LE +2.50DS	N : BO 6^ : D : BO 6^	RE 5.50D LE 5.00D
2	RE 6/18 LE 6/5	RE +3.00DS LE +0.50DS	N : BO 2^ : D : BO 2^	RE 2.00D LE 2.00D
3	RE 6/9 LE 6/6	RE -4.00DS LE -1.25DS	N : BI 8^ : D : BI 2^	RE 1.00D LE 1.50D
4	RE 6/12 LE 6/4	RE +2.00DS LE +0.50DS	N : BI 4^ : D : BI 4^	RE 7.25D LE 7.75D
5	RE 6/18 LE 6/5	RE -4.50DS LE -2.00DS	N : BI 4^ : D : BI 4^	RE 6.50D LE 7.50D
6	RE 6/4 LE 6/9	RE -1.25DS LE -2.50DS	N : BI 6^ : D : BI 6^	RE 6.50D LE 6.00D
7	RE 6/9 LE 6/4	RE -0.25DS LE -2.50DS	N : BI 4^ : D : BI 4^	RE 6.00D LE 8.00D
8	RE 6/5 LE 6/24	RE +0.50DS LE +3.75DS	N : BO 6^ : D : BO 6^	RE 6.00D LE 3.00D
9	RE 6/12 LE 6/5	RE -5.00DS LE -Plano	N : BI 6^ : D : BI 1^	RE 4.50D LE 6.00D

Key: RE: Right Eye LE: Left Eye N: Near D: Distant BI: Base In: BO: Base Out D: Dioptres of Accommodation DS: Dioptre Sphere DC: Dioptre Cylinder ^: Prism Dioptres -: Concave Lens +: Convex Lens;

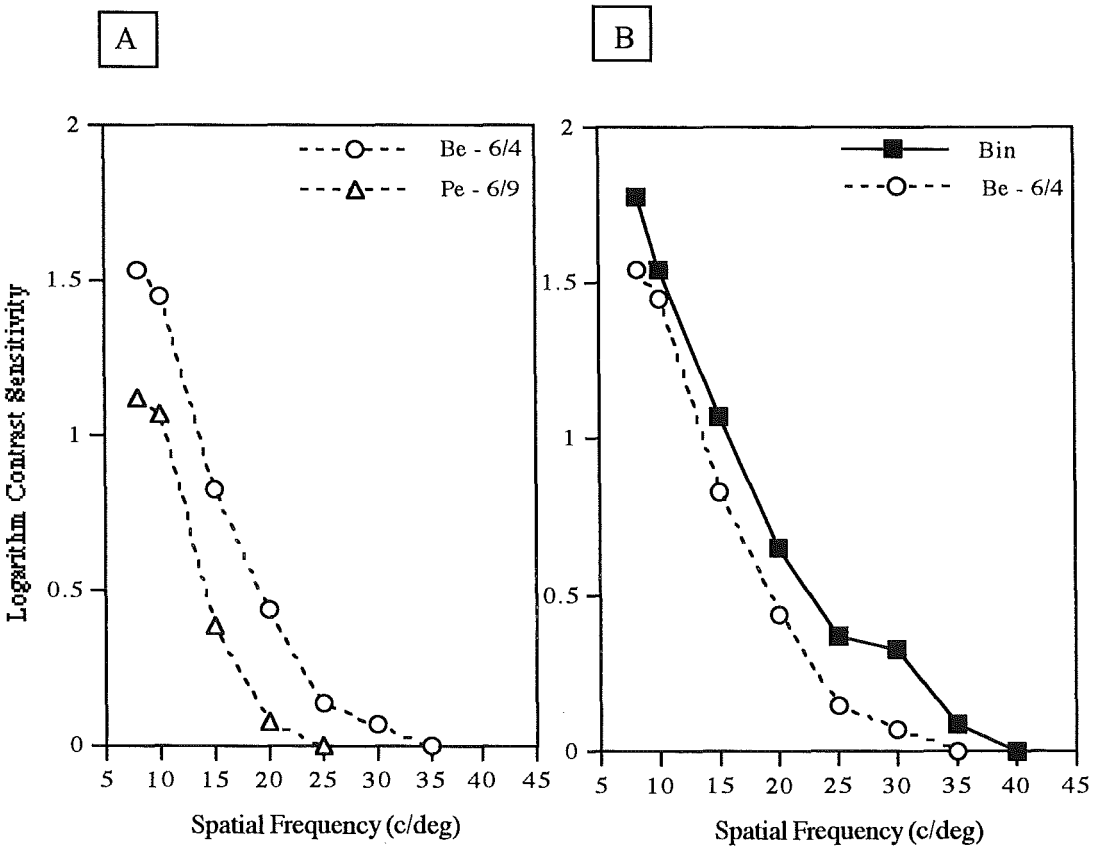


Figure 36. Logarithm contrast sensitivity against increasing spatial frequency for a simple anisometropic amblyope, Subject 7. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A Monocular viewing through the better eye (Be) and the poorer eye (Pe).
B Monocular viewing through the better eye (Be) (same data as in **A**) and binocular viewing (Bin).

3.1.2.3 Contrast Sensitivity: Group Data

The results in Figure 37 show the difference between the logarithm contrast sensitivities for the better eye (Be) with those of the poorer eye (Pe). The overall reduction in the logarithm contrast sensitivities of the poorer eye was a mean of 0.26 log units. In addition, this difference between the better eye and the poorer eye was reasonably uniform across the range of spatial frequencies examined. Enhancement by a mean of 0.13 log units under binocular conditions of viewing was evident when compared with the better eye, the increase in binocular logarithm contrast sensitivities being relatively similar across the spatial frequency range of 8c/deg to 35 c/deg (Figure 37). None of

the 9 amblyopes could discriminate the grating pattern at 40 c/deg with either the better eye or binocularly, and this has been represented as zero logarithm contrast sensitivity units in Figure 37.

Thus, in this group of 9 simple anisometropic amblyopes, the logarithm contrast sensitivity was consistently reduced for the amblyopic eye (Pe) with a mean reduction of 45% ± 9%SE over the range of spatial frequencies (Figure 37): this was statistically significant ($n = 9$; $t = 4.93$; $P = 0.001$; one sample t-test).

A 3-factor ANOVA confirmed these differences. There was significant variation among subjects comprising this group when the poorer eye was compared to the better eye ($F = 39.25$; $P<0.001$). In addition, the logarithm contrast sensitivity in the poorer eye was significant reduced when compared with that obtained by the better eye ($F = 531.57$; $P<0.001$) and was also significantly different across the range of spatial frequencies ($F = 637.42$; $P<0.001$).

When the binocular contrast sensitivities were compared with the contrast sensitivities of the better eye there was a statistically significant increase in binocular contrast sensitivity of 35% ± 7%SE ($n = 9$; $t = 4.66$; $P = 0.002$; one sample t-test).

The 3-factor ANOVA also confirmed a significant difference, *viz* enhancement in the binocular contrast sensitivities compared with those of the better eye in this group of simple anisometropic amblyopes ($F = 29.50$; $P <.001$). There was also evidence of significant variation among subjects ($F = 48.31$; $P<0.001$) and across the range of spatial frequencies examined ($F = 278.88$; $P<0.001$).

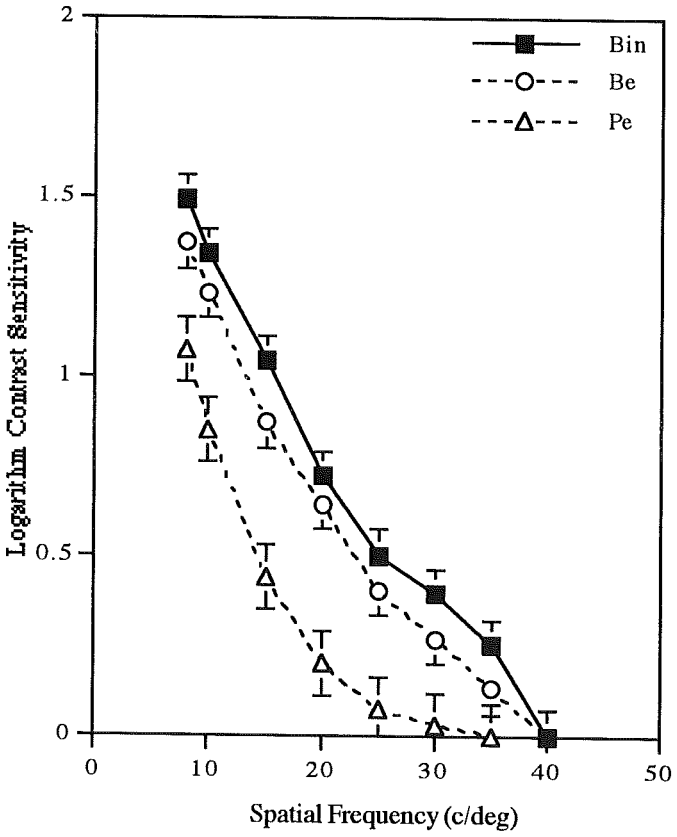


Figure 37. Logarithm contrast sensitivity against increasing spatial frequencies for the simple anisometropic amblyopic group (n=9) for monocular viewing through the better eye (Be), poorer eye (Pe) and for binocular viewing (Bin). Points shown represent the mean ± the pooled standard error of values for each of 9 subjects. Each of these values was itself the mean of 6 determinations.

For each subject the mean percentage reduction in logarithm contrast sensitivity was calculated over the range of spatial frequencies (Table 4).

Table 4 Reduction in linear contrast sensitivities between the better eye and the poorer eye, and the increase in linear contrast sensitivities under binocular viewing compared to those of the better eye, in simple anisometropic amblyopes.

Subject	Better Eye vs Poorer Eye $\frac{(Pe - Be)}{Be} \times 100\%$	Binocular vs Better Eye $\frac{(Bin - Be)}{Be} \times 100\%$
1	-83% ± 5% **	+29% ± 7% *
2	-30% ± 5% **	+47% ± 11% **
3	-13% ± 5% ns	+ 6% ± 6% ns
4	-65% ± 7% **	+28% ± 5% **
5	- 8% ± 3% ns	+77% ± 20% **
6	-27% ± 4% **	+37% ± 11% **
7	-50% ± 8% **	+55% ± 9% **
8	-79% ± 4% **	+22% ± 11% ns
9	-50% ± 4% **	+11% ± 6% ns
Mean	**- 45% ** **	**+35% ** **

Each value is mean ± SE for the spatial frequencies tested in each subject.
Be - Better Eye Pe - Poorer Eye Bin - Binocular Viewing
ns - P>0.05 * P<0.05 ** P<0.01

The mean group difference at each spatial frequency was replotted in linear form to show the differences between the better eye (Be) (normal eye) and the amblyopic eye (Pe), and between binocular viewing and monocular viewing with the better eye (Figure 38 A and B). The contrast sensitivities of the amblyopic eye (Pe) when compared with the normal eye (Be) showed a reduction across the spatial frequency range varying from 32% to 64%, with a

loss of 100% at 35c/deg when the grating pattern could not be discriminated by the amblyopic eye. The mean percentage increase in binocular contrast sensitivities (Bin), compared with those of the better eye (Be), over the range of spatial frequencies examined was reasonably level and varied from 26% to 49% except at 40c/deg when the grating pattern was not detected in either case (Figure 38A).

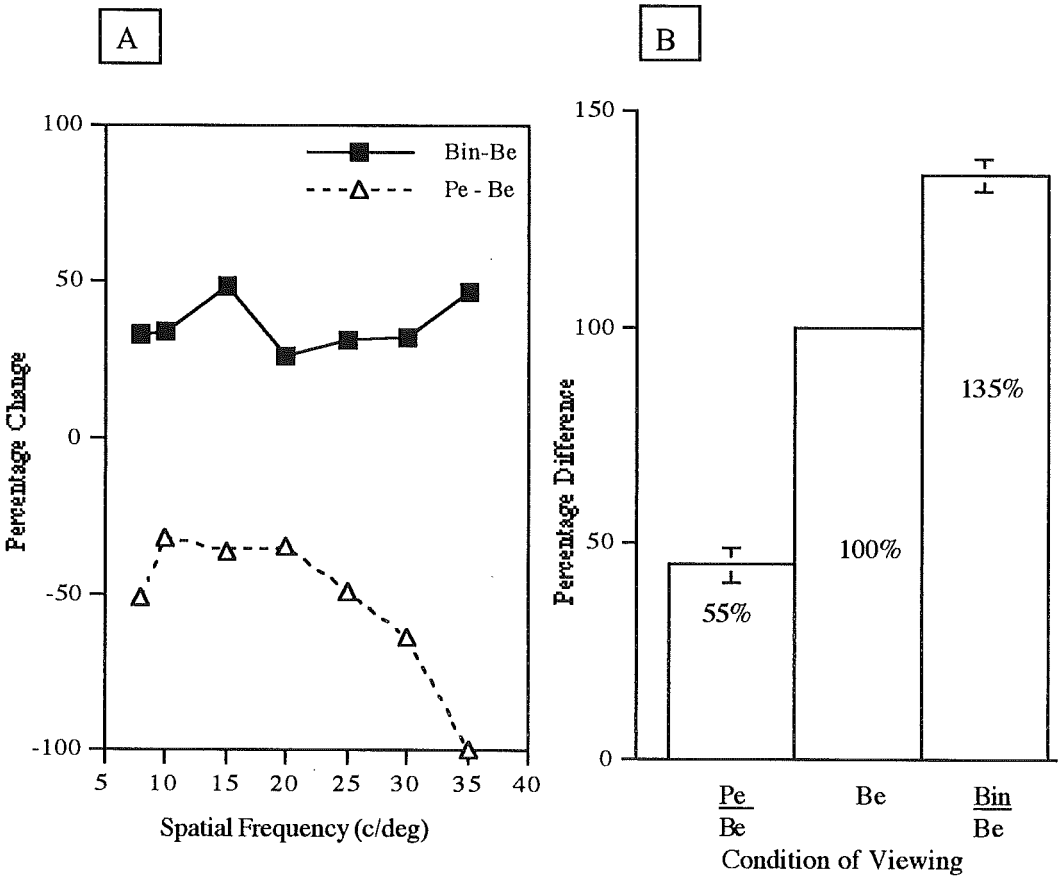


Figure 38. Contrast sensitivity changes in simple anisometropic amblyopes (n=9).
A: Percentage reduction in contrast sensitivity for poorer eye (Pe) and percentage increase for binocular viewing (Bin), each referenced to the better eye (Be) taken as 100%, at different spatial frequencies. The 100% loss at 35c/deg while shown was not included in the overall calculation of the mean percentage reduction in contrast sensitivities.
B: The same data as in **A** but averaged over the spatial frequency range to give a single mean value ± SE.

3.1.3 Micro-esotropic Amblyopes

Six individuals, comprising 2 females and 4 males, satisfied the criteria for inclusion in this group. Ages ranged from 21 years to 31 years, with a mean age of 24 years.

Table 5 Clinical Data for Micro-esotropic Amblyopes

Subject	Visual Acuity	Refractive Error	Angle of Deviation	Accommodation (Amplitude)
1	RE 6/12 LE 6/5	RE +2.50DS LE Plano	N : BO 12^: D : BO 6^ N : BO 6^ SPCT	RE 4.00D LE 7.50D
2	RE 6/12 LE 6/5	RE +7.50DS LE +5.50DS	N : BO 6^ : D : BO 4^ N : BO 6^ SPCT	RE 4.75D LE 5.25D
3	RE 6/4 LE 6/12	RE +1.75DS LE +3.50DS	N : BO 4^ : D : BO 2^ N : BO 4^ SPCT	RE 8.50D LE 8.50D
4	RE 6/6 LE 6/12	RE - 0.50DS LE +1.00DS	N : BO 10^: D: BO 10^ N : BO 4^ SPCT	RE 6.50D LE 5.50D
5	RE 6/9 LE 6/5	RE +1.00DS LE +0.75DS	N : BO 6^ : D : BO 6^ N : BO 6^ SPCT	RE 7.75D LE 8.00D
6	RE 6/4 LE 6/9	RE +1.25DS LE +3.00DS	N : BO 4^ : D : BO 4^ N : BO 4^ SPCT	RE 7.75D LE 7.25D

Key: RE: Right Eye LE: Left Eye N: Near D: Distance BI: Base In
BO: Base Out D: Dioptres of Accommodation DS: Dioptre Sphere
DC: Dioptre Cylinder ^: Prism Dioptres -: Concave Lens +: Convex Lens
SPCT: Simultaneous Prism Cover Test

(Note: the angle of deviation prefixed by N and D is the total angle of deviation, *i.e.* the angle of heterophoria plus the angle of heterotropia, if present; the angle of deviation prefixed by SPCT is the angle of heterotropia alone (see Methods page 91).

3.1.3.1 Ocular Status

All individuals exhibited an esotropia. The manifest deviation measured by simultaneous prism and cover test (SPCT) varied between 4^ and 6^ (approximately 2 and 3 degrees). The total angle of deviation, *i.e.* the magnitude of heterotropia and superimposed heterophoria detected by normal prism and cover test, ranged from 2^ to 12^ (Table 5). The visual acuity in the amblyopic eye was 6/9 or 6/12, while that of the normal eye was at least 6/6. Within this limited sample of 6 participants, there was no correlation between

the depth of amblyopia, expressed as decimal Snellen acuity, and the angle of squint when Spearman's rank correlation was applied to the data (0.00; P>0.05). In all cases, parafoveal fixation was present in the amblyopic eye. As a consequence of the presence of esotropia and parafoveal fixation, anomalous binocular single vision was present in all participants together with central suppression in the squinting eye. The amplitude of accommodation was 4.00D to 8.50D. The pupil diameter was 3mm to 4mm in each eye, in all subjects.

3.1.3.2 Contrast Sensitivity: Individual Data

For each subject, contrast sensitivities expressed in logarithmic form at spatial frequencies 8, 10, 15, 20, 25, 30, and, when possible, 35 c/deg were obtained for left and right eye viewing and then for binocular viewing.

An example of the marked difference in logarithm contrast sensitivity for viewing with the normal and amblyopic eye is shown for Subject 1 in Figure 39. The results show a marked depression of the logarithm contrast sensitivity of the poorer eye (Pe) in which a visual acuity of 6/12 was recorded with anisometropia of 2.50DS. The range of comparison became truncated because it was made over the spatial frequency range up to when the amblyopic eye no longer saw the grating pattern, *i.e.* 20c/deg. (Figure 39A). To make comparisons over the whole range *i.e.* above 20c/deg. when the grating pattern was not seen at all by the amblyopic eye, an underestimation of the deficit would have resulted. The mean reduction in logarithm contrast sensitivity between the better (Be) and poorer eye (Pe) was 0.88 log units over the range of spatial frequencies. This represents a mean reduction of 87% ± 3%SE which was significant (P<0.01, paired t-test). When the logarithm contrast sensitivities for binocular viewing (Bin) were compared to those of the better eye (Be), there was a small increase at all spatial frequencies (Figure 51B). The mean increase was 0.06 log units (15% ± 6% SE) which proved to be statistically significant (P<0.05, paired t- test).

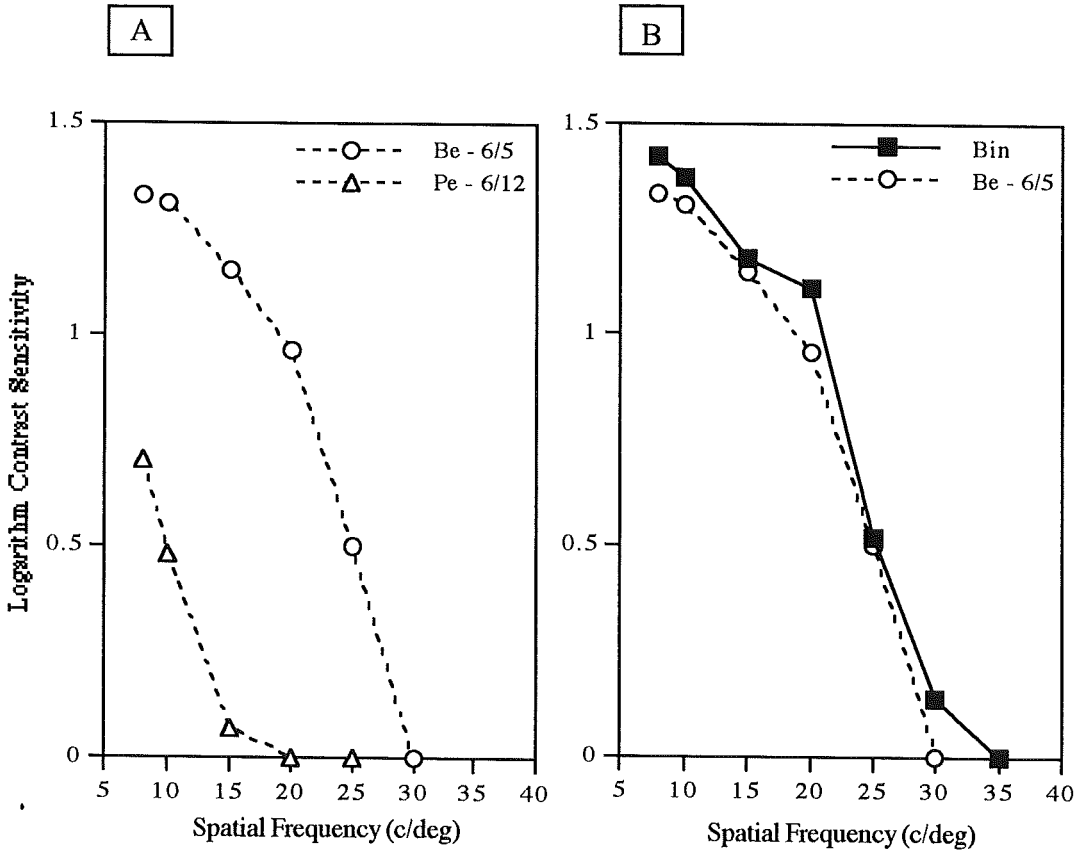


Figure 39. Logarithm contrast sensitivity against increasing spatial frequency for micro-esotropic amblyope, Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Monocular viewing through the better eye (Be) and the poorer eye (Pe).
B. Monocular viewing through the better eye (Be) (same data as in **A**) and binocular viewing (Bin).

3.1.3.3 Contrast Sensitivity: Group Data

The mean contrast sensitivity functions for the group of 6 subjects under the three conditions of viewing are shown in Figure 40, in which the nature of the logarithm contrast sensitivity difference between viewing conditions for Subject 1 is confirmed. There was a consistent and similar reduction in logarithm contrast sensitivity over the range of spatial frequencies examined for comparison between the poorer eye (Pe) and better eye (Be) viewing. A steady increment in the logarithm contrast sensitivity under binocular viewing conditions when compared with the logarithm contrast sensitivities for the better eye (Be) over the range of spatial frequencies was also evident. None of the 6 individuals comprising this group could discriminate the grating pattern at 40

c/deg with either the better eye, the poorer eye or binocularly, and this is represented as zero logarithm contrast sensitivity units in Figure 40.

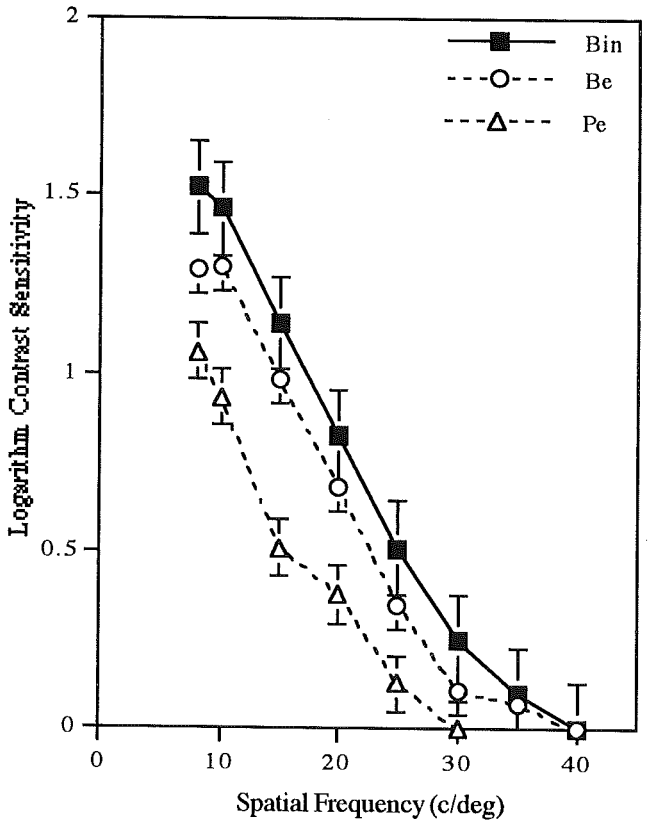


Figure 40. Logarithm contrast sensitivity for the group of micro-esotropic amblyopes (n=6) for monocular viewing through the better eye (Be), poorer eye (Pe) and for binocular viewing (Bin). Points shown represent the mean ± the pooled standard error of values for each of 6 subjects. Each of these values was itself the mean of 6 determinations.

Over the range of spatial frequencies studied, the contrast sensitivities for the amblyopic eye (Pe) were significantly reduced, compared with those for the normal eye (Be), by 0.31 log units representing a decrease of 51% ± 9%SE (n = 6; t = 5.57; P = 0.003; one sample t-test).

This was confirmed by the 3-factor ANOVA which showed evidence of significant variation among the subjects comprising this group (F = 99.95; P<0.001) together with a significant reduction in logarithm contrast sensitivity in the poorer eye compared with that obtained through the better eye in these subjects (F = 316.96; P<0.001). The ANOVA also demonstrated a significant difference in the findings across the range of spatial frequencies examined (F = 262.54; P<0.001).

When the binocular contrast sensitivities were compared to those of the better eye (Be), a mean increase in contrast sensitivity of 0.132 log units, representing a 35% ± 17%SE enhancement, was shown. This was reflected in all the subjects with the exception of subject 5, (Table 6) in whom the binocular contrast sensitivities were reduced when compared to those of the better eye. The overall increase in binocular logarithm contrast sensitivities was not statistically significantly different when the one sample t-test was applied to the mean percentage differences in subjects comprising this group (n = 6; t = 2.09; P = 0.09;) (Table 6).

However, when a 3-factor ANOVA was applied to the data there was a statistically significant enhancement in binocular contrast sensitivities compared with those of the better eye (F = 51.93; P<0.001). There was also a significant variation among subjects (F = 30.94; P<0.001) and across the range of spatial frequencies examined (F = 452.55: P<0.001).

Table 6. Reduction in linear contrast sensitivities averaged over spatial frequencies studied between better and poorer eye and increase under binocular viewing compared with the better eye in micro-esotropic amblyopes.

Subject	Better Eye vs Poorer Eye $\frac{(Pe - Be)}{Be} \times 100\%$	Binocular vs Better Eye $\frac{(Bin - Be)}{Be} \times 100\%$
1	-87% ± 3% **	+15% ± 6% *
2	-43% ± 7% **	+67% ± 30% *
3	-70% ± 6% **	+25% ± 10% ns
4	-40% ± 6% **	+37% ± 10% **
5	-42% ± 8% **	-26% ± 10% ns
6	-26% ± 7% *	+90% ± 21% *
Mean	**-51% ****	**+35% ns**

Each value is mean ± SE for the spatial frequencies tested in each subject.
Be - Better Eye Pe - Poorer Eye Bin - Binocular Viewing
ns - P>0.05 * P<0.05 ** P<0.01

When the mean group difference at each spatial frequency was replotted in linear form (Figure 41), there were notable differences in the contrast sensitivities of the amblyopic eye (Pe) when compared with the normal eye (Be) over the range of spatial frequencies. Reductions ranging from 32% to 58% were evident (Figure 41A), with a mean loss of 51% ± 9%. In order not to underestimate the resultant deficit in logarithm contrast sensitivity of the poorer eye (Pe) when compared with the better eye (Be), the range of comparison was once again limited to, and was made over, the spatial frequency range up to when the amblyopic eye no longer detected the grating pattern, *i.e.* 8c/deg to 25c/deg (Figure 41A). The mean percentage increase at each spatial frequency in binocular contrast sensitivity (Bin) compared with that of the better eye (Be) varied from 13% to 47% (Figure 41A), the mean percentage increase being 35% ± 17% (Figure 41B).

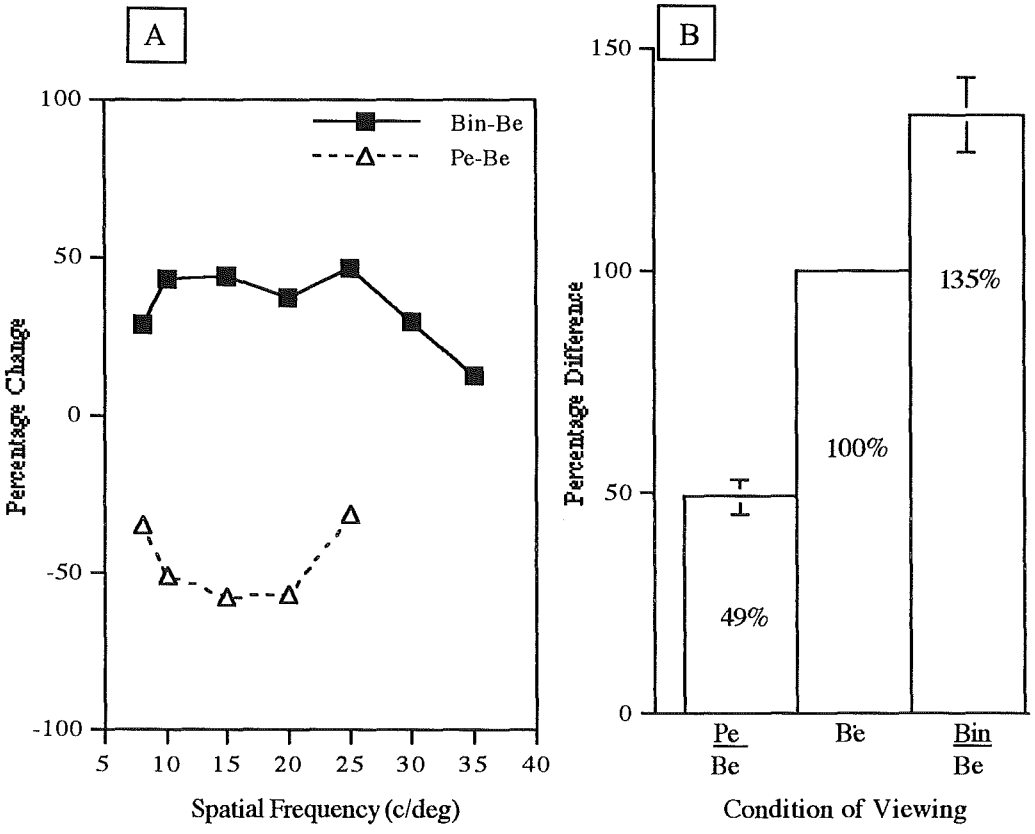


Figure 41. Contrast sensitivity changes in micro-esotropic amblyopes (n=6).
A: Percentage reduction in contrast sensitivity for poorer eye (Pe) and percentage increase for binocular viewing (Bin), each referenced to the better eye (Be) taken as 100% at different spatial frequencies.
B: The same data as in **A** but averaged over spatial frequencies to give a single mean value ± SE.

3.1.4 Esotropic Amblyopes with Anomalous BSV

Three female individuals, ranging in age from 19 to 47 years, with a mean age of 29 years, comprised this group of esotropic amblyopes with abnormal BSV.

3.1.4.1 Ocular Status

A constant (non-intermittent) esotropia of between 2 to 7 degrees (4^ to 14^) was present and anomalous BSV demonstrable in all cases. The severity of amblyopia resulted in visual acuities varied from 6/9 to 6/18. Foveal fixation in the amblyopic, squinting eye was also demonstrable in each case. In one individual (Subject 1) anisometropia was present (Table 7) and in Subject 3, a right esotropia and dissociated vertical deviation (DVD) were evident. Accurate assessment of the state of fixation, by ophthalmoscopy, was difficult in Subject 3 due to the presence of small, jerky oscillatory movements of the eye under examination (manifest latent nystagmus) which is an accompanying feature of DVD. Pupils were equal in size in all individuals and were between 3mm and 5mm in diameter. The amplitude of accommodation ranged from 5.00D and 8.50D.

Table 7 Clinical Data for Esotropic Amblyopes with Anomalous BSV

Subject	Visual Acuity	Refractive Error	Angle of Deviation	Accommodation (Amplitude)
1	RE 6/9 LE 6/5	RE +4.75DS LE +3.50DS	N : BO 14^ :D : BO 6^	RE 8.25D LE 8.50D
2	RE 6/18 LE 6/5	RE +1.00DS LE +0.50DS	N : BO 4^ : D : BO 4^	RE 8.00D LE 8.25D
3	RE 6/9 LE 6/6	RE -0.25DS LE -0.25DS	N : BO 6^ : D :BO 6^	RE 5.00D LE 5.50D

Key: RE: Right Eye LE: Left Eye N: Near D: Distant BO: Base Out
D: Dioptres of Accommodation DS: Dioptre Sphere DC: Dioptre Cylinder:
^: Prism Dioptres -: Concave Lens +: Convex Lens

(Note: the angle of deviation prefixed by N and D is the total angle of deviation, *i.e.* the angle of heterophoria plus the angle of heterotropia, if present).

3.1.4.2 Contrast Sensitivity: Individual Data

For each subject, the contrast sensitivities expressed in logarithmic form at spatial frequencies 8, 10, 15, 20, 25, 30 and 35 c/deg were obtained for left and right eye viewing and then for binocular viewing.

Subject 1

In Subject 1, a definite downward shift of the contrast sensitivity function for viewing through the amblyopic eye (Pe) compared with the normal eye (Be) (Figure 42A) is present. The results show a mean reduction in logarithm contrast sensitivity over the range of spatial frequencies between the normal (Be) and amblyopic eye (Pe) of 0.25 log units. This represented a mean reduction of 44% ± 4%SE which was significant (P<0.01, paired t-test).

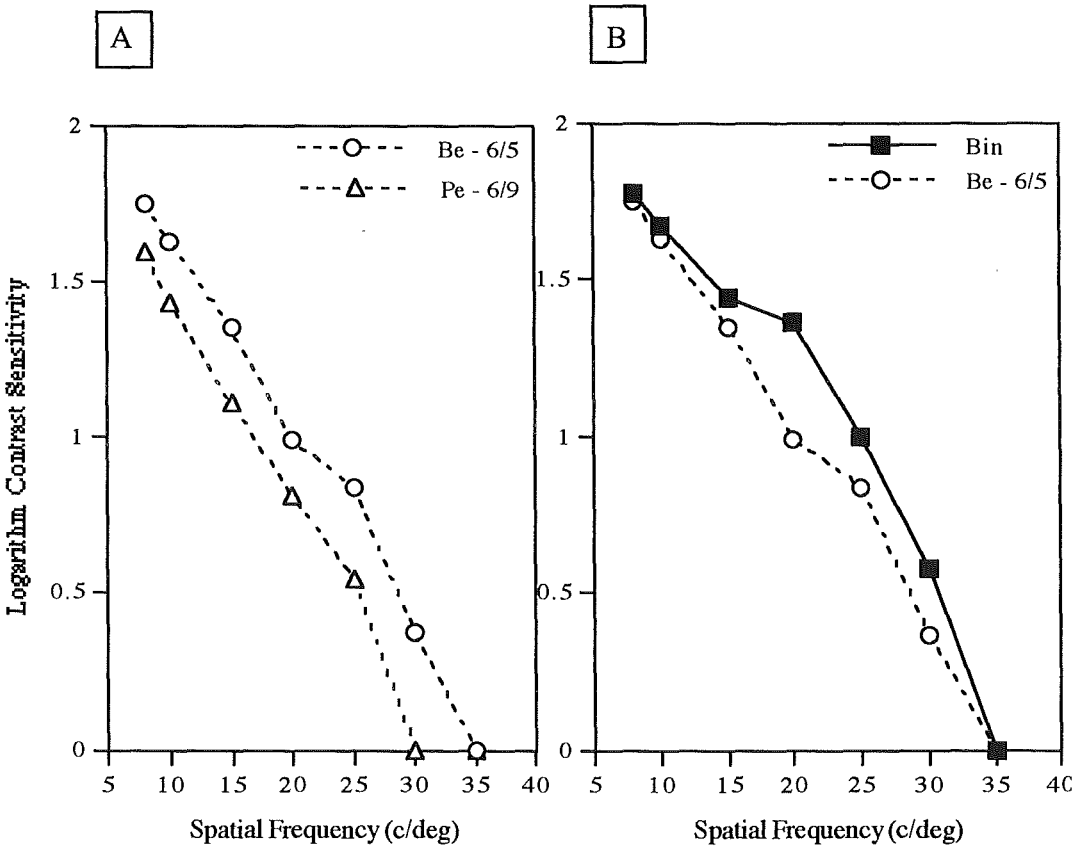


Figure 42. Logarithm contrast sensitivity for esotropic amblyopes with anomalous binocular single vision, Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A Monocular viewing through the better eye (Be) and the poorer eye (Pe).
B Monocular viewing through the better eye (Be) (same data as in **A**) and binocular viewing (Bin).

When the binocular logarithm contrast sensitivities were averaged over the spatial frequencies and compared to those of the better eye, an increase of 0.17 log units (48% ± 20%SE) was present, which was not statistically significant (P >0.05, paired t-test).

Subject 2

Subject 2 also exhibited a downward shift of the contrast sensitivity function for viewing through the amblyopic eye (Pe) compared with the normal eye (Be) (Figure 43A). The results show a mean percentage reduction of 85% ± 12% (P<0.01, paired t-test) over the range of spatial frequencies examined. This represented a mean reduction in logarithm contrast sensitivity of 0.83 log units. The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye by 26% ± 8% (P<0.05, paired t-test) (Figure 43B). This increase was statistically significant.

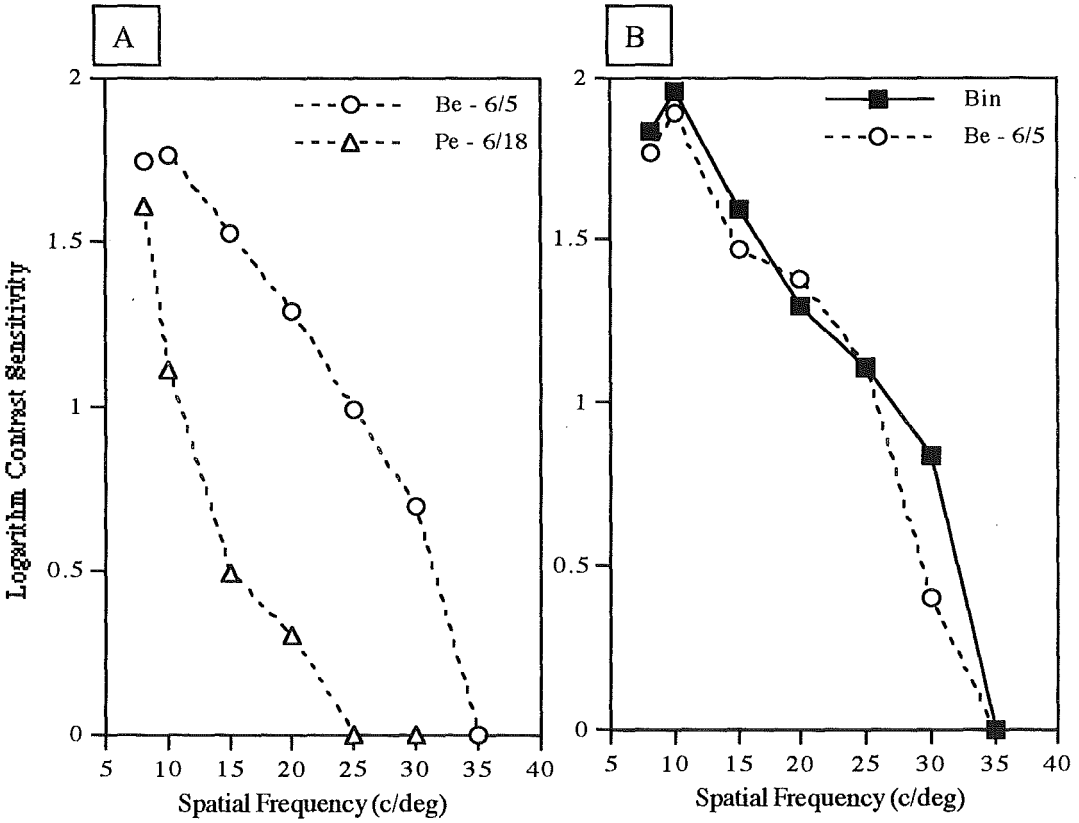


Figure 43. Logarithm contrast sensitivity for esotropic amblyopes with anomalous binocular single vision, Subject 2. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A Monocular viewing through the better eye (Be) and the poorer eye (Pe).
B Monocular viewing through the better eye (Be) (same data as in **A**) and binocular viewing (Bin).

Subject 3

The contrast sensitivity findings for Subject 3 were similar to the other two subjects comprising this group. The contrast sensitivity function for viewing through the amblyopic eye (Pe) compared with the normal eye (Be) was considerably reduced (Figure 44A). The results show a mean reduction in logarithm contrast sensitivity over the range of spatial frequencies between the normal (Be) and amblyopic eye (Pe) of 0.25 log units. This represented a mean reduction of 44% ± 12%SE which was not significant (Table 8). The binocular contrast sensitivity (Bin) exceeded that of the better eye (Be) by 59% ± 21%SE (P=0.05, paired t-test) (Figure 44B).

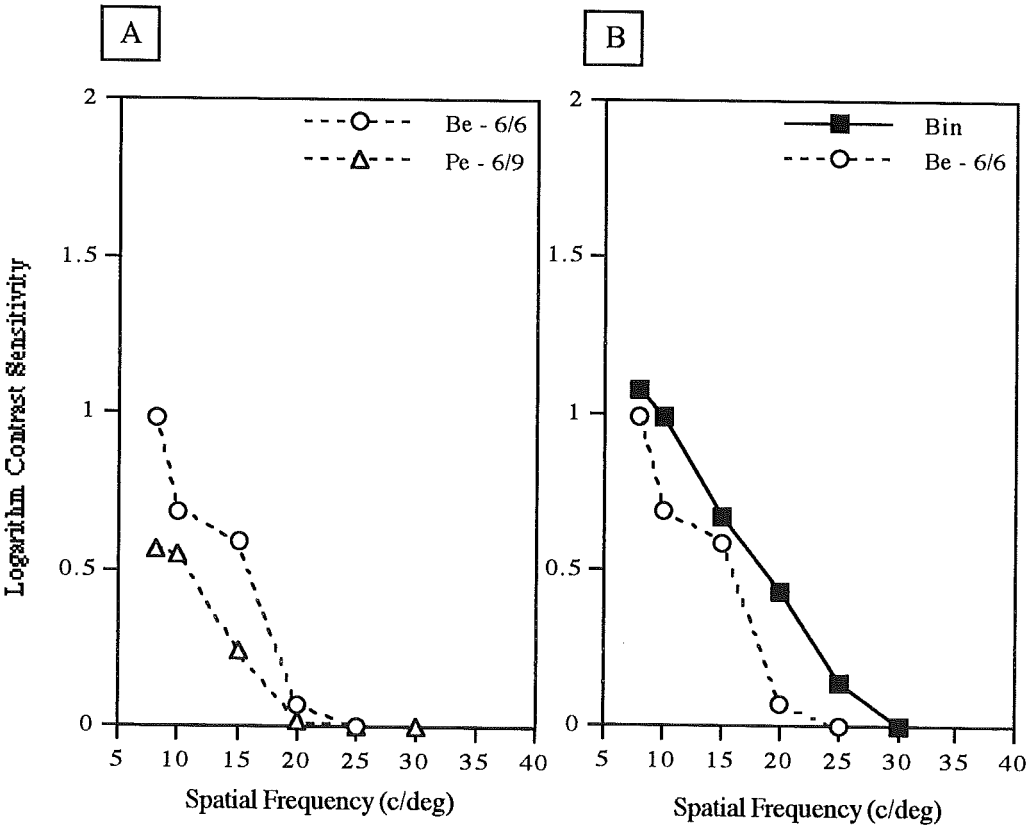


Figure 44. Logarithm contrast sensitivity for esotropic amblyopes with anomalous binocular single vision, Subject 3. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A Monocular viewing through the better eye (Be) and the poorer eye (Pe).
B Monocular viewing through the better eye (Be) (same data as in **A**) and binocular viewing (Bin).

When the mean group difference at each spatial frequency was calculated and plotted in linear form (Figure 45), there were notable differences in the contrast sensitivities of the amblyopic eye (Pe) when compared with the normal eye (Be) over the range of spatial frequencies. The contrast sensitivities for the amblyopic eye (Pe) were significantly reduced compared with those for the normal eye (Be). This mean percentage reduction ranged from 44% to 69% (Figure 45), with an overall mean percentage reduction of 58% ± 14% which was significant ($n = 3$; $t = 4.22$; $P = 0.05$, one sample t-test. (Table 8).

The significant reduction in mean percentage contrast sensitivity in the poorer eye of these subjects compared with that obtained through the better eye was also confirmed by the 3-factor ANOVA in which the logarithm contrast sensitivity of the poorer eye was found to be significant less than that obtained through the better eye ($F = 158.24$; $P<0.001$). In keeping with the findings in the other groups, there was a significant variation among subjects ($F = 232.28$; $P<0.001$) and significant differences across the range of spatial frequencies ($F = 169.50$; $P<0.001$). Inspection of the graphically depicted means showed a relatively uniform reduction in the mean from the lower to the higher spatial frequencies.

For binocular viewing (Bin), the contrast sensitivities were greater at all spatial frequencies compared with those of the better eye (Be) with an increase ranging from 16% to 78% (Figure 45), and an overall mean percentage enhancement of 44% ± 10%SE ($n = 3$; $t = 4.57$; $P = 0.04$; one sample t-test) (Table 8). This was confirmed by the 3-factor ANOVA which showed evidence of significant variations between the three subjects ($F = 1962.38$; $P<0.001$). The binocular contrast sensitivities were significantly greater than those obtained by the better eye ($F = 115.01$; $P<0.001$). The logarithm contrast sensitivities across the range of spatial frequencies examined were also different ($F = 790.31$; $P <0.001$). Inspection of the means revealed a rather unequal change from the lower to higher spatial frequencies.

Table 8 Reduction in linear contrast sensitivities averaged over spatial frequencies studied between better and poorer eye and increase under binocular viewing compared with the better eye in esotropic amblyopes with anomalous BSV.

Subject	Better Eye vs Poorer Eye $\frac{(Pe - Be)}{Be} \times 100\%$	Binocular vs Better Eye $\frac{(Bin - Be)}{Be} \times 100\%$
1	-44% ± 4% **	+48% ± 20% ns
2	-85% ± 12% **	+26% ± 8% *
3	-44% ± 12% ns	+59% ± 21% *
Mean	**-58% ***	**+44% ***

Each value is mean ± SE for the spatial frequencies tested in each subject.
Be - Better Eye Pe - Poorer Eye Bin - Binocular Viewing
ns - P>0.05 * P<0.05 ** P<0.01.

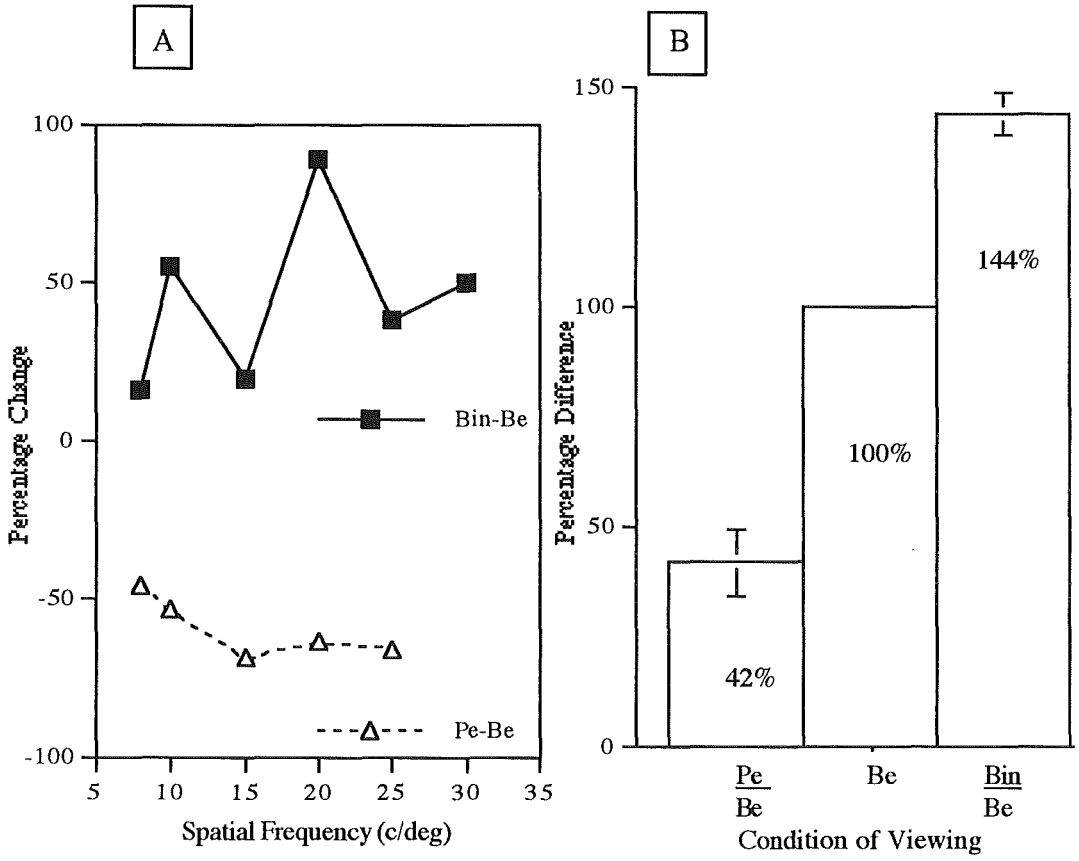


Figure 45. Contrast sensitivity changes in esotropic amblyopes with anomalous BSV (n=3).
A: Percentage reduction in contrast sensitivity for poorer eye (Pe) and percentage increase for binocular viewing (Bin), each referenced to the better eye (Be) taken as 100%, at different spatial frequencies.
B: The same data as in **A**, for the three individuals comprising this group, but averaged over spatial frequencies to give a single mean value.

3.1.5 Esotropic Amblyopes without BSV

Five individuals comprised this group, 2 male and 3 female participants. The mean age was 34 years and the age range was between 19 and 46 years.

3.1.5.1 Ocular Status

All individuals exhibited a constant esotropia, with visual acuity through the affected eye ranging from 6/9 to 6/60 (Table 9). Foveal fixation in the amblyopic eye in 4 individuals was evident with one participant demonstrating eccentric fixation of 2 degrees (subject 4). BSV was not demonstrable in any individual in this group. There was no correlation between the depth of amblyopia, taken as decimal Snellen acuity, and the angle of strabismus when Spearman's rank correlation test was applied (0.20). Pupil sizes were equal in both eyes in all cases and varied from 4mm to 5mm in diameter.

Table 9 Clinical Data for Esotropic Amblyopes without BSV

Subject	Visual Acuity	Refractive Error	Angle of Deviation	Accommodation (Amplitude)
1	RE 6/24 LE 6/5	RE +5.00DS LE +4.00DS	N : BO 12^ : D : BO 11^ L/R10^ L/R 11^	RE 3.00D LE 4.25D
2	RE 6/18 LE 6/5	RE -1.00DS LE -2.75DS	N : BO 30^ : D : BO 30^	RE 3.00D LE 7.50D
3	RE 6/5 LE 6/18	RE +5.00DS LE +6.50DS	N : BO 10^ : D : BO 10^ L/R 4^ L/R 4^	RE 8.00D LE 7.50D
4	RE 6/60 LE 6/5	RE +1.50DS LE - 0.75DS	N : BO 6^ : D : BO 6^	RE 2.75D LE 7.00D
5	RE 6/6 LE 6/9	RE -1.00DS LE -1.50DS	N : BO 8^ : D : BO 8^	RE 1.50D LE 1.25D

Key: RE: Right Eye: LE: Left Eye N: Near D: Distant BI: Base In BO: Base Out: D: Dioptres of Accommodation: DS: Dioptre Sphere DC: Dioptre Cylinder ^: Prism Dioptres -: Concave Lens +: Convex Lens L/R: Left Hypertropia (a vertical squint in which the left eye is elevated).

(Note: the angle of deviation prefixed by N and D is the total angle of deviation, *i.e.* the angle of heterophoria plus the angle of heterotropia, if present).

3.1.5.2 Contrast Sensitivity: Individual Data

For each subject, contrast sensitivities expressed in logarithmic form, at spatial frequencies 8, 10, 15, 20, 25, 30, and 35 and 40 c/deg when possible, were obtained for left and right eye viewing and then for binocular viewing[1]

A typical example of the contrast sensitivity function in this group of individuals is exemplified by the results for Subject 2, although the performance of the "normal" eye (Be), in this case, is less than might be expected as the spatial frequencies above 25c/deg could not be discriminated, even though Snellen acuity was 6/5 (Figure 46A).

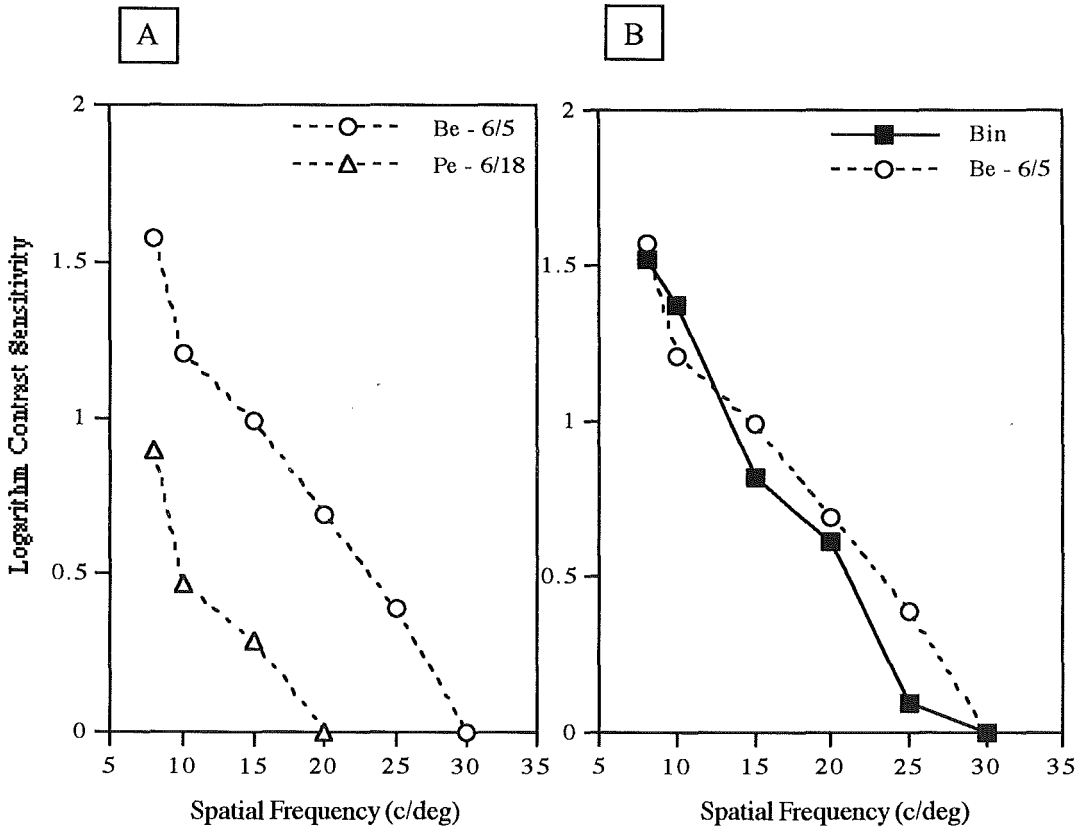


Figure 46. Logarithm contrast sensitivity against increasing spatial frequency for esotropic amblyope without BSV, Subject 2. Each point is the mean of six determinations with standard error values of less than ±0.05, which fall within the symbol size.
A. Monocular viewing through the better eye (Be) and the poorer eye (Pe).
B. Monocular viewing through the better eye (Be) (same data as in **A**) and binocular viewing (Bin).

[1] (in this and all other groups without BSV, the term "binocular viewing" is used in its widest sense and should not be taken as implying that BSV is present. It should be regarded as viewing with both eyes open (BEO).

For viewing through the amblyopic eye, the logarithm contrast sensitivities were markedly depressed and spatial frequencies above 15c/deg could not be resolved. The reduction in the contrast sensitivities for the poorer eye (Pe) was significant with a mean decrease of 0.67 log units over the range of spatial frequencies studied. This represented a mean reduction of 79% ± 4% SE. which was significant ($P<0.01$, paired t-test).

Unlike the previous groups, the logarithm contrast sensitivities under binocular conditions of viewing (Bin) were reduced compared with those of the better eye (Be) (Figure 46B). A mean decrease of 0.088 log units was demonstrable, representing a loss of 18% ± 16% SE, though this was not statistically significant ($P=0.06$, paired t-test).

3.1.5.3 Contrast Sensitivity: Group Data

The group logarithm contrast sensitivities reflected those found in Subject 2. There was a marked and significant reduction in logarithm contrast sensitivities in the poorer eye (Pe) when compared to the better eye (Be).

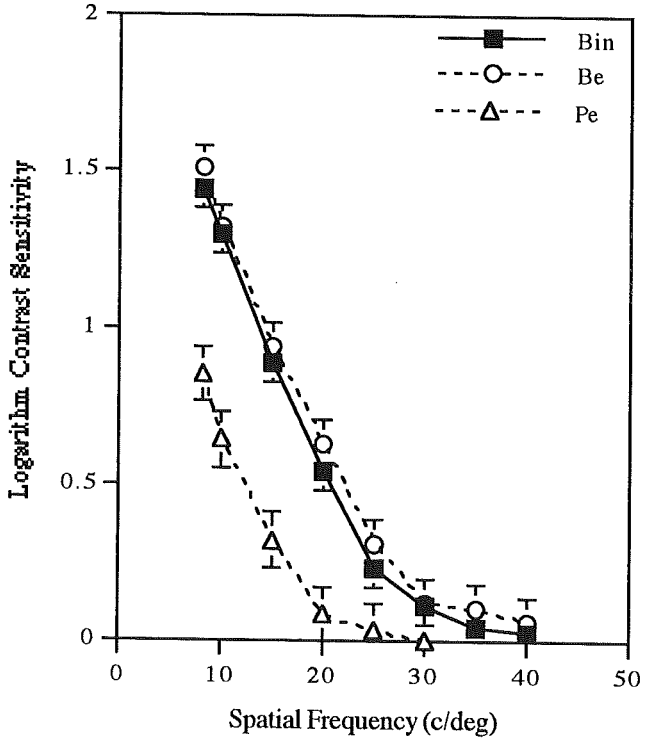


Figure 47. The logarithm contrast sensitivity against increasing spatial frequency for the group of esotropic amblyopes without BSV (n=5). Points shown represent the mean ± the pooled standard error of values for each of 5 subjects. Each of these values was itself the mean of 6 determinations.

The mean percentage contrast sensitivity loss in the poorer eye, when calculated over the range of spatial frequencies examined, was 65% ± 9%SE (n = 5; t = 7.47; P = 0.002; one sample t-test) (Figure 47).

The 3-factor ANOVA showed significant variation between subjects comprising this group (F = 56.37; P <0.001). Between eye analysis indicated a significant difference between the poorer and better eyes with the poorer eye exhibiting a significant decrease in logarithm contrast sensitivity values compared with the better eye (F = 783.52; P<0.001). There was also evidence of differences among spatial frequencies (F = 195.49; P <0.001).

The binocular contrast sensitivity (Bin) values in this group differed from previous groups in that they were marginally less than those of the better eye (Be) (Figure 47). The mean percentage reduction averaged over the spatial frequencies studied was 13% ± 2%SE (n = 5; t = 6.65; P = 0.003; one sample t-test) which was statistically significant when compared with the better eye (Be) (Table 10)

Table 10 Reduction in linear contrast sensitivities averaged over spatial frequencies studied between better and poorer eye, and reduction between binocular viewing and better eye in esotropic amblyopes without BSV.

Subject	Better Eye vs Poorer Eye $\frac{(Pe - Be)}{Be} \times 100\%$	Binocular vs Better Eye $\frac{(Bin - Be)}{Be} \times 100\%$
1	-73% ± 9% **	-11% ± 3% *
2	-79% ± 4% **	-18% ± 16% ns
3	-75% ± 3% **	-14% ± 8% ns
4	-68% ± 10% **	- 7% ± 2% *
5	-31% ± 2% **	-17% ± 5% *
Mean	**-65% ****	**-13% ****

Each value is mean ± SE for the spatial frequencies tested in each subject.
Be - Better Eye Pe - Poorer Eye Bin - Binocular Viewing
ns - P>0.05 * P<0.05 ** P<0.01

The 3-factor ANOVA revealed evidence of significant differences between subjects (F = 86.42; P <0.001) as well as a significant decrease in binocular contrast sensitivities compared with those obtained through the better eyes of subjects comprising this group (F = 31.28; P <0.001). Among the spatial frequencies there was considerable variation (F = 595.26; P<0.001).

The data shown in Figure 47, when replotted in linear form (Figure 48), showed that the reduction between the amblyopic eye and the normal eye varied between 47% and 73% across the range of spatial frequencies, with an overall mean reduction of 65% being recorded. A decrease in binocular contrast sensitivities (Bin) was also evident at all spatial frequencies when compared to the logarithm contrast sensitivities of the better eye (Be). The percentage reduction varied from 5% to 18% (Figure 47), with a mean percentage loss of 13% which was significant.

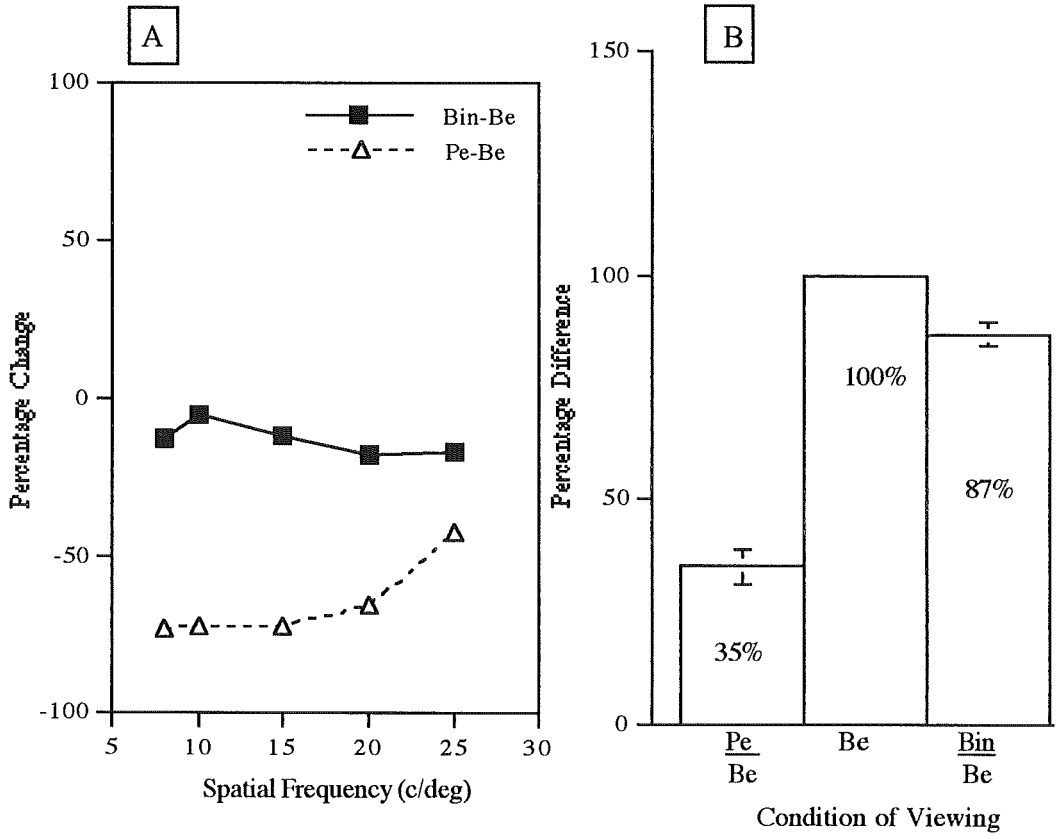


Figure 48. Contrast sensitivity changes in esotropic amblyopes without BSV (n=5)
A: Percentage reduction in contrast sensitivity for poorer eye (Pe) and for binocular viewing (Bin), each referenced to the better eye (Be) taken as 100%, at different spatial frequencies.
B: The same data as in **A** but averaged over spatial frequencies to give a single mean value ± SE.

3.1.6 Non-Amblyopic Esotropes without BSV

Four individuals satisfied the criteria for inclusion in this group, 2 females and 2 males. The age range was from 18 to 26 years.

3.1.6.1 Ocular Status

All subjects demonstrated constant esotropia of between 12^ to 25^ (approximately 6 to 12.5 degrees) without BSV, constant suppression (central and peripheral), Snellen acuity of 6/6 or better in each eye, and uniocular foveal fixation in the squinting eye on ophthalmoscopy (Table 11). Pupil sizes were equal in both eyes and varied from 4mm to 5mm .

Table 11 Clinical Data for Non-Amblyopic Esotropes without BSV

Subject	Visual Acuity	Refractive Error	Angle of Deviation	Accommodation (Amplitude)
1	RE 6/6 LE 6/6	Nil	N : BO 18^ : D : BO 12^	RE 8.00D LE 8.00D
2	RE 6/5 LE 6/5	Nil	N : BO 25^ : D : BO 25^ L/R16^ L/R 16^	RE 6.00D LE 6.50D
3	RE 6/5 LE 6/5	RE -1.50DS LE -1.75DS	N : BO 16^ : D : BO 12^	RE 9.00D LE 9.25D
4	RE 6/4 LE 6/4	RE +5.25DS LE +4.75DS	N : BO 18^ : D : BO 18^	RE 6.50D LE 6.75D

Key: RE: Right Eye: LE: Left Eye N: Near D: Distant BI: Base In BO: Base Out: D: Dioptres of Accommodation: DS: Dioptre Sphere DC: Dioptre Cylinder ^: Prism Dioptres -: Concave Lens +: Convex Lens L/R: Left Hypertropia (a vertical squint in which the left eye is elevated).
(Note: the angle of deviation prefixed by N and D is the total angle of deviation).

3.1.6.2 Contrast Sensitivity: Individual Data

For each subject, contrast sensitivities expressed in logarithmic form at spatial frequencies 8, 10, 15, 20, 25, 30, 35c/deg and when possible 40c/deg, were obtained for left and right eye viewing and then for binocular viewing. Normal and equal visual acuity, measured using the Snellen chart, was present in both eyes in all subjects, although the grating pattern at the higher spatial frequencies of 35c/deg and 40c/deg was not resolved (Table 11).

The findings for Subject 1 are typical of this group as a whole. Contrast sensitivities were lower in one eye, designated the poorer eye (Pe) compared with those for the other eye, designated the better eye (Be). This reduction, when averaged over the range of spatial frequencies studies, had a mean of 0.25 log units, representing a reduction of 44% ± 5% SE, which was significant ($P<0.01$, paired t-test) (Figure 49A). The binocular logarithm contrast sensitivities were reduced over the entire spatial frequency range studied except at 30c/deg, compared with those of the better eye. (Figure 49B). The mean binocular logarithm contrast sensitivity was 0.13 log units less when compared with the mean value for the better eye, representing a mean reduction of 26% ± 6% SE; ($P<0.05$, paired t-test).

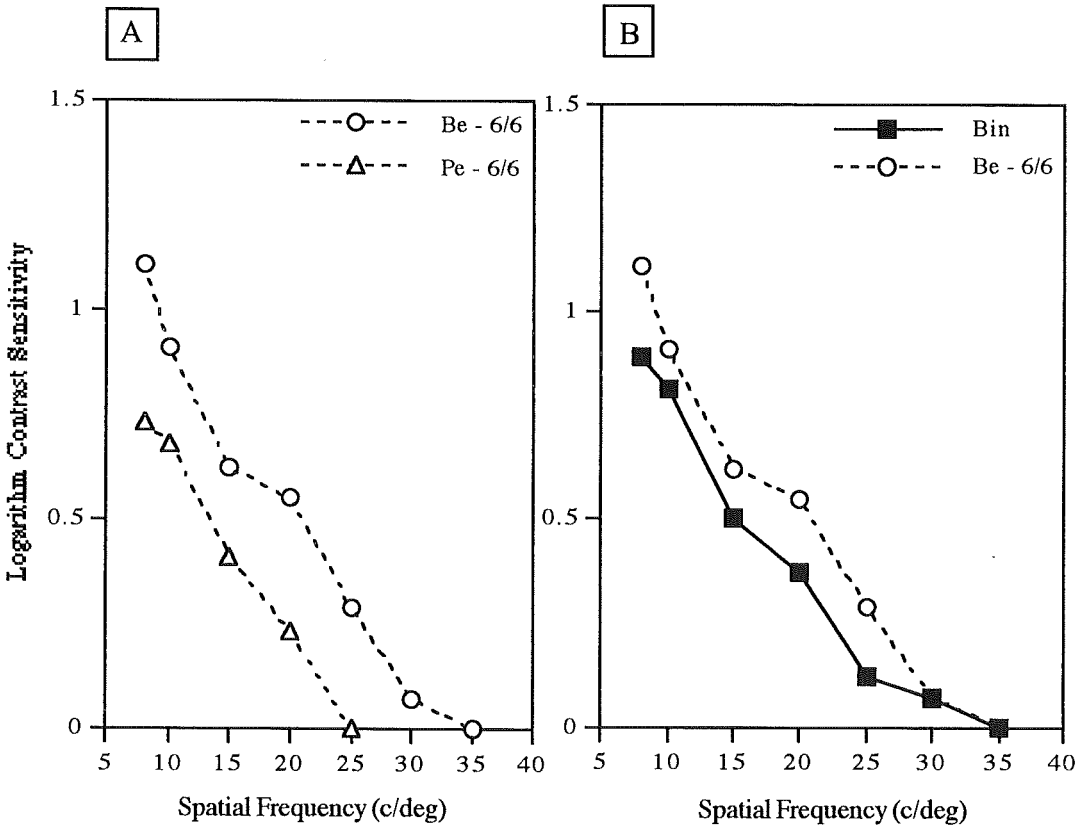


Figure 49. Logarithm contrast sensitivity against increasing spatial frequency for non-amblyopic esotrope without BSV, Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Monocular viewing through the better eye (Be) and the poorer eye (Pe).
B. Monocular viewing through the better eye (Be) (same data as in **A**) and binocular viewing (Bin).

3.1.6.3 Contrast Sensitivity: Group Data

The logarithm contrast sensitivities through the poorer eye (Pe) for this group of 4 subjects were depressed compared with those for the better eye (Be). The differences between the poorer eye and the better eye were substantial up to 25c/deg, but thereafter were reduced (Figure 49). The contrast sensitivities averaged over the range of spatial frequencies for the poorer eye (Pe) were significantly less than those for the better eye (Be) by 34% ± 8% SE ($n = 4$; $t = 4.16$; $P = 0.02$; one sample t-test) (Table 12).

A 3-factor ANOVA confirmed this significant reduction in poorer eye contrast sensitivities compared with those of the better eye ($F = 125.43$; $P<0.001$) in subjects comprising this group and the variation among subjects within the group ($F = 271.93$; $P<0.001$) and across the range of spatial frequencie ($F = 543.0$; $P<0.001$).

The binocular contrast sensitivities were marginally less than those achieved with the better eye. The mean percentage reduction was 11% ± 6% SE, but this was shown not to be statistically significant ($n = 4$; $t = 1.78$; $P = 0.17$) when analysis of the mean binocular percentage change was undertaken by one sample t-test (Table 12). This lack of statistical significance was also confirmed by the 3-factor ANOVA ($F = 3.57$; $P = 0.06$). A significant variation among subjects ($F = 304.40$; $P<0.001$) and spatial frequencies ($F = 670.31$: $P<0.001$) was, however, still evident.

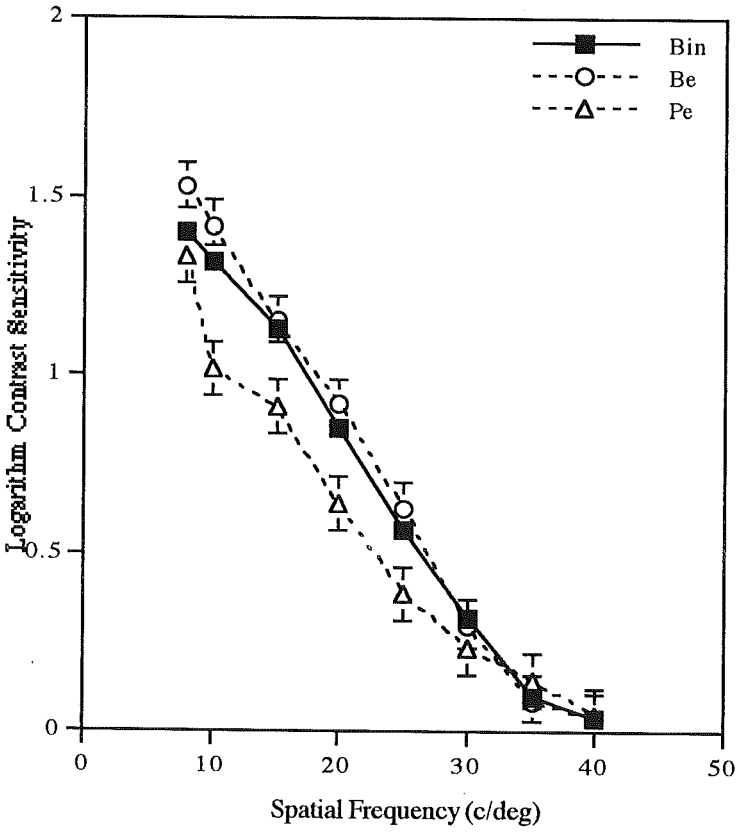


Figure 50. Logarithm contrast sensitivity for the group of non-amblyopic esotropes without binocular single vision (n=4) for monocular viewing through the better eye (Be), poorer eye (Pe) and for binocular viewing (Bin). Points shown represent the mean ± the pooled standard error of values for each of 4 subjects. Each of these values was itself the mean of 6 determinations.

Table 12. Reduction in linear contrast sensitivities averaged over spatial frequencies studied between the better and poorer eye, and reduction between binocular viewing and better eye in non-amblyopic esotropes without anomalous BSV.

Subject	Better Eye vs Poorer Eye $\frac{(Pe - Be)}{Be} \times 100\%$	Binocular vs Better Eye $\frac{(Bin - Be)}{Be} \times 100\%$
1	-44% ± 5% **	-26% ± 6% *
2	-22% ± 4% **	+ 2% ± 6% ns
3	-51% ± 9% **	- 5% ± 11% ns
4	-18% ± 3% *	-14% ± 2% **
Mean	**-34% ***	**-11% ns**

Each value is mean ± SE for the spatial frequencies tested in each subject.
Be - Better Eye Pe - Poorer Eye Bin - Binocular Viewing
ns - P>0.05 * P<0.05 ** P<0.01

The data shown in Figure 50 were replotted in linear form (Figure 51), and showed that the change in mean percentage contrast sensitivities between the better eye (Be) and the poorer eye (Pe) across the range of spatial frequencies varied from -60% at the lower spatial frequency of 10c/deg to +2% at the higher spatial frequency of 40c/deg (Figure 51A).

A decrease in binocular contrast sensitivities (Bin) was also evident in all but one individual, Subject 2, at all spatial frequencies when compared to the logarithm contrast sensitivities of the better eye (Be) (Table 12). The percentage reduction varied from -26% at 8c/deg to +5% at 30c/deg (Figure 51A).

Thus, in this non-amblyopic group, the mean percentage differences across the range of spatial frequencies examined, when the better eye was compared with the poorer eye, and the binocular contrast sensitivities were compared to those through the better eye, were less at the higher spatial frequencies.

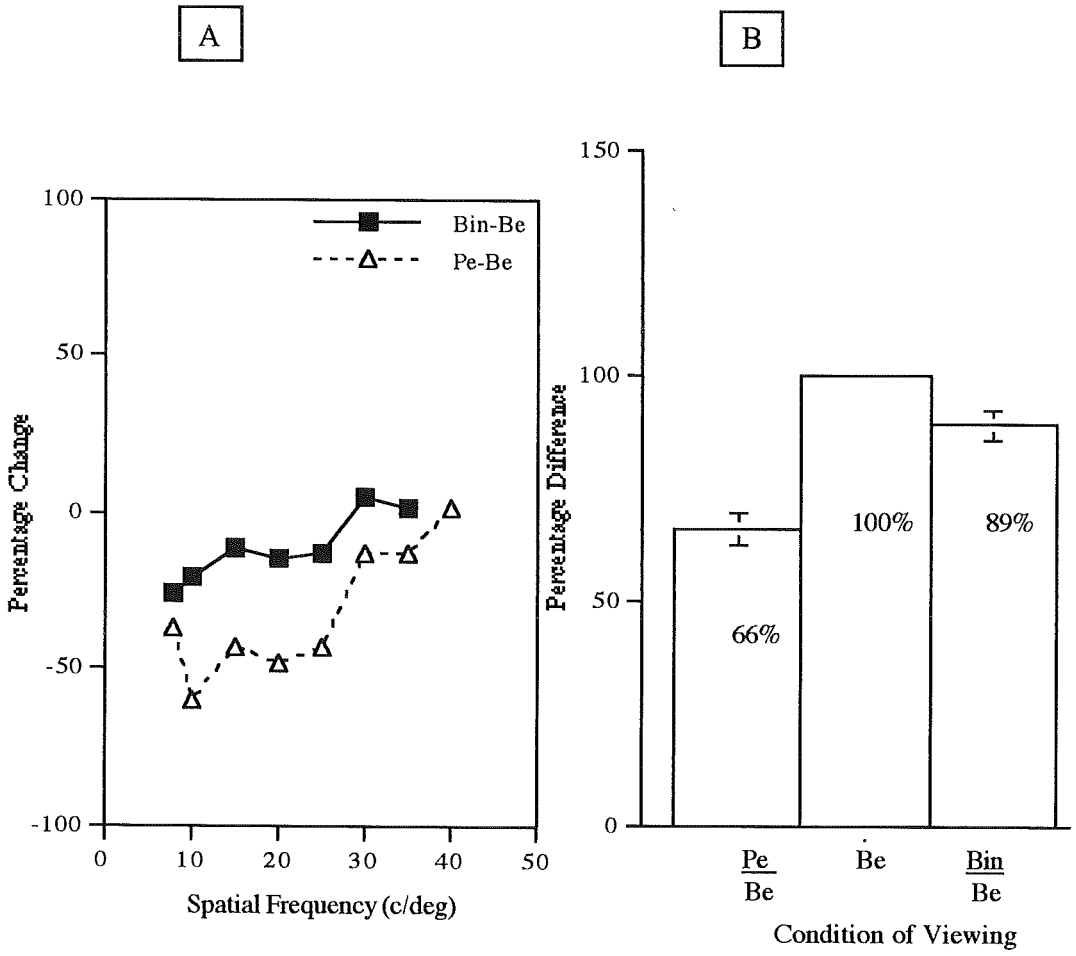


Figure 51. Contrast sensitivity changes in non-amblyopic esotropes without BSV (n=4). **A**: Percentage reduction in contrast sensitivity for poorer eye (Pe) and for binocular viewing (Bin), each referenced to the better eye (Be) taken as 100%, at different spatial frequencies. **B**: The same data as in **A** but averaged over spatial frequencies to give a single mean value ± SE.

3.1.7 Exotropic Amblyopes without BSV

Two female individuals, 37 years and 52 years of age, comprised this group.

3.1.7.1 Ocular Status

Both subjects in this group exhibited consecutive exotropia. Amblyopia in the squinting eye and absence of BSV were evident. Fixation in the amblyopic eye, in both cases, was foveal. One individual exhibited a dissociated vertical deviation (DVD). Pupil diameters were equal in both eyes, both subjects having a diameter of 4mm. The amplitude of accommodation in Subject 1 was less than that of the other participant in this group (Table 13); however, it was sufficient for her needs with regard to the distance of the experiment.

Table 13 Clinical Data for Exotropic Amblyopes without BSV

Subject	Visual Acuity	Refractive Error	Angle of Deviation	Accommodation (Amplitude)
1	RE 6/6 LE 6/36	RE +0.75DS LE +2.25DS	N : BI 16^ : D : BI 16^ R/L 6^ R/L 8^	RE 2.0D LE 2.0D
2	RE 6/9 LE 6/6	RE +2.75DS LE +1.00DS	N : BI 18^ : D : BI 18^	RE 7.0D LE ¯ 0D

Key: RE: Right Eye: LE: Left Eye N: Near D: Distant BI: Base In
D: Dioptres of Accommodation: DS: Dioptre Sphere DC: Dioptre Cylinder
^: Prism Dioptres -: Concave Lens +: Convex Lens R/L: Right Hypertropia (a vertical squint in which the right eye is elevated).
(Note: the angle of deviation prefixed by N and D is the total angle of deviation).

3.1.7.2 Contrast Sensitivity: Individual Data

For each subject, contrast sensitivities expressed in logarithmic form were measured at spatial frequencies 8, 10, 15, 20, 25, and 30c/deg for left and right eye viewing and then for binocular viewing.

Subject 1

For Subject 1, logarithm contrast sensitivities of the poorer eye (Pe) were much reduced compared with those of the better eye (Be) (Figure 52A). However, there was only a marginal difference in the logarithm contrast sensitivities under binocular conditions of viewing (Bin) when compared to those of the better eye (Figure 52B). The mean decrease in logarithm contrast sensitivity, averaged over the spatial frequency range between the poorer, amblyopic eye (Pe) and the normal eye (Be) was 0.9 log units, represented a significant mean reduction of 87% ± 3%SE ($P<0.01$, paired t-test). The reduction in the binocular logarithm contrast sensitivity (Bin) when compared to that of the better eye (Be) was 0.05 log units, representing an overall reduction of 11% ± 7%SE, which was not significantly different ($P=0.2$, paired t-test) (Table 14).

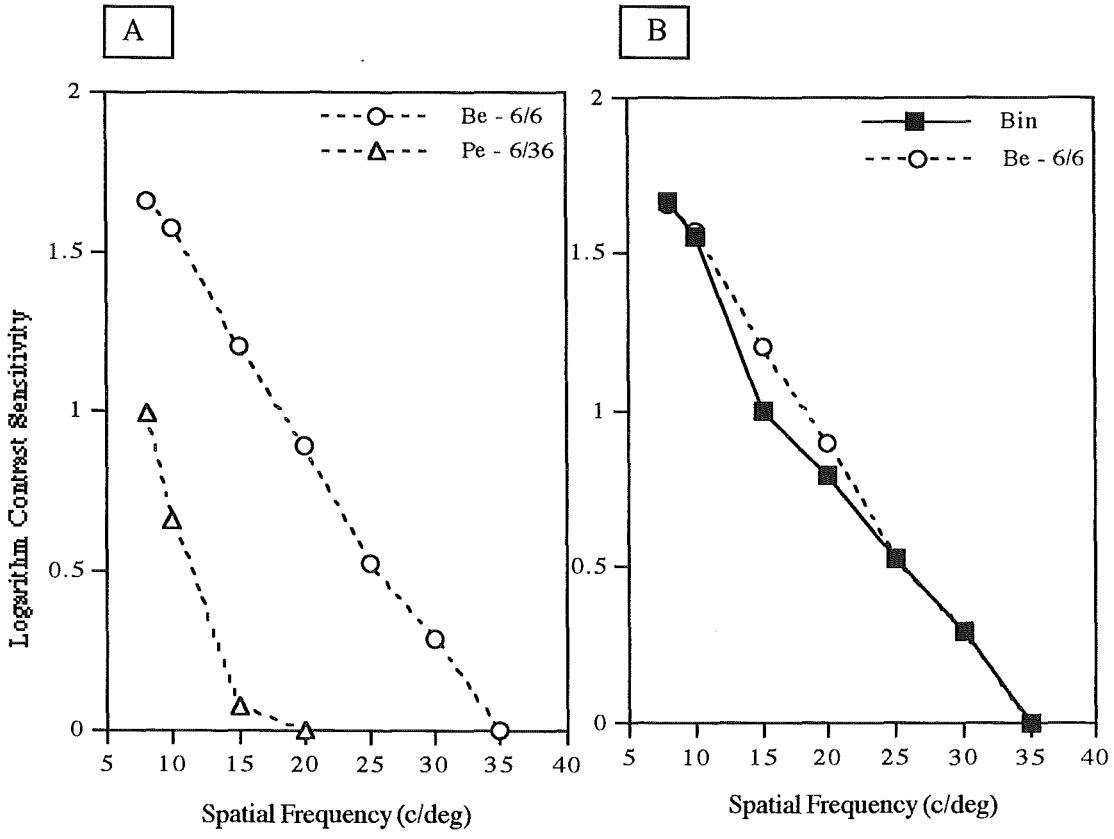


Figure 52. Logarithm contrast sensitivity for amblyopic exotrope without BSV, Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A: For monocular viewing through the better eye (Be) and through the poorer eye (Pe)
B: For binocular viewing (Bin) and through the better eye (Be) (same data as in **A**).

Subject 2

The results for Subject 2 reflect the general pattern of Subject 1. Figure 53A shows a marked shift downwards in the logarithm contrast sensitivities for the amblyopic eye (Pe) compared to those of the better eye (Be). A small reduction in the binocular logarithm contrast sensitivities (Bin) occurred, compared with those of the better eye (Figure 53B).

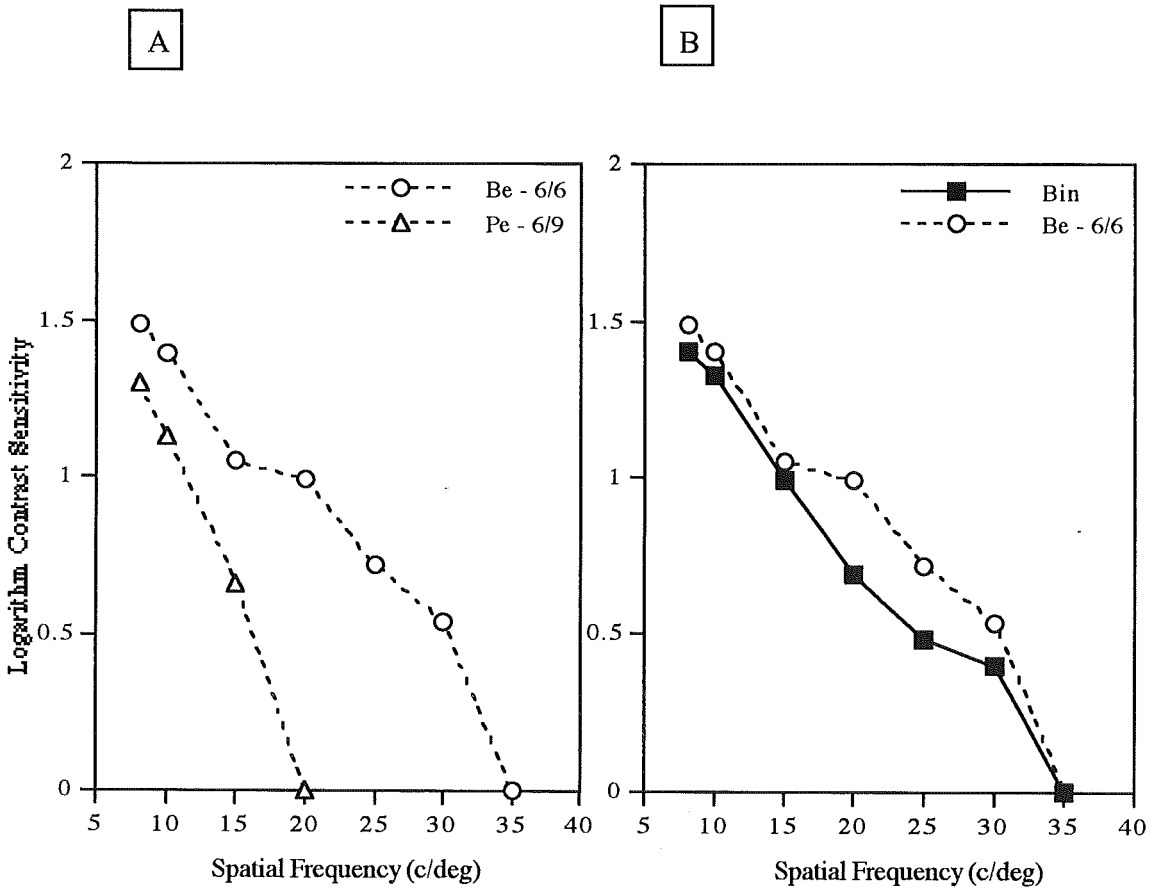


Figure 53. Logarithm contrast sensitivity for amblyopic exotrope without BSV, Subject 2. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. For monocular viewing through the better eye (Be) and through the poorer eye (Pe)
B. For binocular viewing (Bin) and through the better eye (Be) (same data as in **A**).

The mean decrease in logarithm contrast sensitivity, averaged over the range of spatial frequencies, of 0.36 log units in the amblyopic eye (Pe), when compared to those for the normal eye represents a loss of 56% ± 12% SE ($P<0.05$, paired

t-test) (Figure 53A). Under binocular conditions of viewing (Bin), a reduction of 0.15 log units occurred when compared with the better eye. This represented a statistically significant decrease of 29% ± 6% SE (P<0.01, paired t-test) (Figure 53B; Table 14).

Table 14 Reduction in linear contrast sensitivity averaged over spatial frequencies studied between better and poorer eye, and between binocular viewing and better eye in exotropic amblyopes without BSV

Subject	Better Eye vs Poorer Eye $\frac{(Pe - Be)}{Be} \times 100\%$	Binocular vs Better Eye $\frac{(Bin - Be)}{Be} \times 100\%$
1	-87% ± 3% **	-11% ± 7% ns
2	-56% ± 12% *	-29% ± 6% **
Mean	**-72%**	**-20%**

Each value is mean for the spatial frequencies in each subject tested.
Be - Better Eye Pe - Poorer Eye Bin - Binocular Viewing
ns - P>0.05 * P<0.05 ** P<0.01

When the mean change in percentage contrast sensitivities between the better eye (Be) and the poorer eye (Pe) for the 2 subjects comprising this group was calculated for each spatial frequency tested, there was a percentage reduction of between 57% to 100% (Figure 54A). In this case, the deficit in contrast sensitivity of the poorer eye (Pe), compared with the better eye (Be), was made over the spatial frequency range up to 20c/deg. Contrast sensitivities were also reduced (from 9% to 39%) across the range of spatial frequencies examined when the binocular contrast sensitivities (Bin) were compared with those for the better eye (Figure 54A).

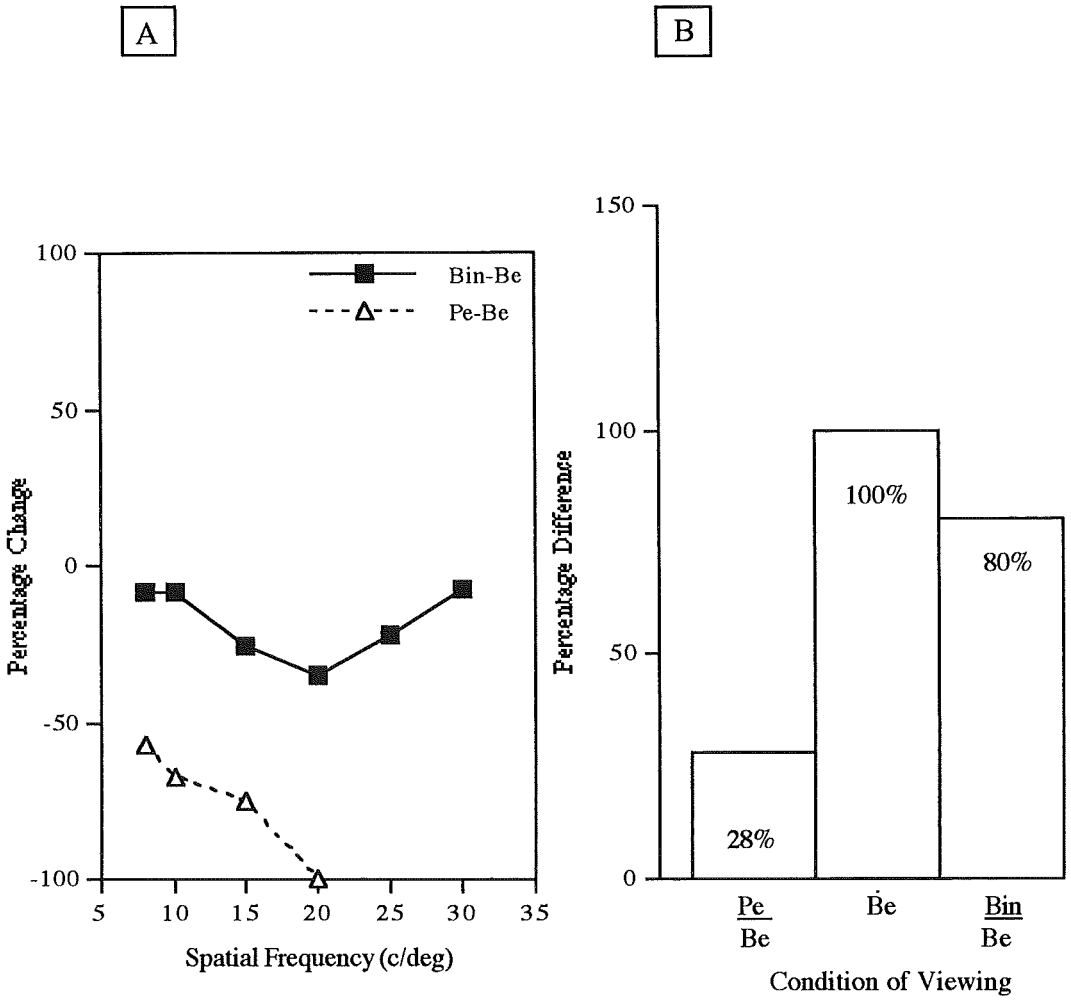


Figure 54. Contrast sensitivity changes in exotropic amblyopes without BSV (n=2).
A: Percentage reduction in contrast sensitivity for poorer eye (Pe) and for binocular viewing (Bin), each referenced to the better eye (Be) taken as 100%, at different spatial frequencies.
B: The same data as in **A**, for the two individuals comprising this group, ' t averaged over spatial frequencies to give a single mean value. SE has been omitted as n=2 only.

3.1.8 Non-Amblyopic Exotropes without BSV

Two male individuals, aged 34 years and 38 years, comprised this group.

3.1.8.1 Ocular Status

Each participant exhibited a constant exotropia without BSV with visual acuity of 6/5 or better in each eye (Table 15), constant suppression and foveal fixation on ophthalmoscopy. Pupil sizes in the right and left eyes of both subjects measured 4mm.

Table 15 Clinical Data for non-amblyopic exotropes without BSV

Subject	Visual Acuity	Refractive Error	Angle of Deviation	Accommodation (Amplitude)
1	RE 6/5 LE 6/5	Nil	N:BI 16^: D:BI 16^	RE 6.00D LE 6.00D
2	RE 6/4 LE 6/4	RE -2.50DS LE -0.50DS	N:BI 12^: D:BI 12^	RE 8.00D LE 8.00D

Key: RE: Right Eye: LE: Left Eye N: Near D: Distant BI: Base In
D: Dioptres of Accommodation: DS: Dioptre Sphere DC: Dioptre Cylinder
^: Prism Dioptres -: Concave Lens +: Convex Lens
(Note: the angle of deviation prefixed by N and D is the total angle of deviation).

3.1.8.2 Contrast Sensitivity: Individual Data

For each subject, contrast sensitivity expressed in logarithmic form was obtained at spatial frequencies 8, 10, 15, and 20c/deg for left and right eye viewing, and then for binocular viewing. Despite the presence of normal visual acuity (Table 15), neither subject was able to detect the presence of the grating pattern at 25c/deg. In both cases, the logarithm contrast sensitivities were better in one eye, denoted the better eye (Be) compared with those of the other eye, denoted the poorer eye (Pe).

Subject 1

The logarithm contrast sensitivities of the poorer eye (Pe) in this subject were slightly depressed compared with those of the better eye (Be) (Figure 55A). A mean reduction in logarithm contrast sensitivity of 0.25 log units, averaged over

the range of spatial frequencies, was evident when the poorer eye (Pe) was compared with the better eye (Be). This represents a reduction of 44% ± 5% SE which was significant (P<0.01; paired t-test). The binocular logarithm contrast sensitivities were also reduced compared with monocular viewing through the better eye by a mean of 0.23 log units, which represents a decrease of 41% ± 6% SE: (P<0.01, paired t-test), compared with the better eye (Be) (Figure 55B).

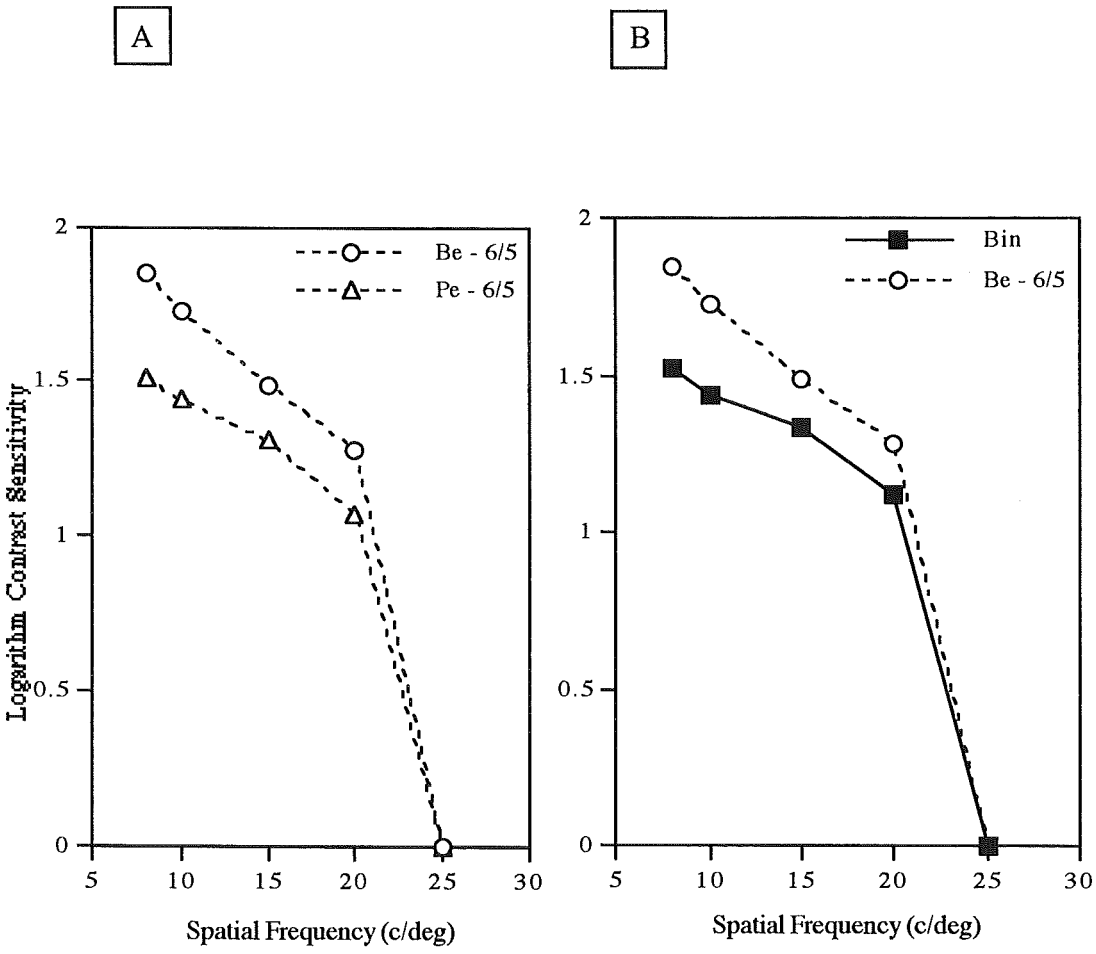


Figure 55. Logarithm contrast sensitivity for non-amblyopic exotrope without BSV, Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Monocular viewing through the better eye (Be) and through the poorer eye (Pe).
B. Binocular viewing (Bin) and through the better eye (Be) (same data as in **A**).

Subject 2

The logarithm contrast sensitivities in the poorer eye in this subject were consistently less than those of the better eye (Figure 56A). Under binocular conditions of viewing, the logarithm contrast sensitivities were also less than those of the better eye (Figure 56B).

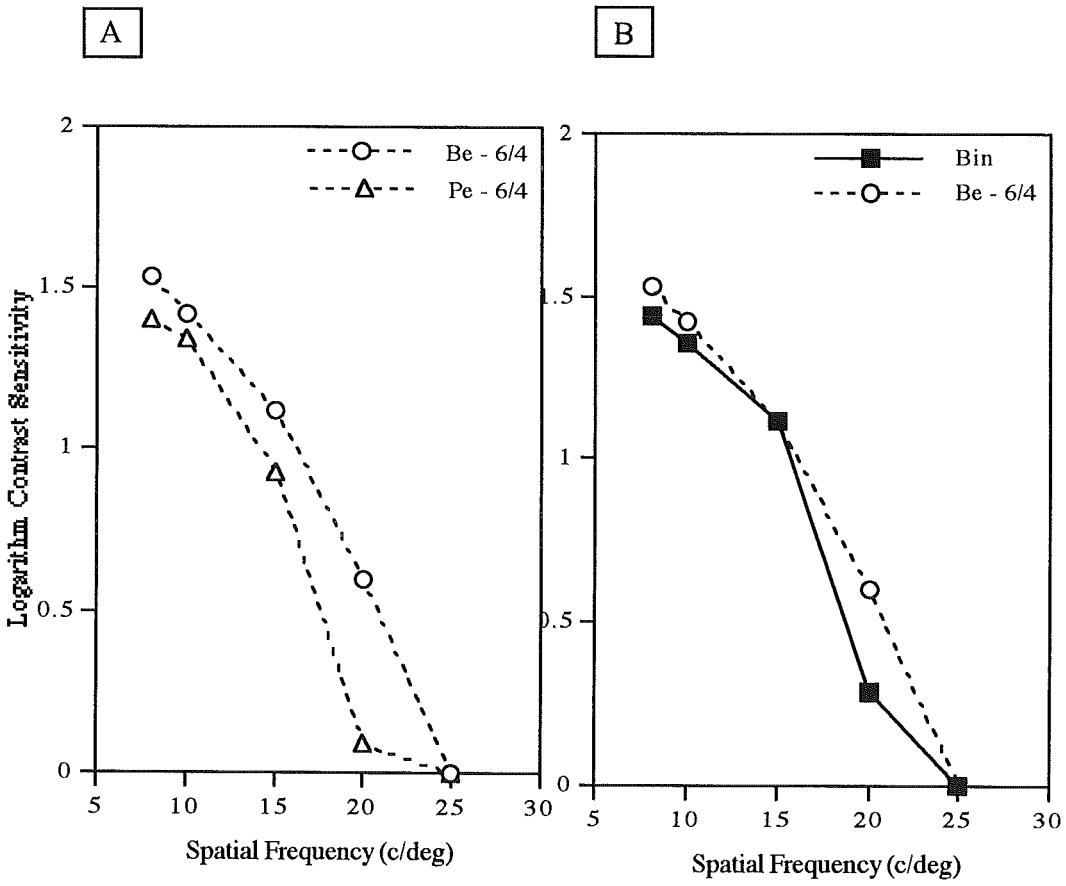


Figure 56. Logarithm contrast sensitivity for non-amblyopic exotrope without BSV, Subject 2. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Monocular viewing through the better eye (Be) and through the poorer eye (Pe).
B. Binocular viewing (Bin) and through the better eye (Be) (same data as in **A**). SE has been omitted as n=2 only.

The logarithm contrast sensitivities through the poorer eye (Pe), when compared to those through the better eye (Be), were reduced by a mean of 0.23 log units over the range of spatial frequencies studied. This represents a statistically significant percentage reduction of 41% ± 6%SE ($P<0.01$, paired t-test) (Figure

56A, Table 16). A mean reduction in binocular logarithm contrast sensitivities (Bin) of 0.11 log units was recorded when compared to the logarithm contrast sensitivities achieved by the better eye (Be). This represents a decrease of 22% ± 11% SE; however this was not significant (P=0.1, paired t-test) (Figure 56B, Table 16).

The data shown in Figures 55 and 56 were then replotted in linear form against spatial frequency for this small group of subjects (n=2), with the contrast sensitivities for the better eye expressed in each case as 100% (Figure 57).

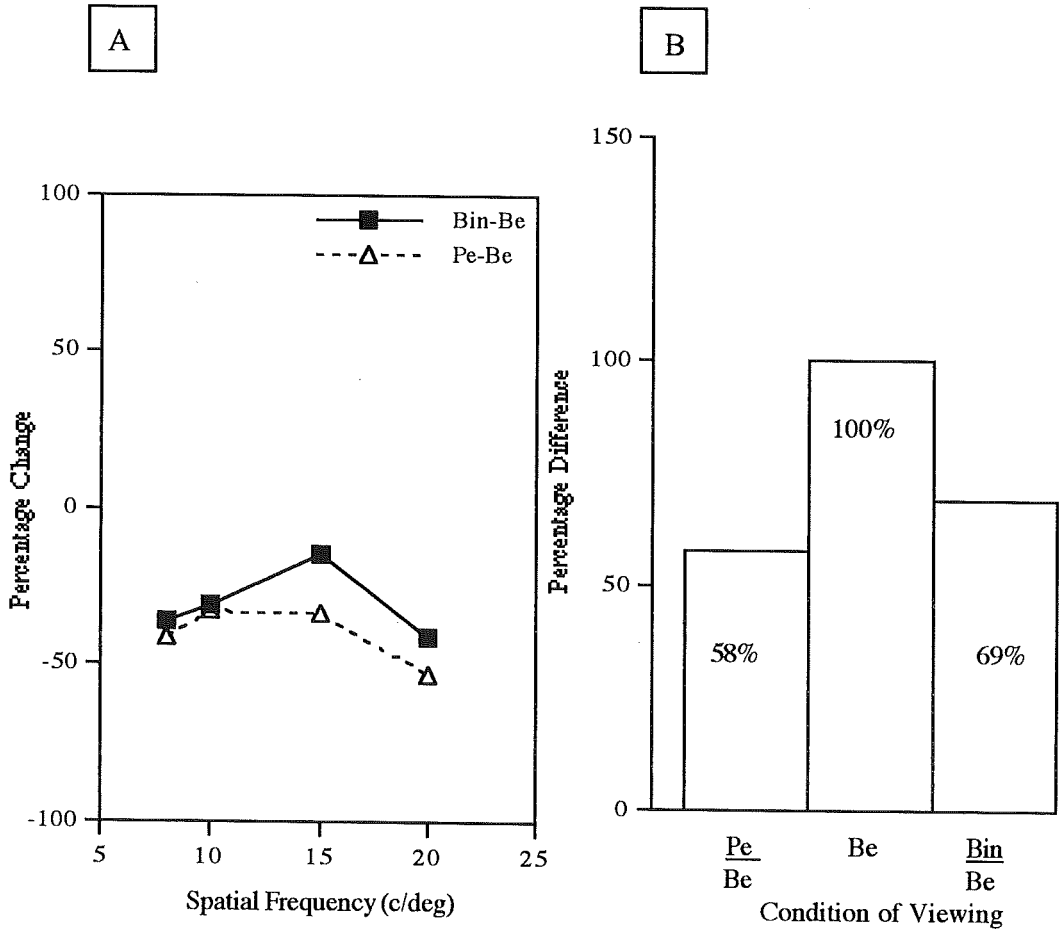


Figure 57. Contrast sensitivity changes in non-amblyopic exotropes without BSV (n=2). **A:** Percentage reduction in contrast sensitivity for poorer eye (Pe) and for binocular viewing (Bin), each referenced to the better eye (Be) taken as 100%, at different spatial frequencies. **B**: The same data as in **A**, for the two individuals comprising this group, but averaged over spatial frequencies to give a single mean value. SE has been omitted as n=2 only.

The change in mean percentage contrast sensitivities between the better eye (Be) and the poorer eye (Pe) for the 2 subjects comprising this group showed a percentage reduction of between 33% and 53% across the range of spatial frequencies examined (Figure 57A). The mean percentage loss in binocular contrast sensitivities (Bin) across the range of spatial frequencies studied when compared to those of the better eye (Be) ranged from 15% to 41% (Figure 57A).

Table 16 Reduction in linear contrast sensitivity averaged over spatial frequencies studied between better and poorer eye, and between binocular viewing and better eye in non-amblyopic exotropes without BSV (n=2).

Subject	Better Eye vs Poorer Eye $\frac{(Pe - Be)}{Be} \times 100\%$	Binocular vs Better Eye $\frac{(Bin - Be)}{Be} \times 100\%$
1	-44% ± 5% **	-41% ± 6% **
2	-41% ± 6% **	-22% ± 11% ns
Mean	**-42%**	**-31%**

Each value is mean for the spatial frequencies tested in each subject.
Be - Better Eye Pe - Poorer Eye Bin - Binocular Viewing
ns - P>0.05 * P<0.05 ** P<0.01

3.1.9 Summary

In the groups in which BSV was present *viz.* normals, simple anisometropic amblyopes, microtropic anisometropic amblyopes and esotropic amblyopes with anomalous BSV, binocular contrast sensitivities were increased, compared with those for monocular viewing through the better eye. There was an overall mean percentage increase of 32% in the four groups with BSV. These have been grouped together in in tabular form (Table 17) and in a summary graph (Figure 58A).

Table 17 Percentage increase in the binocular contrast sensitivity averaged over spatial frequencies studied in groups with BSV and percentage reduction in binocular contrast sensitivity averaged over spatial frequencies studied in groups without BSV

Group	$\frac{(Bin - Be)}{Be} \times 100\%$	Group	$\frac{(Bin - Be)}{Be} \times 100\%$
Control Group with normal BSV	+15% ** {F = 81.64 **}	Esotropic Amblyopes without BSV	-13% ** {F = 31.28 **}
Simple Anisometropic Amblyopes with normal BSV	+35% ** {F = 29.50 **}	Non-Amblyopic Esotropes without BSV	-11% ns {F = 3.57 ns}
Micro-esotropic amblyopes with anomalous BSV	+35% ns {F = 51.93 **}	Exotropic Amblyopes without BSV	-20% (+) {F (+) }
Esotropic Amblyopes with anomalous BSV	+44% * {F = 115.01 **)	Non-Amblyopic Exotropes without BSV	-31% (+) {F (+) }
Mean	**+32%**		**-19%**

P. ns - not significant. * P<0.05 ** P<0.01 (+) not tested as n = 2
{F - F factor obtained when analysis of data was undertaken using the 3 factor analysis of variance, the ANOVA statistical test}

In those groups in which BSV was absent *viz.* esotropic amblyopes, exotropic amblyopes, non-amblyopic esotropes, and non-amblyopic exotropes, there was an overall percentage loss contrast sensitivity in all groups (Figure 58B). The overall mean percentage decrease in binocular contrast sensitivity of the four groups was 19% (Table 17).

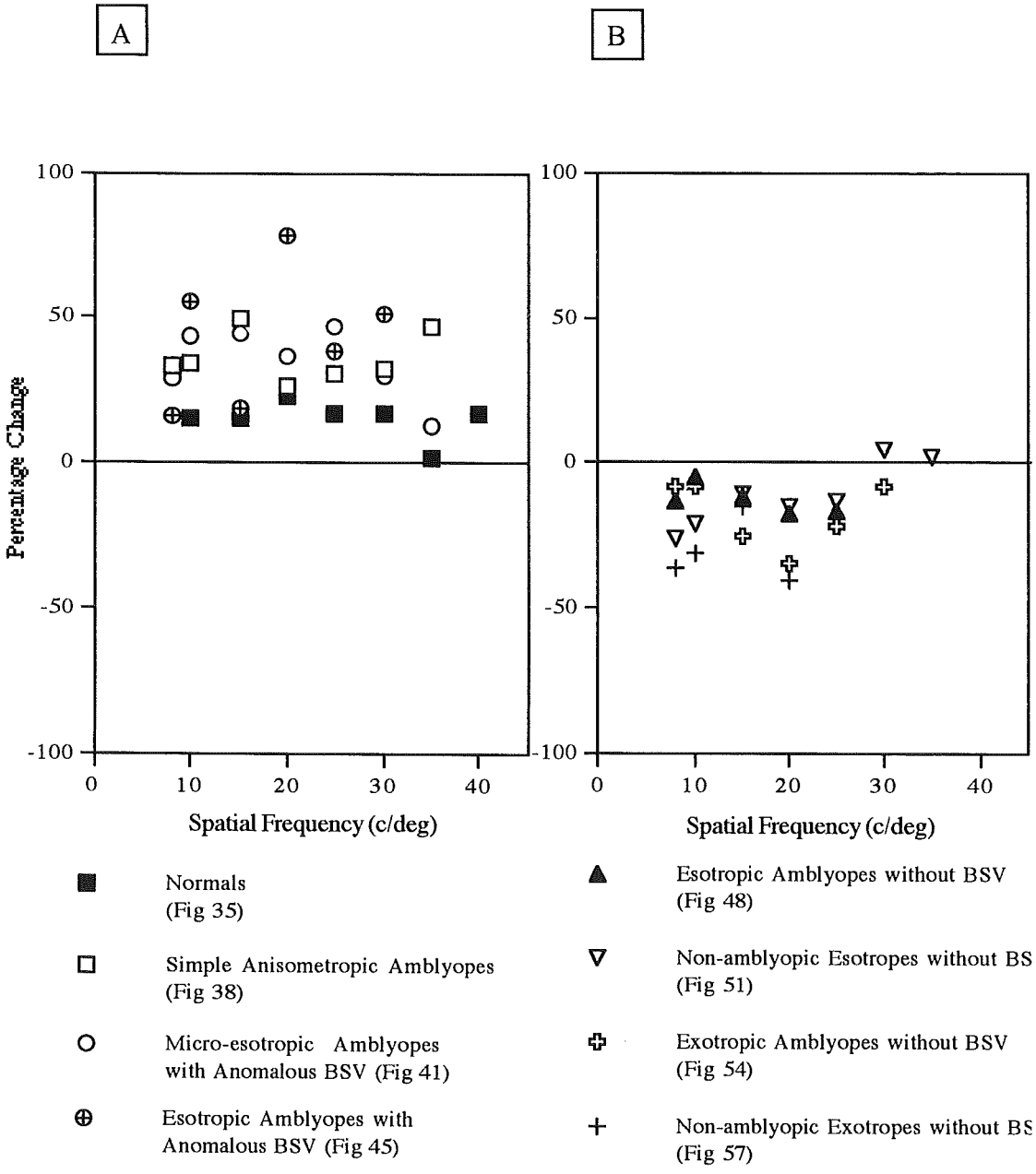


Figure 58. Summary of mean percentage change in contrast sensitivity for binocular viewing compared with monocular viewing through the better eye at each spatial frequency tested.
A. Groups showing an increase in binocular contrast sensitivity.
B. Groups showing a decrease in binocular contrast sensitivity
(Figure from which data are taken is given in parenthesis).

3.2 Neutralisation of the Angle of Strabismus

In addition to examining the contrast sensitivity of strabismics under monocular and binocular conditions of viewing, contrast sensitivity was determined for binocular viewing after the angle of strabismus had been corrected by placing a glass prism(s) of appropriate total strength and base direction distributed in front of one or both eyes. Thus, the normal binocular contrast sensitivities (Bin) were measured and compared with those achieved under conditions of bifoveal stimulation (Bin^) in all subjects comprising the strabismic groups described in Section 3.1.

3.2.1 Micro-esotropic Amblyopes

Individuals comprising this group of amblyopes exhibited a small angle esotropia of five degrees (ten prism dioptres) or less, amblyopia and parafoveal fixation in the squinting eye. In addition, anomalous BSV, where a different parafoveal point in the squinting eye corresponds with the fovea of the fixating eye (Figure 9), was present. Neutralisation of the angle of microtropia would thus effect binocular viewing involving foveal viewing by the normal eye and parafoveal viewing with the monocular parafoveal fixation point in the microtropic eye. For convenience this has been referred to as bifoveal viewing.

3.2.1.1 Contrast Sensitivity: Individual Data

After the angle of strabismus was neutralised, the bifoveal logarithm contrast sensitivities (Bin^) in Subject 1 of this group were shifted slightly downwards when compared with those achieved under binocular conditions of viewing (Bin) (Figure 59A), with the highest spatial frequencies of 35c/deg and 40c/deg remaining undetected. The mean reduction in bifoveal contrast sensitivity (Bin^) across the spatial frequency range of 8 to 30c/deg compared to that under binocular conditions of viewing (Bin) was 0.20 log units, which represented a mean percentage loss of 37% ± 5% SE ($P<0.01$, paired t-test.)(Figure 59A). The bifoveal logarithm contrast sensitivities (Bin^) were also less than those for monocular viewing through the better eye (Be), which also was unable to discern a grating pattern of 30c/deg (Figure 59B). There was a mean reduction

over the spatial frequency range of 0.13 log units, equivalent to a mean percentage decrease of 26% ± 7%SE, which was significant (P<0.01, paired t-test).

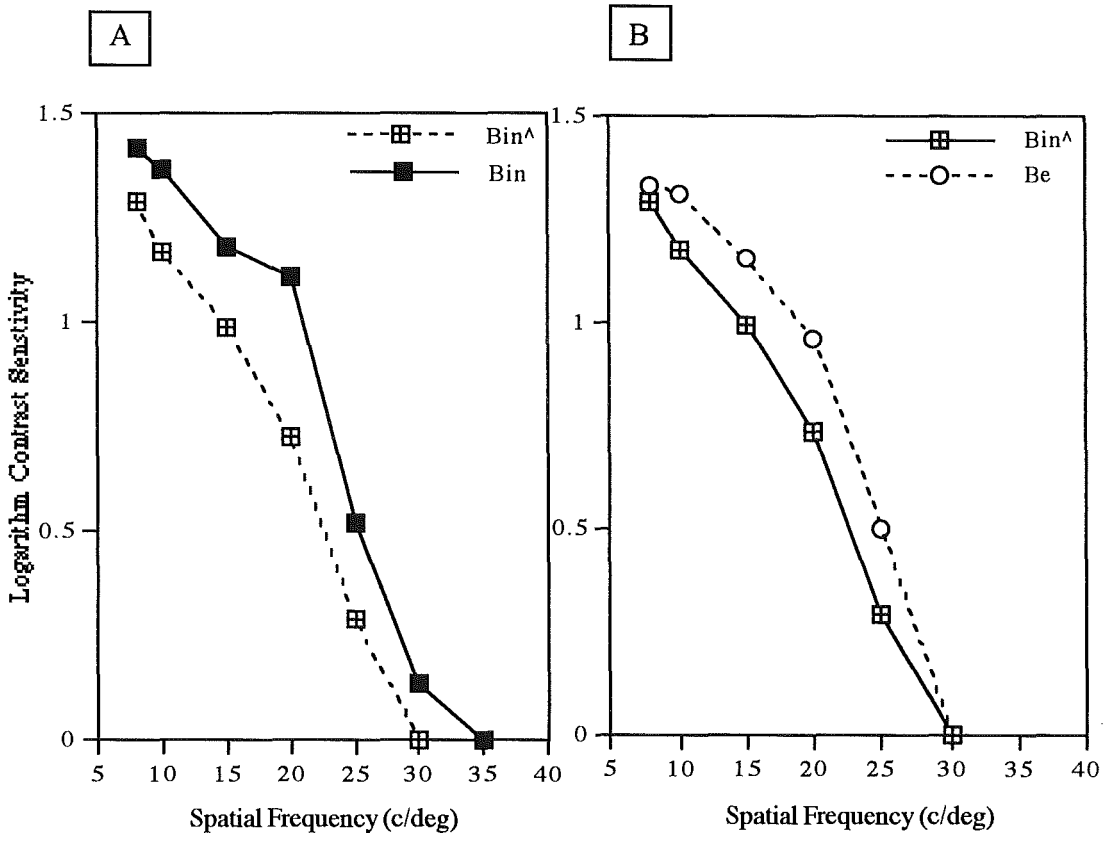


Figure 59. Logarithm contrast sensitivity against increasing spatial frequency for micro-esotropic amblyope, Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Binocular viewing (Bin) (same data as in Figure 39B) and under conditions of bifoveal stimulation (Bin^)
B. Monocular viewing through the better eye (Be) (same data as in Figure 39A) and under conditions of bifoveal stimulation (Bin^) (same data as in **A**).

3.2.1.2 Contrast Sensitivity: Group Data

The group logarithm contrast sensitivities were similar to those of Subject 1 in that the bifoveal logarithm contrast sensitivities (Bin^) were consistently depressed by a mean of 0.13 log units over the range of spatial frequencies compared with those under binocular conditions of viewing (Bin) (Figure 60A). This represented a loss of 26% ± 5% SE which was significant (n = 6; t = 5.53; P = 0.003; one sample t-test). (Table 18). A 3-factor ANOVA also revealed that the bifoveal contrast sensitivities were significantly poorer than binocular

contrast sensitivities in subjects comprising this group (F = 183.96; P <0.001). In addition, there was significant variation in the bifoveal logarithm contrast sensitivities within the group (F = 13.69; P<0.001) and across the range of spatial frequencies (F = 877.13; P<0.001).

The bifoveal contrast sensitivities (Bin^) were similar to those for viewing with the better eye (Figure 60B). There was no statistically significant difference between the bifoveal binocular contrast sensitivities (Bin^) compared with those of the better eye (Be) averaged over the range of spatial frequencies (-2% ± 11%) (n = 6; t = 0.2; P = 0.8; one sample t-test) (Figure 60B). No significant difference in the bifoveal contrast sensitivities when compared to those of the better eye (F = 2.49; P = 0.06) was evident when the data were reanalysed using the ANOVA test.

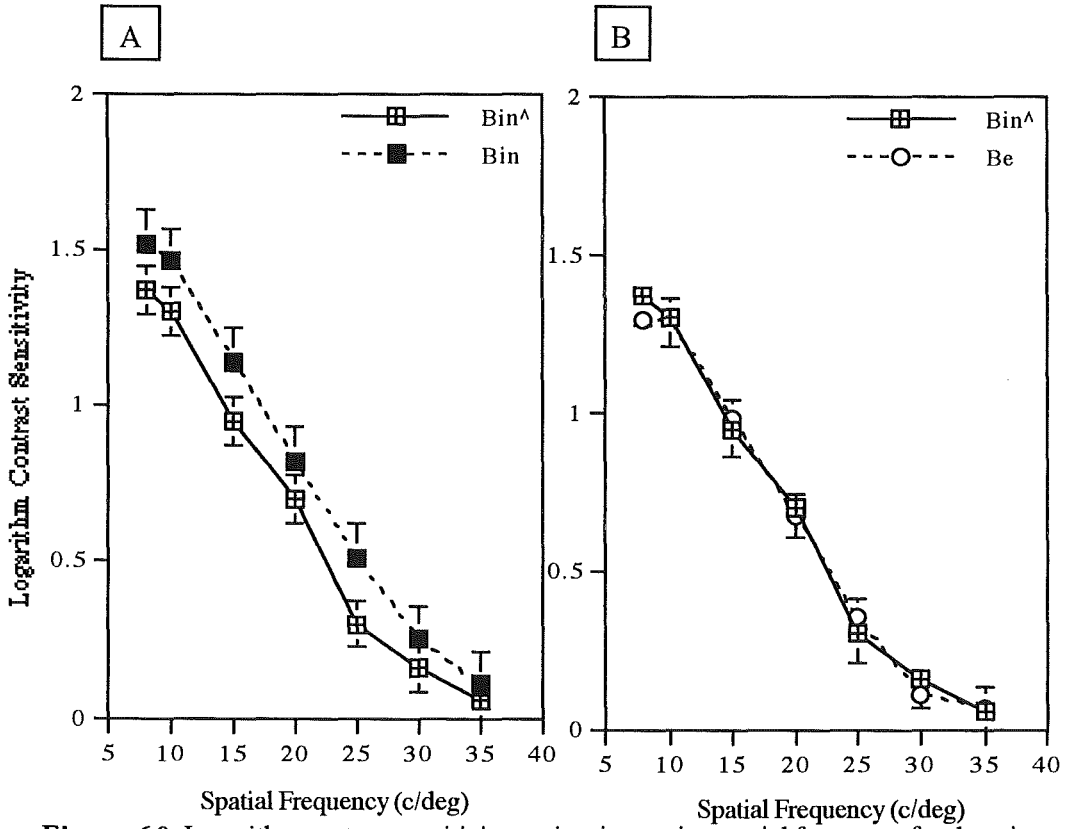


Figure 60. Logarithm contrast sensitivity against increasing spatial frequency for the micro-esotropic amblyopes. Points shown represent the mean ± the pooled standard error of values for each of the 6 subjects. Each of these values was itself the mean of 6 determinations.

A. Binocular viewing (Bin) (same data as in Figure 40) and under conditions of bifoveal stimulation (Bin^).

B. Monocular viewing through the better eye (Be) (same data as in Figure 40) and under bifoveal conditions of viewing (Bin^) (same data as in **A**). The logarithm contrast sensitivity under bifoveal conditions of viewing and that for the better eye at 10c/deg are superimposed.

Table 18 Reduction in contrast sensitivity averaged over spatial frequencies studied under conditions of bifoveal stimulation and binocular viewing, and the change under conditions of bifoveal stimulation and the better eye.

Subject	Bifoveal Stimulation vs Binocular $\frac{(Bin^{\wedge} - Bin)}{Bin} \times 100\%$	Bifoveal Stimulation vs Better Eye $\frac{(Bin^{\wedge} - Be)}{Be} \times 100\%$
1	-37% ± 5% **	-26% ± 7% **
2	-23% ± 7% **	+27% ± 7% ns
3	-21% ± 8% ns	- 5% ± 4% ns
4	- 8% ± 4% ns	+23% ± 12% ns
5	-26% ± 5% **	-39% ± 16% ns
6	-39% ± 7% **	+ 7% ± 8% ns
Mean	**-26% ****	**-2% ns**

Each value is mean ± SE for the spatial frequencies tested in each subject.
Be - Better Eye Bin - Binocular Viewing Bin^ - Bifoveal Viewing
ns.- P>0.05 * P<0.05 ** P<0.01

When the angle of strabismus was neutralised and the mean values for bifoveal viewing (Bin^) at each spatial frequency were compared to those under binocular conditions of viewing (Bin) (Figure 61), a percentage reduction, under conditions of bifoveal stimulation, ranging from 20% to 33%, with a mean reduction of 26% ± 5% was present (Table 18, Figure 62A). There was no consistent difference between the bifoveal contrast sensitivities (Bin^) when compared to those of the better eye (Be) over the range of spatial frequencies examined (Figure 61). The mean percentage change ranged from +20% to -14% with an overall mean percentage decrease of 2% ± 11% SE in the contrast sensitivity function under bifoveal conditions of viewing when compared to that of the better eye, which was not statistically significant (P = 0.8, one sample t-test) (Figure 62B). The 3 factor ANOVA did, however, indicate significant variation in logarithm contrast sensitivity across the range of spatial frequencies examined (F = 381.63; P<0.001).

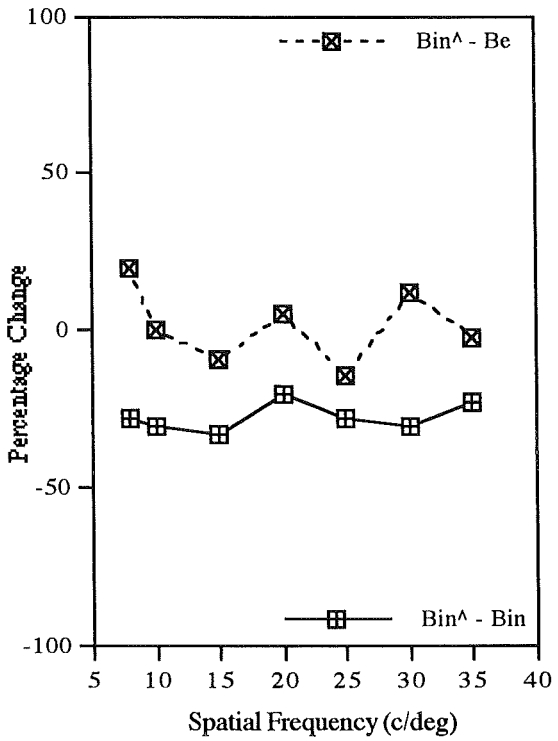


Figure 61. Mean percentage change in contrast sensitivity in micro-esotropic amblyopes (n=6) at each spatial frequency under conditions of bifoveal stimulation (Bin^) compared with normal binocular viewing (Bin) and with the better eye viewing (Be).

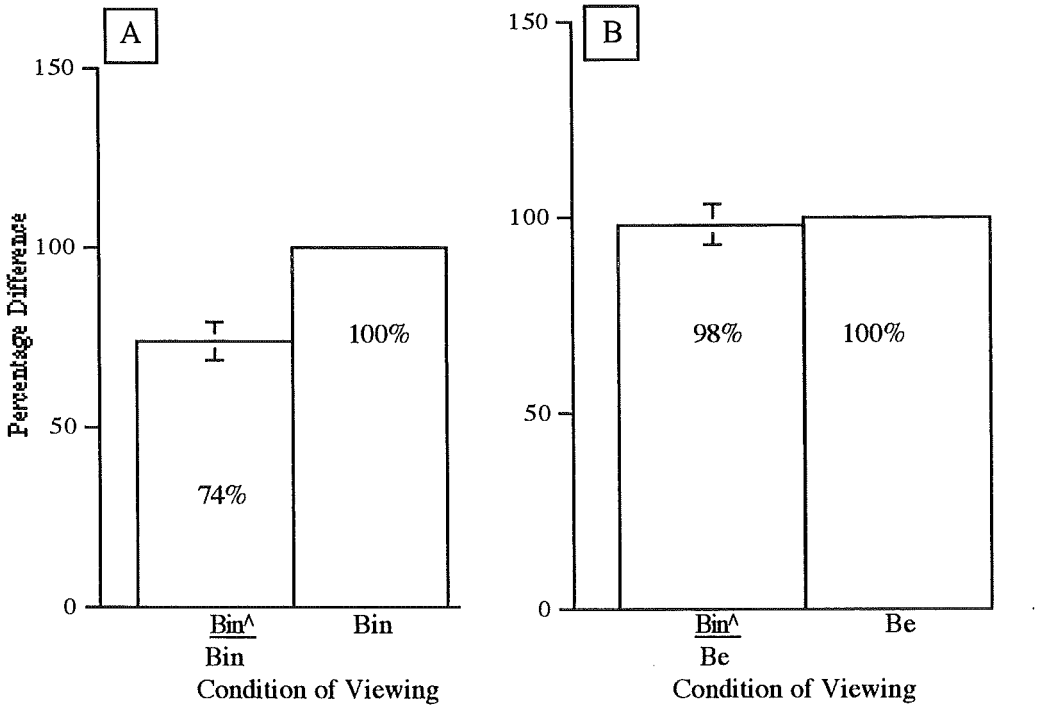


Figure 62. Contrast sensitivity changes in micro-esotropic amblyopes (n=6).
A. Percentage contrast sensitivity under conditions of bifoveal stimulation (Bin^), referenced to the binocular contrast sensitivity (Bin) taken as 100% (Bin^/Bin), averaged over spatial frequencies 8c/deg to 35c/deg to give a single mean value ± SE.
B. The same data as in **A** (Bin^), referenced to the better eye (Be) taken as 100%, averaged over spatial frequencies 8c/deg to 35c/deg to give a single mean value ± SE.

3.2.2 *Esotropic Amblyopes with Anomalous BSV*

The three esotropic amblyopes comprising this group of subjects exhibited a constant esotropia, amblyopia of varying degree and anomalous BSV (Table 7).

3.2.2.1 *Contrast Sensitivity: Individual Data:*

In Subject 1 of this strabismic group, a reduction in logarithm contrast sensitivity was evident under conditions of bifoveal stimulation (Bin^) when compared to the binocular logarithm contrast sensitivities (Bin) (Figure 63A).

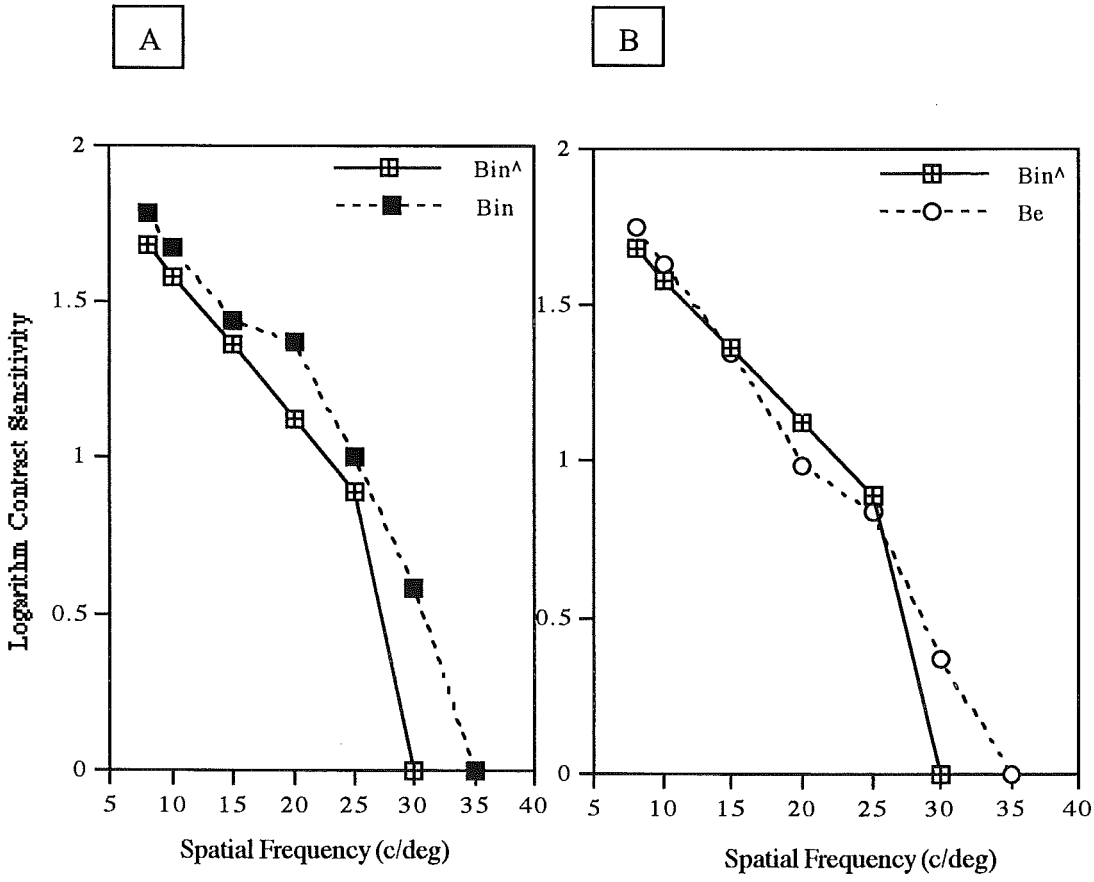


Figure 63. Logarithm contrast sensitivity against increasing spatial frequency for esotropic amblyope with anomalous BSV, Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Binocular viewing (Bin) (same data as in Figure 42B) and under conditions of bifoveal stimulation (Bin^).
B. Monocular viewing through the better eye (Be) (same data as in Figure 42A) and under conditions of bifoveal stimulation (Bin^) (same data as in **A**).

The mean reduction, over the range of spatial frequencies studied, was 0.2 log units, representing a mean percentage decrease of 37% ± 9% SE which was significant (P<0.05, paired t-test). When the bifoveal logarithm contrast sensitivities (Bin^) were compared to those of the better eye (Be), they were marginally lower, with the greatest loss at the higher spatial frequency of 30c/deg (Figure 63B). The mean decrease was 0.025 log units representing a mean percentage reduction of 6% ± 13% which was not significant (P = 0.6, paired, t-test).

Subject 2

In Subject 2, a reduction in logarithm contrast sensitivity was also evident under conditions of bifoveal stimulation (Bin^) when compared to the binocular logarithm contrast sensitivities (Bin) (Figure 64A). The mean reduction, over the range of spatial frequencies studied, was 0.15 log units which represented a mean percentage decrease of 29% ± 12% which was not significant (P >0.05, paired t-test). A small increase in logarithm contrast sensitivity was evident when the contrast sensitivity obtained under bifoveal conditions of viewing (Bin^) was compared with that obtained through the better eye (Be) (Figure 64B). This was not statistically significant (5% ± 13%; P. >0.05, paired t-test).

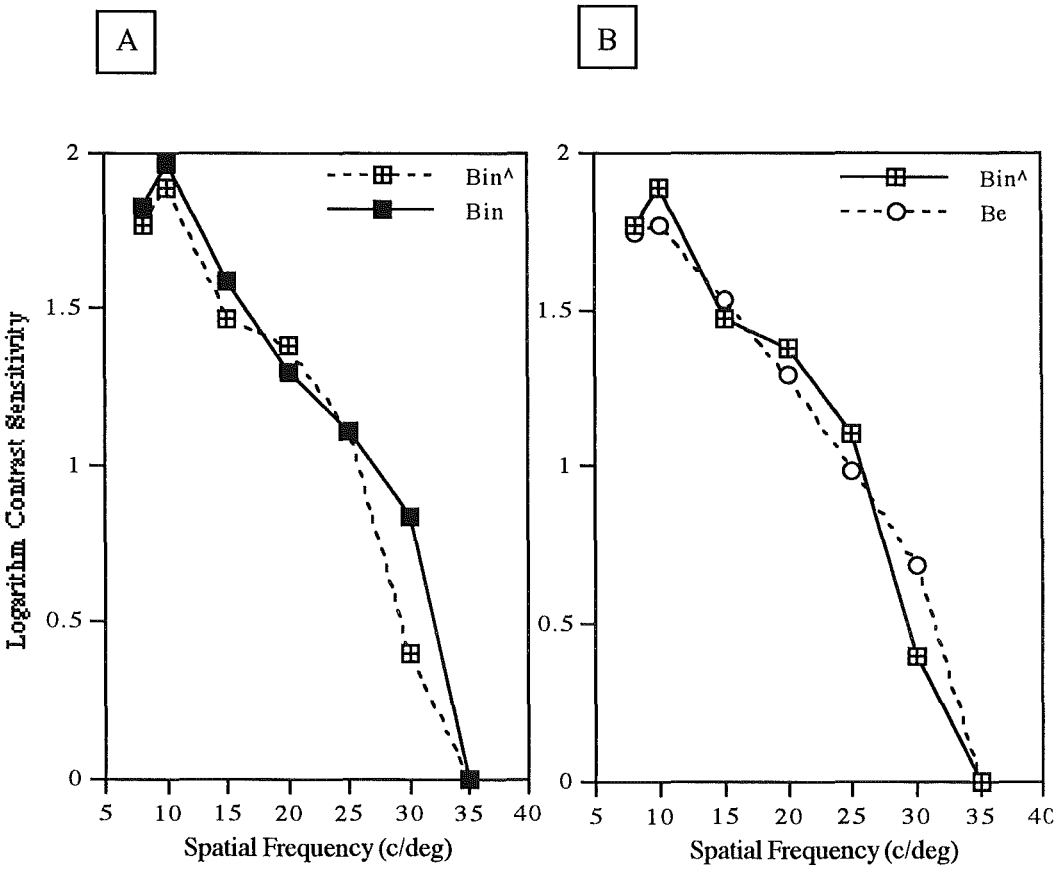


Figure 64 Logarithm contrast sensitivity against increasing spatial frequency for esotropic amblyope with anomalous BSV, Subject 2. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Binocular viewing (Bin) (same data as in Figure 43B) and under conditions of bifoveal stimulation (Bin^).
B. Monocular viewing through the better eye (Be) (same data as in Figure 43A) and under conditions of bifoveal stimulation (Bin^) (same data as in **A**).

Subject 3

In this subject when the bifoveal contrast sensitivity (Bin^), over the range of spatial frequencies examined, was compared to that obtained under binocular conditions of viewing (Bin) a decrease of 0.03 log units was evident. This represented a mean percentage reduction of 7% ± 11% which was not significant (P>0.05, paired t-test) (Figure 65A). When the bifoveal contrast sensitivity (Bin^) was compared to that obtained by the better eye (Be) an increase of 38% ± 11% which was not significant (P>0.05, paired t-test) was evident (Figure 65B) (Table 19).

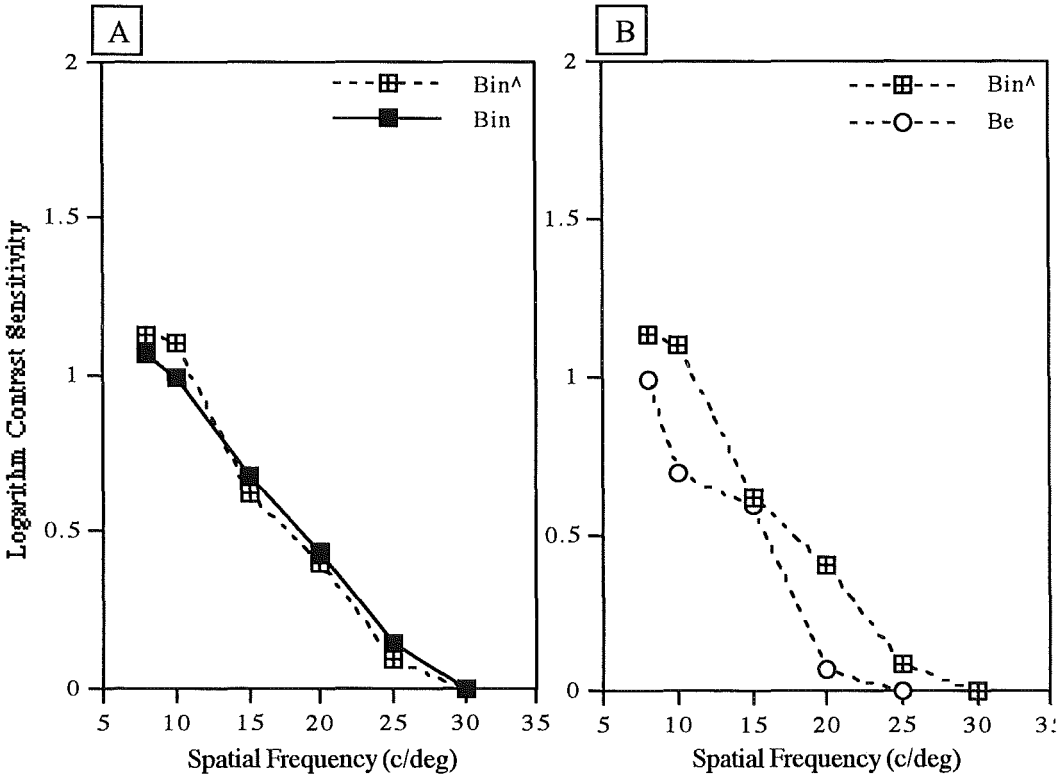


Figure 65 Logarithm contrast sensitivity against increasing spatial frequency for esotropic amblyope with anomalous BSV, Subject 3. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Binocular viewing (Bin) (same data as in Figure 44B) and under conditions of bifoveal stimulation (Bin^).
B. Monocular viewing through the better eye (Be) (same data as in Figure 44A) and under conditions of bifoveal stimulation (Bin^) (same data as in **A**).

Table 19 Reduction in contrast sensitivity averaged over spatial frequencies studied under bifoveal conditions of viewing and binocular viewing, and the change between bifoveal viewing and the better eye

Subject	Bifoveal Stimulation vs Binocular $\frac{(Bin^{\wedge} - Bin)}{Bin} \times 100\%$	Bifoveal Stimulation vs Better Eye $\frac{(Bin^{\wedge} - Be)}{Be} \times 100\%$
1	-37% ± 9% *	- 6% ± 13% ns
2	-29% ± 12% ns	+ 5% ± 13% ns
3	- 7% ± 11% ns	+ 38% ± 11%ns
Mean	**-24% ns**	**+12% ns**

Each value is mean ± SE for the spatial frequencies tested in each subject tested.
Be - Better Eye Bin - Binocular Viewing Bin^ - Bifoveal Viewing
ns.- P>0.05 * P<0.05; ** P<0.01

The mean difference between bifoveal contrast sensitivity (Bin^) and that under binocular (Bin) and monocular conditions of viewing (Be) for the group of 3 subjects at each spatial frequency was replotted in linear form (Figure 66). The bifoveal contrast sensitivities were reduced compared to the binocular contrast sensitivities (Bin), by between 9% and 30% and the differences compared to those for the better eye (Be) varied from 40% to -9% (Figure 66).

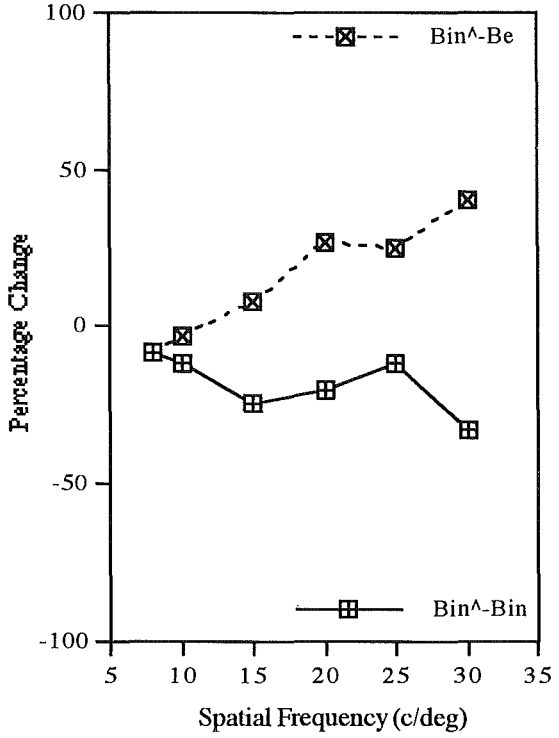


Figure 66. Mean percentage change in contrast sensitivity in esotropic amblyopes with anomalous BSV (n=3) at each spatial frequency under conditions of bifoveal stimulation (Bin^) compared with normal binocular viewing (Bin) and with better eye viewing (Be).

A 3-factor ANOVA showed that there was no significant difference in the logarithm contrast sensitivity obtained under bifoveal conditions of viewing (Bin^) and that obtained binocularly (Bin) ($F = 0.00$; $P = 0.99$). In addition, there was no significant variation within the subjects comprising this small group ($F = 2.89$; $P = 0.06$) although there was a considerable variation in contrast sensitivity across the range of spatial frequencies examined ($F = 5.7$; $P < 0.001$). A similar result was obtained when bifoveal logarithm contrast sensitivity was compared to that through the better eye. There was no statistically significant difference 9F = 1.06; P = 0.3).

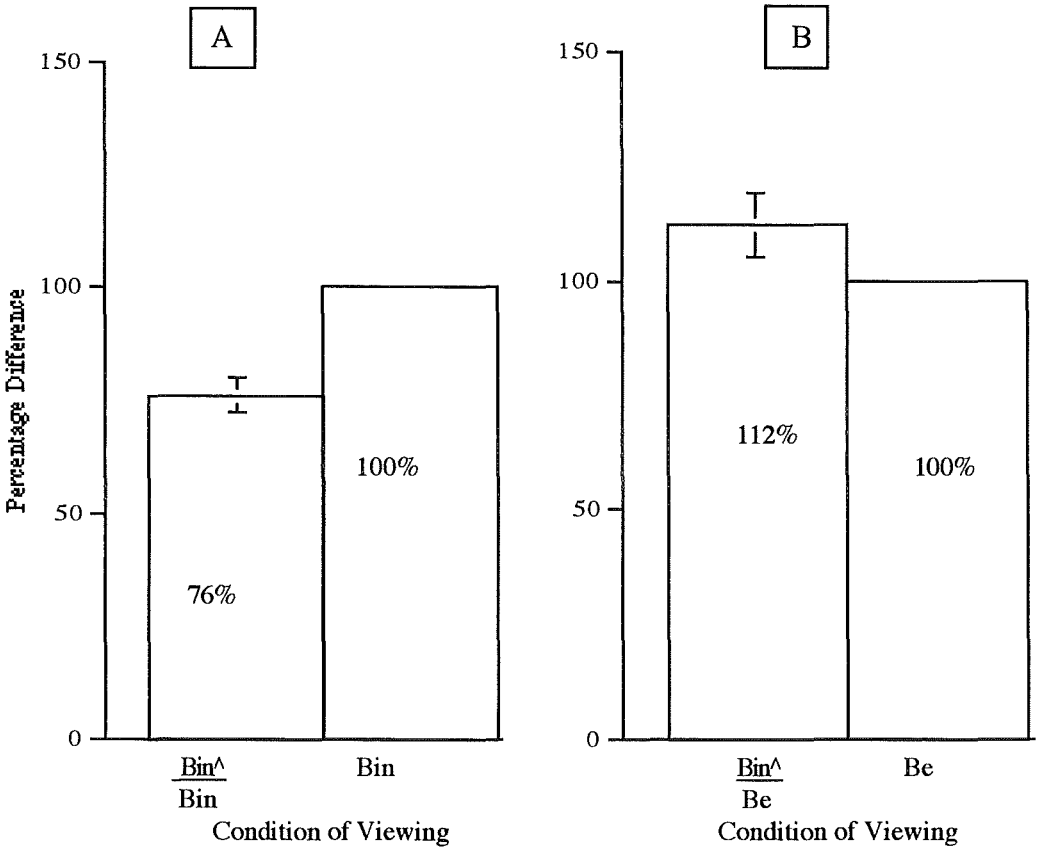


Figure 67. Contrast sensitivity changes in esotropic amblyopes with anomalous BSV (n=3).
A. Percentage contrast sensitivity under conditions of bifoveal stimulation referenced to that under binocular conditions of viewing, taken as 100% (Bin^/Bin), averaged over spatial frequencies 8c/deg to 30c/deg to give a single mean value ± SE.
B. The same data as in **A** (Bin^), referenced to the better eye (Be) taken as 100% (Bin^/Be), averaged over spatial frequencies 8c/deg to 30c/deg to give a single mean value ± SE.

3.2.3 Esotropic Amblyopes without BSV

Five individuals comprised this group of esotropic amblyopes in which BSV was absent. Amblyopia varying in depth from 6/9 to 6/60 was evident (Table 9). In all but one participant, foveal fixation in the squinting eye was demonstrable on monocular viewing.

3.2.3.1 Contrast Sensitivity: Individual Data

In Subject 2, the logarithm contrast sensitivities for bifoveal viewing (Bin^) were reduced compared with those for normal binocular viewing (Bin) (Figure

68A) and with those for better eye viewing (Be) (Figure 68B). The grating pattern could not be detected above 25c/deg.

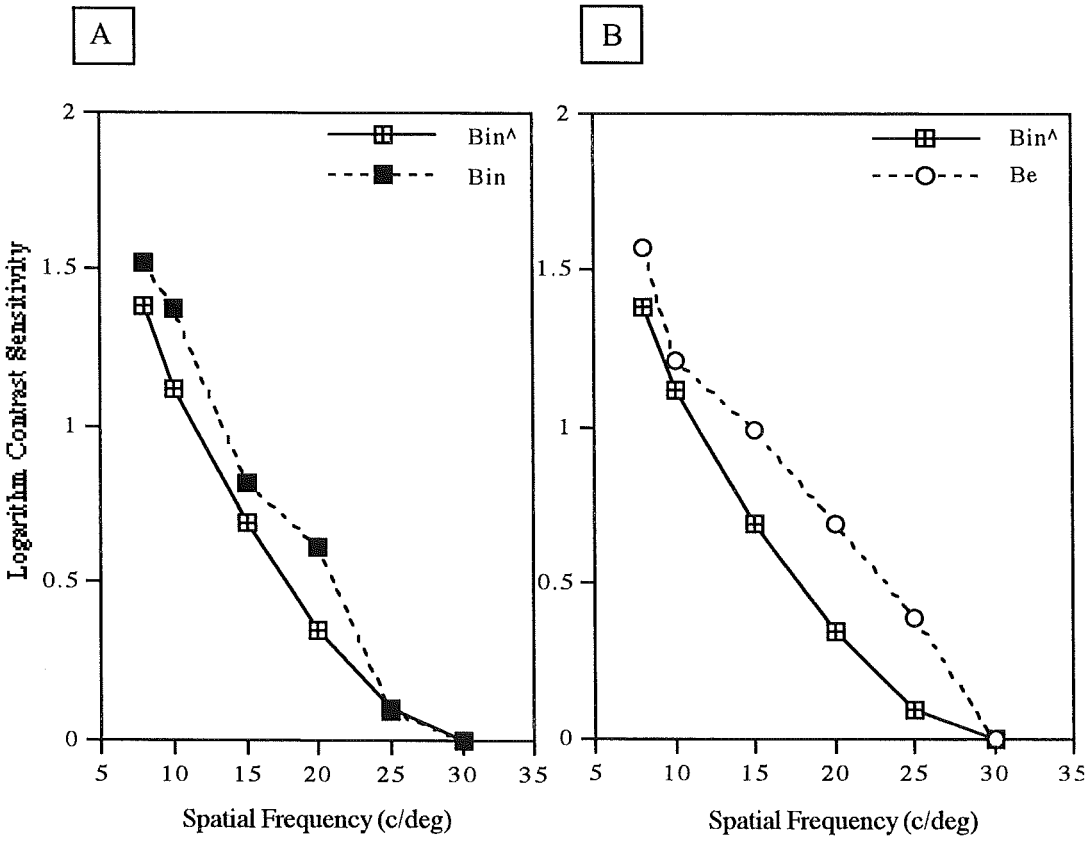


Figure 68. Logarithm contrast sensitivity against increasing spatial frequency for esotropic amblyope without BSV, Subject 2. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Binocular viewing (Bin) (same data as in Figure 46B) and under conditions of bifoveal stimulation (Bin^).
B. Monocular viewing through the better eye (Be) (same data as in Figure 46A) and under bifoveal conditions of viewing (Bin^) (same data as in **A**).

A reduction of 0.15 log units over the range of spatial frequencies studied was evident, under conditions of bifoveal stimulation (Bin^), when compared to binocular viewing (Bin) (Figure 68A). This represented a mean percentage decrease of 29% ± 9% SE ($P<0.05$, paired t-test.) which was significant . When the binocular contrast sensitivities (Bin^) were compared to those of the better eye (Be), a reduction of 0.24 log units in the bifoveal logarithm contrast sensitivity was present (Figure 68B). This represented a 43% ± 6% SE ($P<0.05$, paired t-test) reduction which was significant.

3.2.3.2 *Contrast Sensitivity: Group Data*

In this group of 5 esotropic amblyopes, the bifoveal logarithm contrast sensitivities (Bin^) were reduced compared to the binocular logarithm contrast sensitivities (Bin) (Figure 69A).

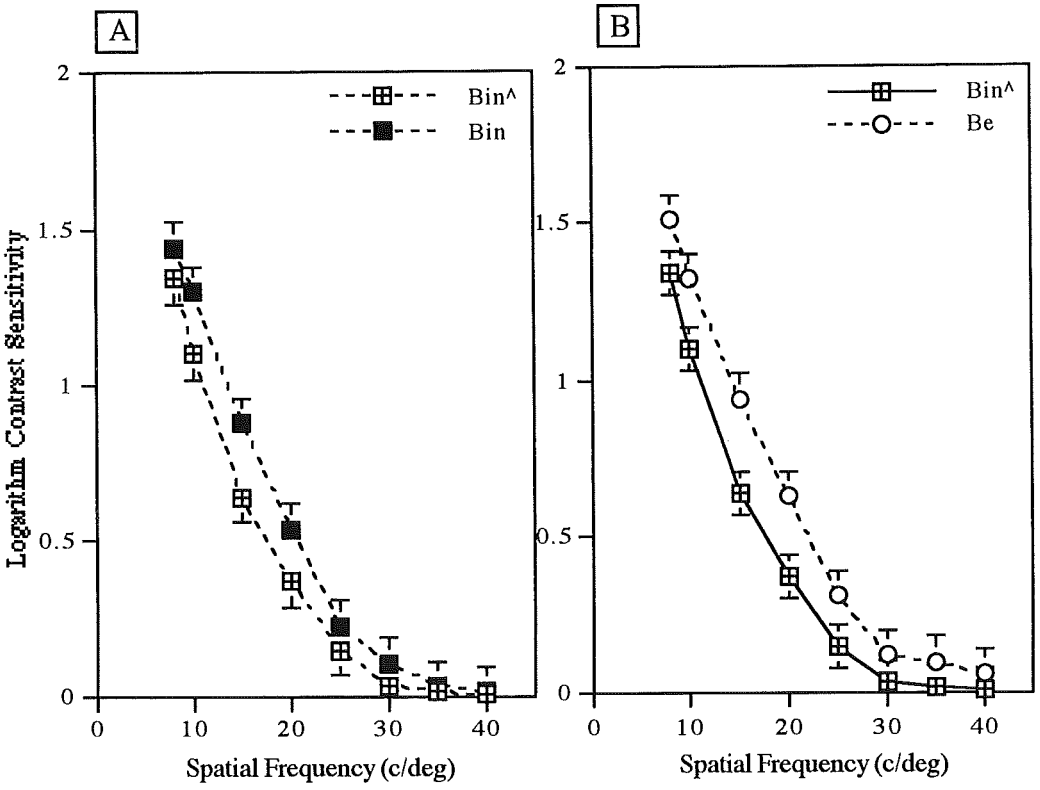


Figure 69. Logarithm contrast sensitivity against increasing spatial frequency for the group of esotropic amblyopes without BSV (n=5). Points shown represent the mean ± the pooled standard error of values for each of the 5 subjects. Each of these values was itself the mean of 6 determinations.

A. Binocular viewing (Bin) (same data as in Figure 47) and under conditions of bifoveal stimulation (Bin^).

B. Monocular viewing through the better eye (Be) (same data as in Figure 47) and under bifoveal conditions of viewing (Bin^) (same data as in **A**).

They were also less than those of the better eye (Figure 69B). A significant reduction of 24% ± 7% SE (n = 5; t = 3.43; P = 0.03; one sample t-test) in the bifoveal contrast sensitivities (Bin^) over the range of spatial frequencies studied was evident when compared to the binocular contrast sensitivities (Bin) (Figure 69A; Table 20). This was confirmed by analysing the data using a 3-factor ANOVA (F = 104.46; P<0.001) which also highlighted the considerable variation between subjects (F = 121.9: P <0.001) and showed evidence of

variation across the range of spatial frequencies examined (F = 1040.98; P<0.001).

In addition, the bifoveal contrast sensitivities (Bin^) were reduced compared with those for viewing through the better eye over the range of spatial frequencies, and a mean overall significant loss of 35% ± 6% SE (n = 5; t = 5.5; P = 0.005; one sample t-test;) occurred over the range of spatial frequencies (Figure 69B; Table 20). This was also confirmed when the data were analysed using a 3-factor ANOVA (F = 211.09; P <0.001).

Table 20 Reduction in contrast sensitivity averaged over spatial frequencies studied under bifoveal conditions of viewing and binocular viewing, and the reduction between bifoveal viewing and the better eye.

Subject	Bifoveal Stimulation vs Binocular $\frac{(Bin^{\wedge} - Bin)}{Bin} \times 100\%$	Bifoveal Stimulation vs Better Eye $\frac{(Bin^{\wedge} - Be)}{Be} \times 100\%$
1	- 44% ± 10% *	- 50% ± 8% *
2	- 29% ± 9% *	- 43% ± 6% *
3	- 34% ± 5% *	- 45% ± 4% **
4	- 13% ± 6% *	- 19% ± 6% *
5	- 4% ± 9% ns	- 21% ± 5% **
Mean	**-24% ***	**-35% ****

Each value is mean ± SE for the spatial frequencies tested in each subject.
Be - Better Eye Bin - Binocular Viewing Bin^ - Bifoveal Stimulation
ns - P>0.05 * P<0.05; ** P<0.01

When the data shown in Figure 69 were replotted in linear form to show the differences in contrast sensitivity across the range of spatial frequencies examined, the reduction in the mean percentage contrast sensitivity varied from 2% to 43% when bifoveal contrast sensitivities (Bin^) were compared to the binocular contrast sensitivities (Bin) (Figure 70). A similar reduction across the spatial frequency range when bifoveal contrast sensitivities (Bin^) were compared to those of the better eye (Be) was evident. This decrease ranged from 11% to 65% (Figure 70).

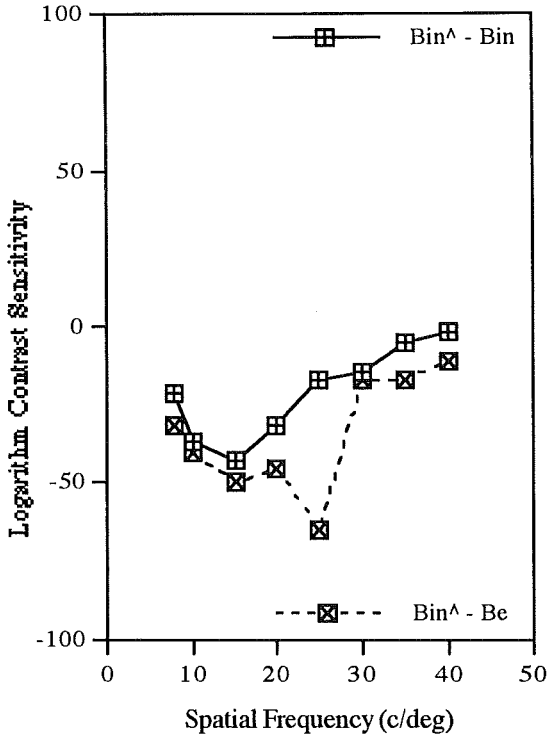


Figure 70. Mean percentage reduction in contrast sensitivity in esotropic amblyopes without BSV (n=5) at each spatial frequency under conditions of bifoveal stimulation (Bin^) compared with normal binocular viewing (Bin) and with better eye viewing (Be).

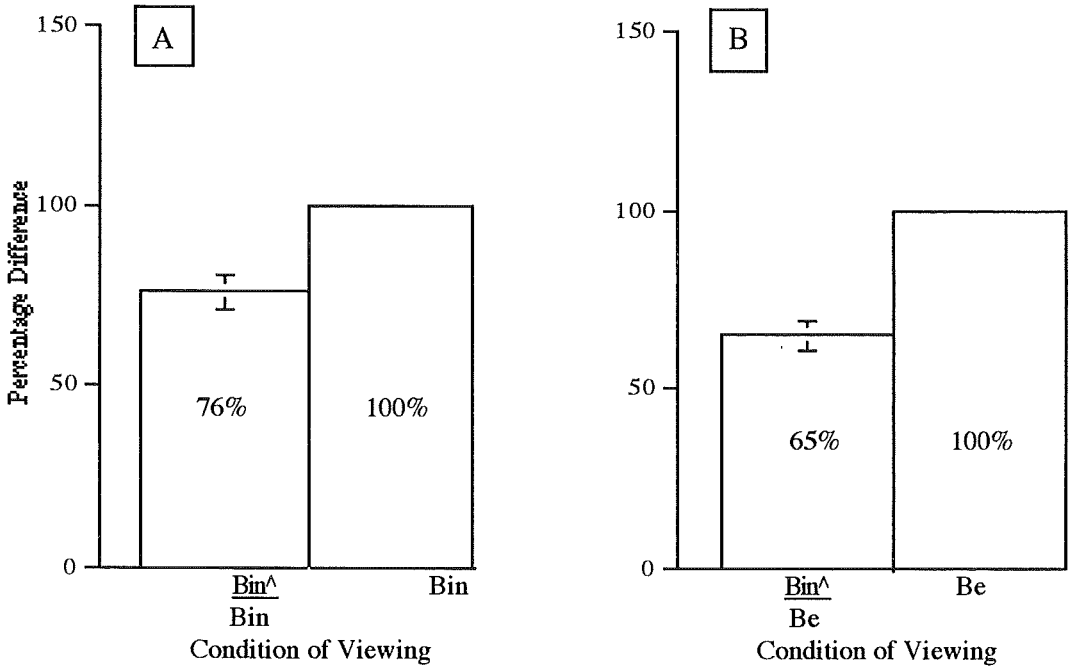


Figure 71. Contrast sensitivity changes in esotropic amblyopes without BSV (n=5).
A. Percentage contrast sensitivity under conditions of bifoveal stimulation referenced to that under binocular conditions of viewing, taken as 100%, (Bin^/Bin) averaged over spatial frequencies 8c/deg to 40c/deg to give a single mean value ± SE.
B. The same data as in **A** (Bin^) referenced to the better eye (Be) taken as 100% (Bin^/Be) averaged over spatial frequencies 8c/deg to 40c/deg to give a single mean value ± SE.

3.2.4 Non-Amblyopic Esotropes without BSV

Four individuals satisfied the criteria for inclusion in this group. All subjects demonstrated a constant esotropia without BSV, Snellen acuity of 6/6 or better in each eye, and uniocular foveal fixation on ophthalmoscopy (Table 11).

3.2.4.1 Contrast Sensitivity: Individual Data

In Subject 1 of this group, the bifoveal logarithm contrast sensitivities (Bin^) were reduced compared with those obtained under binocular conditions of viewing (Bin) (Figure 72A).

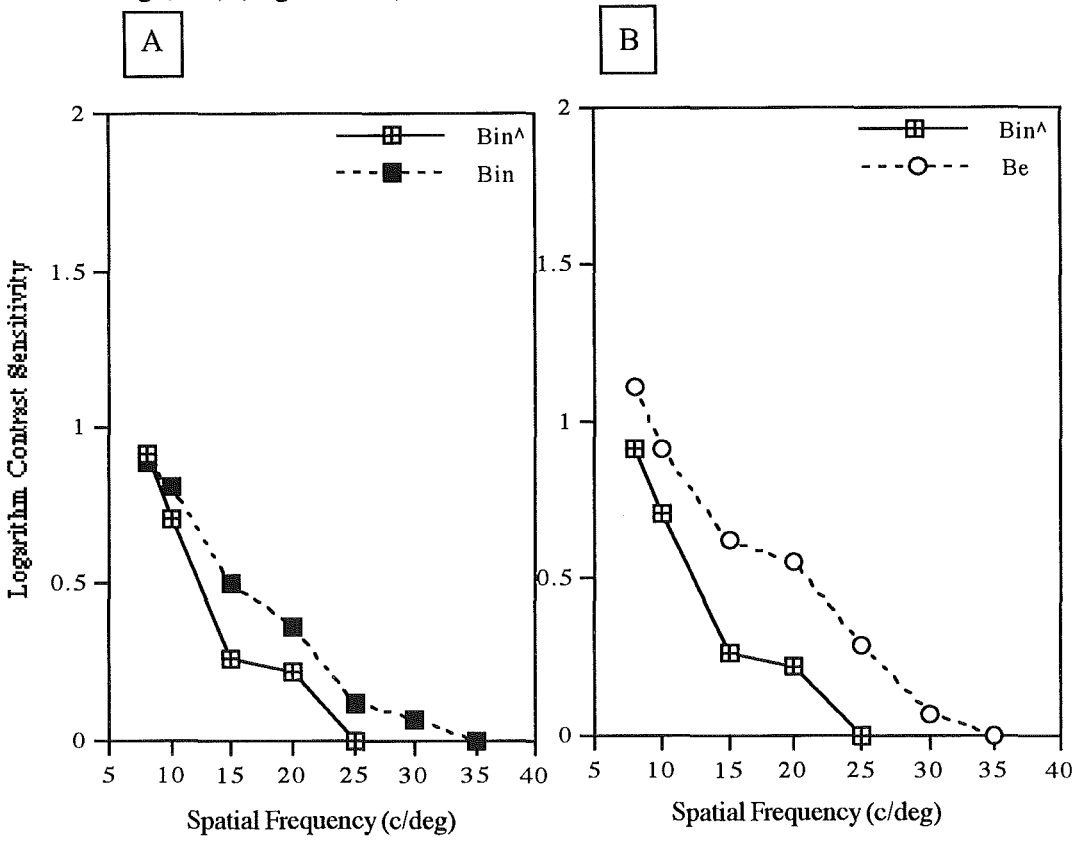


Figure 72. Logarithm contrast sensitivity against increasing spatial frequency for non-amblyopic esotrope without BSV, Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Binocular viewing (Bin) (same data as in Figure 49B) and under conditions of bifoveal stimulation (Bin^).
B. Monocular viewing through the better eye (Be) (same data as in Figure 49A) and under bifoveal conditions of viewing (Bin^) (same data as in **A**).

The highest spatial frequency at which the grating pattern could be resolved by this non-amblyopic subject, under bifoveal viewing conditions, was 20c/deg

and under binocular conditions, 30c/deg. The bifoveal logarithm contrast sensitivities (Bin^), when compared with those obtained through the better eye (Be), were also reduced (Figure 72B).

When the difference in logarithm contrast sensitivities under bifoveal conditions of viewing (Bin^) was compared with those obtained under binocular viewing (Bin) over the range of spatial frequencies studied, a mean reduction in bifoveal contrast sensitivity of 0.12 log units was shown. This represented a mean percentage decrease of 24% ± 8% SE which was significant (P<0.01, t-test.) (Table 21). A mean reduction of 0.28 log units was evident when the bifoveal contrast sensitivities (Bin^) were then compared to those of the better eye (Be). Thus, a mean percentage decrease in bifoveal contrast sensitivity of 48% ± 4% SE, which was a significant loss (P<0.01, t-test), occurred.

3.2.4.2 Contrast Sensitivity: Group Data

All subjects comprising this group showed a reduction in the bifoveal logarithm contrast sensitivities (Bin^) compared with those obtained for normal binocular viewing (Bin) (Figure 73A) and for viewing with better eye (Be) (Figure 73B).

When the logarithm contrast sensitivities of the group under conditions of bifoveal stimulation (Bin^) were compared with those under binocular conditions of viewing (Bin), there was an overall reduction of 0.20 log units over the range of spatial frequencies studied representing a loss of 37% ± 6% SE, which was significant (n = 4; t = 6.12; P = 0.009; one sample t-test) (Figures 73A). The ANOVA also showed evidence of a significant difference in the bifoveal logarithm contrast sensitivity when compared to that obtained under binocular conditions of viewing (F = 81.55; P <0.001).

A slightly greater reduction of 46% ± 6% was evident when the bifoveal logarithm contrast sensitivities (Bin^) were then compared to those through the better eye (Be), and again this loss was significant (n = 4; t = 8.1; P = 0.004; one sample t-test; F =) (Figure 73B, Table 21). (F = 95.76: P<0.001; ANOVA).

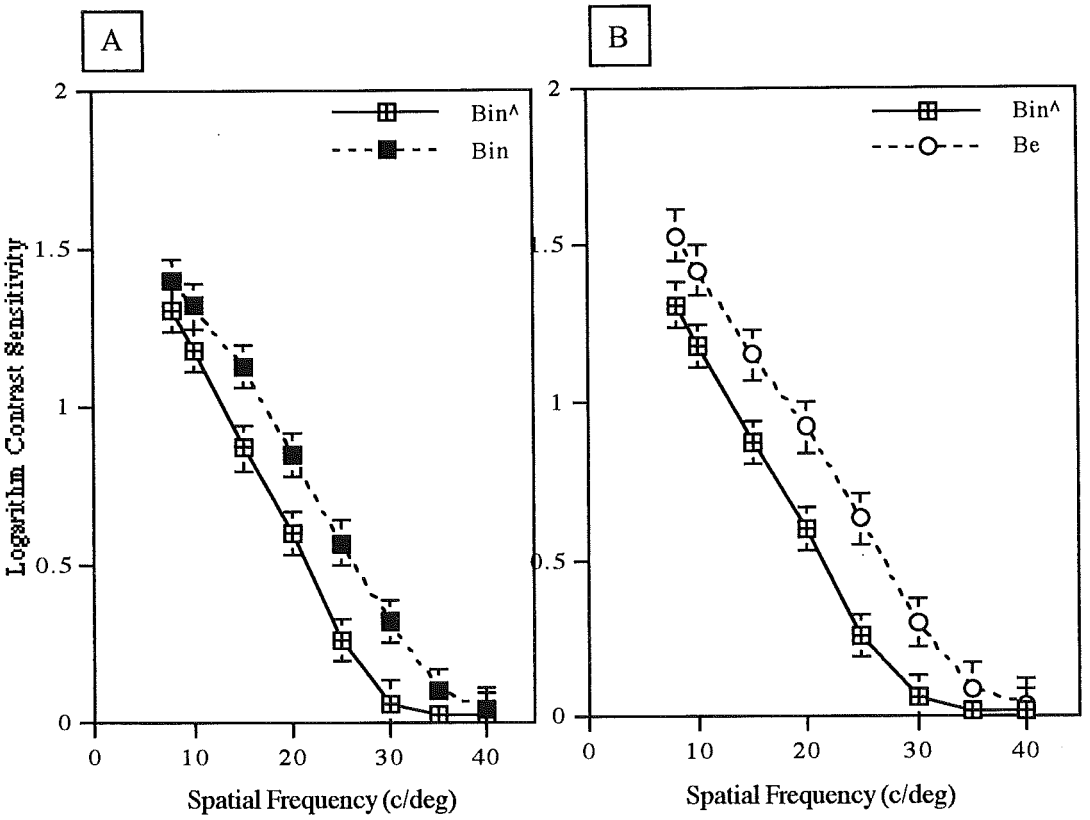


Figure 73. Logarithm contrast sensitivity against increasing spatial frequency for the group of non-amblyopic esotropes without BSV. Points shown represent the mean ± the pooled standard error of values for each of the 4 subjects. Each of these values was itself the mean of 6 determinations.

A. Binocular viewing (Bin) (same data as in Figure 50) and under conditions of bifoveal stimulation (Bin^).

B. Monocular viewing through the better eye (Be) (same data as in Figure 50) and under bifoveal conditions of viewing (Bin^) (same data as in **A**).

Table 21 Reduction in contrast sensitivity averaged over spatial frequencies studied under bifoveal conditions of viewing and binocular viewing, and the reduction between bifoveal viewing and the better eye.

Subject	Bifoveal Stimulation vs Binocular $\frac{(Bin^{\wedge} - Bin)}{Bin} \times 100\%$	Bifoveal Stimulation vs Better Eye $\frac{(Bin^{\wedge} - Be)}{Be} \times 100\%$
1	-24% ± 8% **	-48% ± 4% **
2	-3[illegible] ± 8% *	-32% ± 6% *
3	-39% ± 5% **	-46% ± 7% **
4	-53% ± 6% **	-60% ± 6% **
Mean	**-37% ****	**-46% ****

Each value is mean ± SE for the spatial frequencies tested in each subject
Be - Better Eye Bin - Binocular Viewing Bin^ - Bifoveal Stimulation
ns.- P>0.05 * P<0.05; ** P<0.01

Replotting the data to reflect the mean percentage change in contrast sensitivity across the spatial frequency range showed a reduction in bifoveal contrast sensitivity (Bin^) when compared to the binocular contrast sensitivity (Bin), at the spatial frequencies examined from 16% at 35c/deg to 49% at 25c/deg (Figure 74), with an overall mean reduction of 37% ± 6% which was significant (P<0.01) (Table 21, Figure 75A). When the bifoveal contrast sensitivity was then compared to that of the better eye (Be), there was a 45% loss at 8c/deg increasing to a 55% reduction at 25c/deg (Figure 74). The overall mean percentage reduction was 46% ± 6% which was significant (P<0.01) (Table 21, Figure 75B).

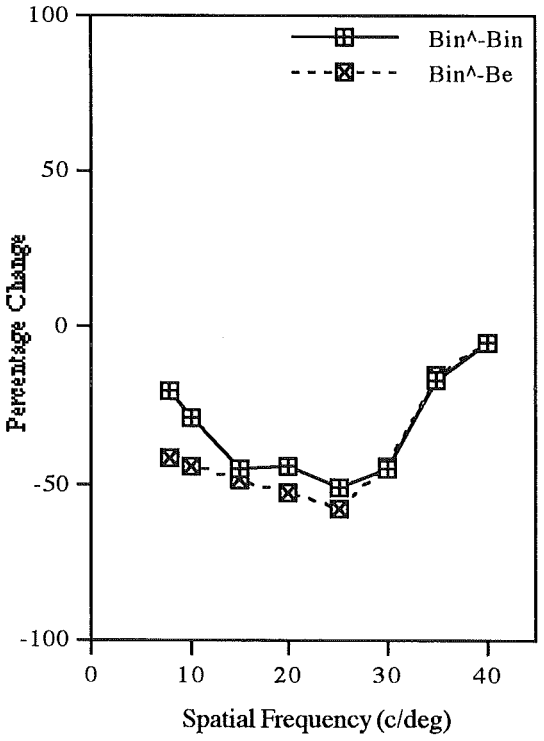


Figure 74. Mean percentage reduction in contrast sensitivity in non-amblyopic esotropes without BSV (n=4) at each spatial frequency under conditions of bifoveal stimulation (Bin^) compared with normal binocular viewing (Bin) and with better eye viewing (Be).

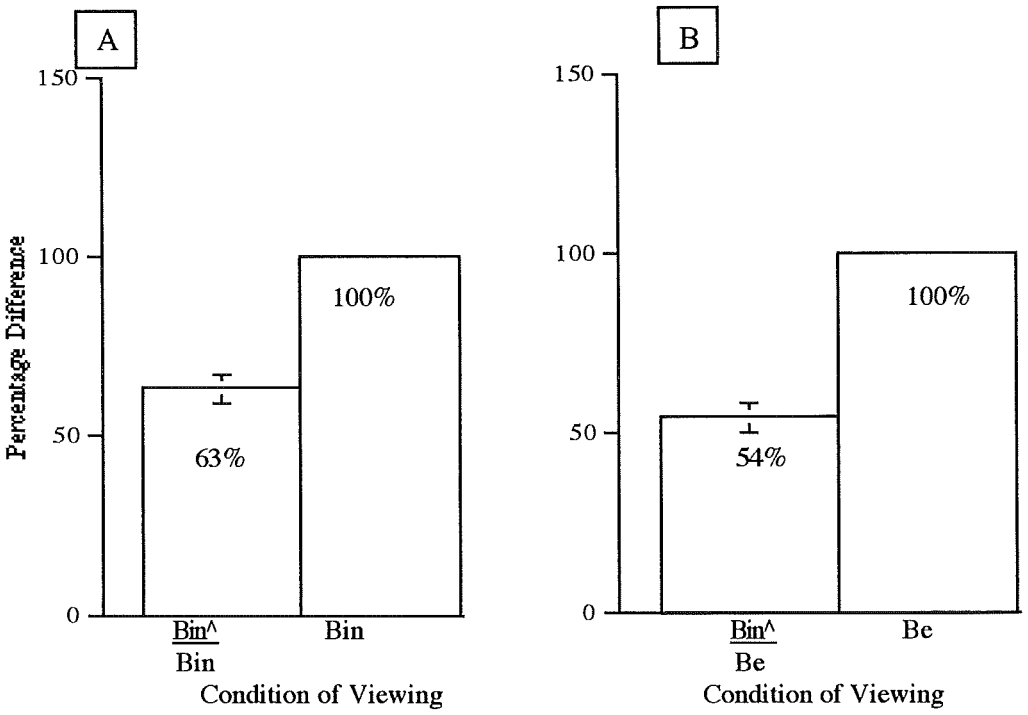


Figure 75. Contrast sensitivity changes in non-amblyopic esotropes without BSV (n=4).
A. Percentage contrast sensitivity under conditions of bifoveal stimulation referenced to that under binocular conditions of viewing, taken as 100%, (Bin^/Bin) averaged over spatial frequencies 8c/deg to 40c/deg to give a single mean value ± SE.
B. The same data as in **A** (Bin^), referenced to the better eye (Be) taken as 100% (Bin^/Be), averaged over spatial frequencies 8c/deg to 40c/deg to give a single mean value ± SE.

3.2.5 Exotropic Amblyopes without BSV

Two exotropic amblyopes without BSV were examined in this study. Both subjects exhibited a constant exotropia which was consecutive to esotropia in childhood, constant suppression and amblyopia in the squinting eye. The deficit in visual acuity in the exotropic eye was greater in Subject 1 who recorded a visual acuity of 6/36; the depth of amblyopia in Subject 2 was considerably less at 6/9 (Table 13).

3.2.5.1 Contrast Sensitivity; Individual Data

Subject 1

The logarithm contrast sensitivities for Subject 1 of this group were less under conditions of bifoveal stimulation (Bin^) compared with those in binocular viewing (Bin) (Figure 76A).

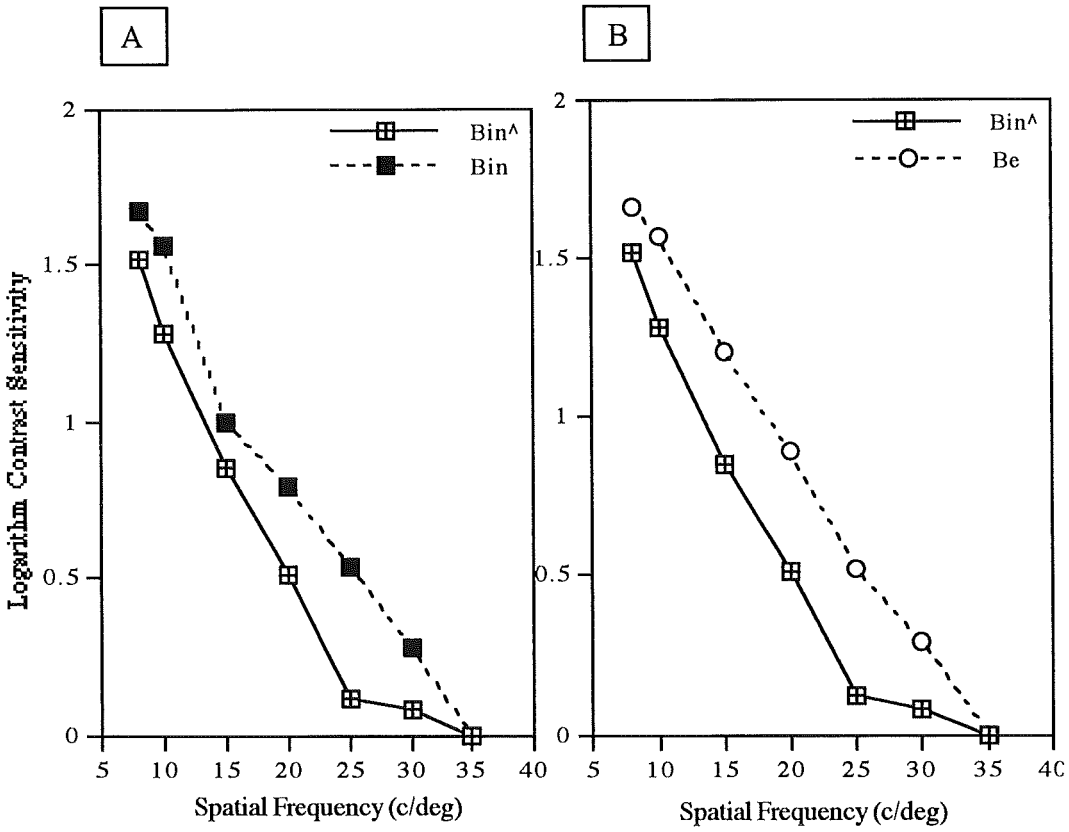


Figure 76. Logarithm contrast sensitivity against increasing spatial frequency for exotropic amblyope without BSV, Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Binocular viewing (Bin) (same data as in Figure 52B) and under conditions of bifoveal stimulation (Bin^).
B. Monocular viewing through the better eye (Be) (same data as in Figure 52A) and under binocular conditions (Bin^) (same data as in **A**).

The extent of the loss in logarithm contrast sensitivity was similar when the bifoveal logarithm contrast sensitivities (Bin^) were compared with those of the better eye (Be) (Figure 76B). The grating pattern at the higher spatial frequencies of 35c/deg and 40c/deg could not be resolved.

A mean reduction of 0.25 log units under conditions of bifoveal stimulation (Bin^) over the range of spatial frequencies studied compared to that achieved under normal binocular viewing conditions (Bin) was evident (Figure 76A). This represented a mean percentage decrease of 44% ± 5% SE which was significant ($P<0.01$, paired t-test) (Figure 76A). Bifoveal contrast sensitivity

(Bin^) was also reduced when compared to that obtained through the better eye (Be). The overall loss of bifoveal logarithm contrast sensitivity, over the range of spatial frequencies, was 0.28 log units which represented a mean percentage reduction of 48% ± 5% SE (P<0.01, paired t-test), and this was also significant (Figure 76B).

When the data shown in Figure 76 were replotted in linear form to show the differences in contrast sensitivity across the range of spatial frequencies examined, the reduction in the mean percentage bifoveal contrast sensitivity (Bin^) varied from 27% to 60% when compared to the binocular contrast sensitivity (Bin) (Figure 77), with an overall mean percentage loss of 44% ± 5% (P<0.01, t test) (Figure 78A). A similar reduction in bifoveal logarithm contrast sensitivity (Bin^) was also evident when compared to that obtained through the better eye (Be) (Figure 77). The mean percentage reduction in this instance varied from 29% to 62% with an overall mean reduction of 48% ± 5% (P<0.01, t-test) (Figure 78B).

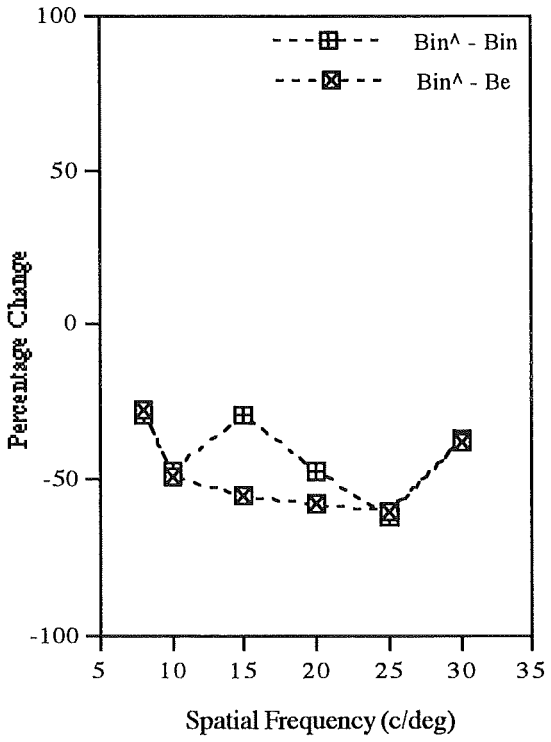


Figure 77. Mean percentage reduction in contrast sensitivity in exotropic amblyope without BSV, Subject 1, at each spatial frequency under conditions of bifoveal stimulation (Bin^) compared with normal binocular viewing (Bin) and with better eye viewing (Be).

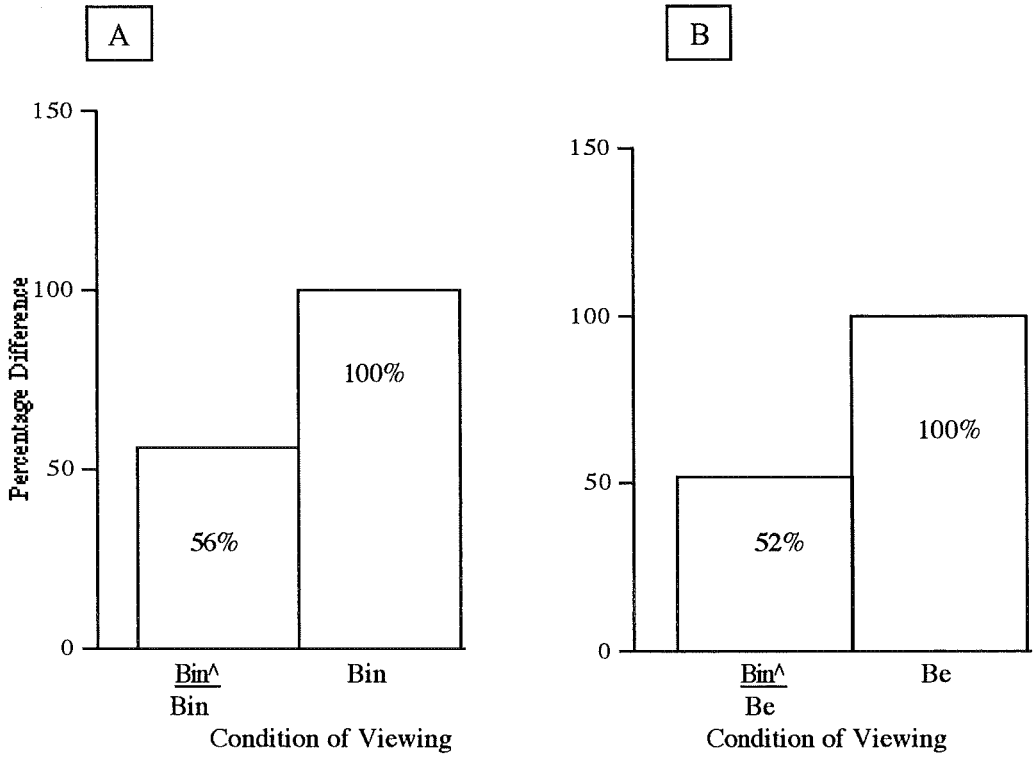


Figure 78. Contrast sensitivity changes in exotropic amblyope without BSV, Subject 1.
A. Percentage contrast sensitivity under conditions of bifoveal stimulation referenced to that under binocular conditions of viewing, taken as 100%, (Bin^/Bin) averaged over spatial frequencies 8c/deg to 30c/deg to give a single mean value ± SE.
B. The same data as in **A** (Bin^) referenced to the better eye (Be), taken as 100%, (Bin^/Be) averaged over spatial frequencies 8c/deg to 30c/deg to give a single mean value ± SE.

Subject 2

In Subject 2 of the exotropic amblyopes without BSV, the bifoveal logarithm contrast sensitivities (Bin^) were less than those under binocular conditions (Bin), with a slightly greater difference at the higher spatial frequencies of 20c/deg, 25c/deg and 30c/deg compared with the difference at the lower spatial frequencies (Figure 79A).

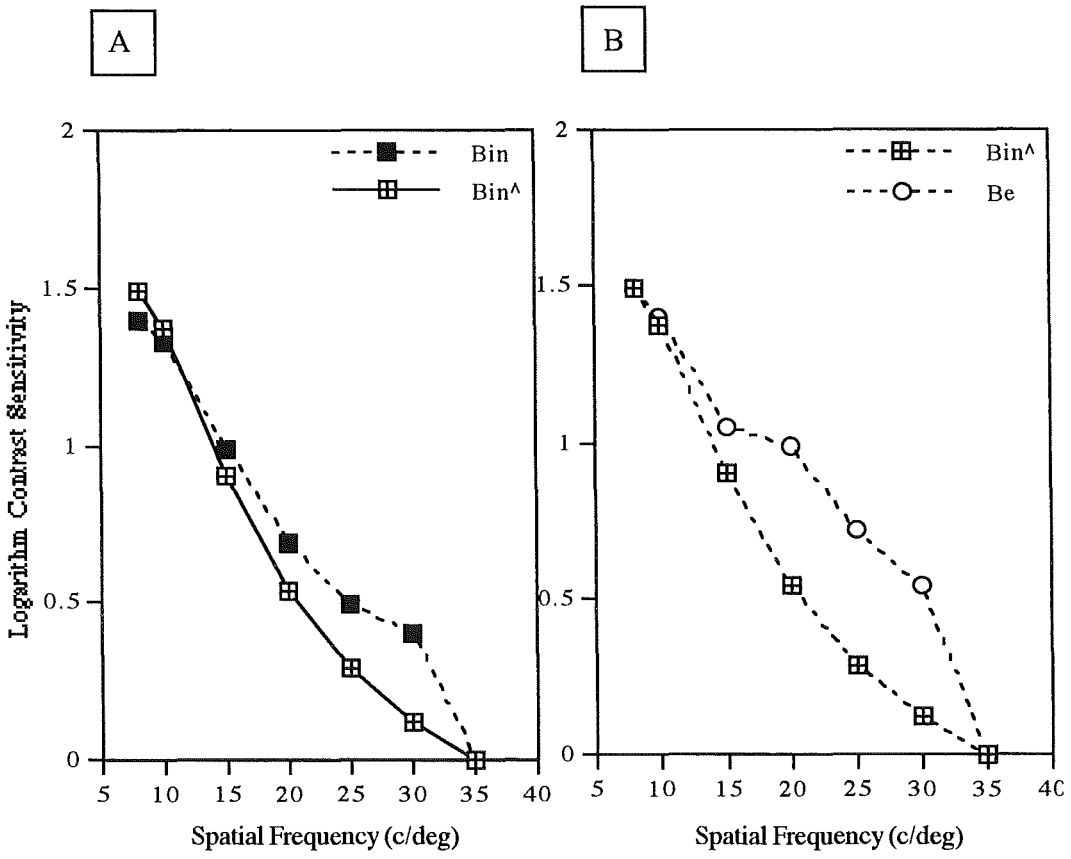


Figure 79. Logarithm contrast sensitivity against increasing spatial frequency for exotropic amblyope without BSV, Subject 2. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Binocular viewing (Bin) (same data as in Figure 53B) and under conditions of bifoveal stimulation (Bin^).
B. Monocular viewing through the better eye (Be) (same data as in Figure 53A) and under binocular conditions (Bin^) (same data as in **A**).

There was a reduction of 0.09 log units in the bifoveal logarithm contrast sensitivity over the range of spatial frequencies studied compared with that obtained under normal binocular conditions of viewing. This represented a 19% reduction (19% ± 11% SE, P.= 0.2, paired t-test) in this second exotropic amblyope (Figures 79A). However, this was not the case when bifoveal logarithm contrast sensitivities were compared to those through the better eye (Be). There was a significant reduction between the two viewing conditions. The bifoveal logarithm contrast sensitivity (Bin^) was reduced by 0.25 log units

over the range of spatial frequencies studied. This represented a significant decrease of 44% ± 12% SE (P<0.05, paired t-test) (Figures 79B).

When the angle of deviation was corrected (Bin^), the percentage change in contrast sensitivity at each of the spatial frequencies examined varied from +23% at the lower spatial frequency of 8c/deg to -47% at the highest spatial frequency at which the grating pattern could be detected, 30c/deg, when calculated against that obtained under normal binocular viewing conditions (Bin) (Figure 80).

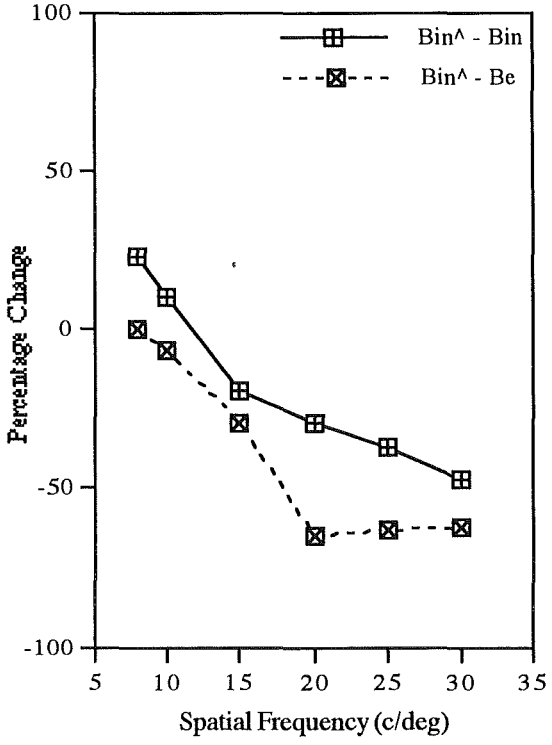


Figure 80. Mean percentage change in contrast sensitivity in exotropic amblyope without BSV, Subject 2, at each spatial frequency under conditions of bifoveal stimulation (Bin^) compared with normal binocular viewing (Bin) and better eye viewing (Be).

The percentage change in bifoveal contrast sensitivity across the range of spatial frequencies examined when compared to that of the better eye showed a similar pattern to that found when bifoveal contrast sensitivities were compared to those obtained binocularly (Figure 80), in that the percentage reduction was considerable at 20c/deg to 30c/deg when compared to the lower spatial

frequencies. The range varied from 0% at 8c/deg to -65% at 20c/deg (Figure 80). The overall mean percentage loss was 44% ± 12% (Figure 81B).

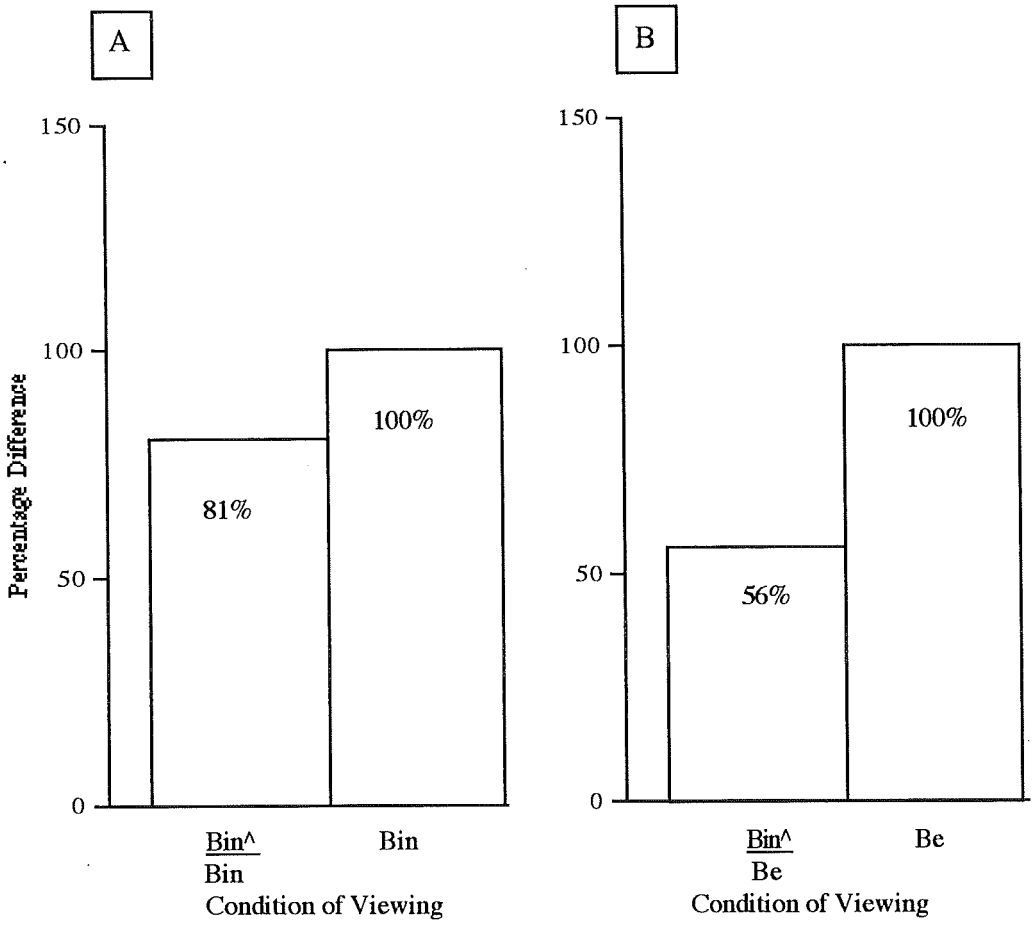


Figure 81. Contrast sensitivity changes in exotropic amblyope without BSV, Subject 2.
A. Percentage contrast sensitivity under conditions of bifoveal stimulation referenced to that under binocular conditions of viewing, taken as 100%, (Bin^/Bin) averaged over spatial frequencies 8c/deg to 30c/deg to give a single mean value ± SE.
B. The same data as in **A** (Bin^) referenced to the better eye (Be) taken as 100% (Bin^/Be) averaged over spatial frequencies 8c/deg to 30c/deg to give a single mean value ± SE.

3.2.6 Non Amblyopic Exotropes without BSV

The two participants in this group exhibited a constant exotropia without BSV, constant suppression and visual acuity of 6/5 or better in each eye (Table 15). Consequently, foveal fixation in the right and the left eyes was present on monocular viewing.

3.2.6.1 Contrast Sensitivity: Individual Data

Subject 1

The logarithm contrast sensitivities for Subject 1 under conditions of bifoveal stimulation (Bin^) showed a non-consistent change in logarithm contrast sensitivity at the spatial frequencies examined when compared with those obtained under normal binocular conditions of viewing (Bin) (Figure 82A). There was a slight increase in the bifoveal logarithm contrast sensitivities at 8c/deg and 10c/deg, but a loss of logarithm contrast sensitivity at the two higher spatial frequencies of 15c/deg and 20c/deg compared to those obtained binocularly (Bin).

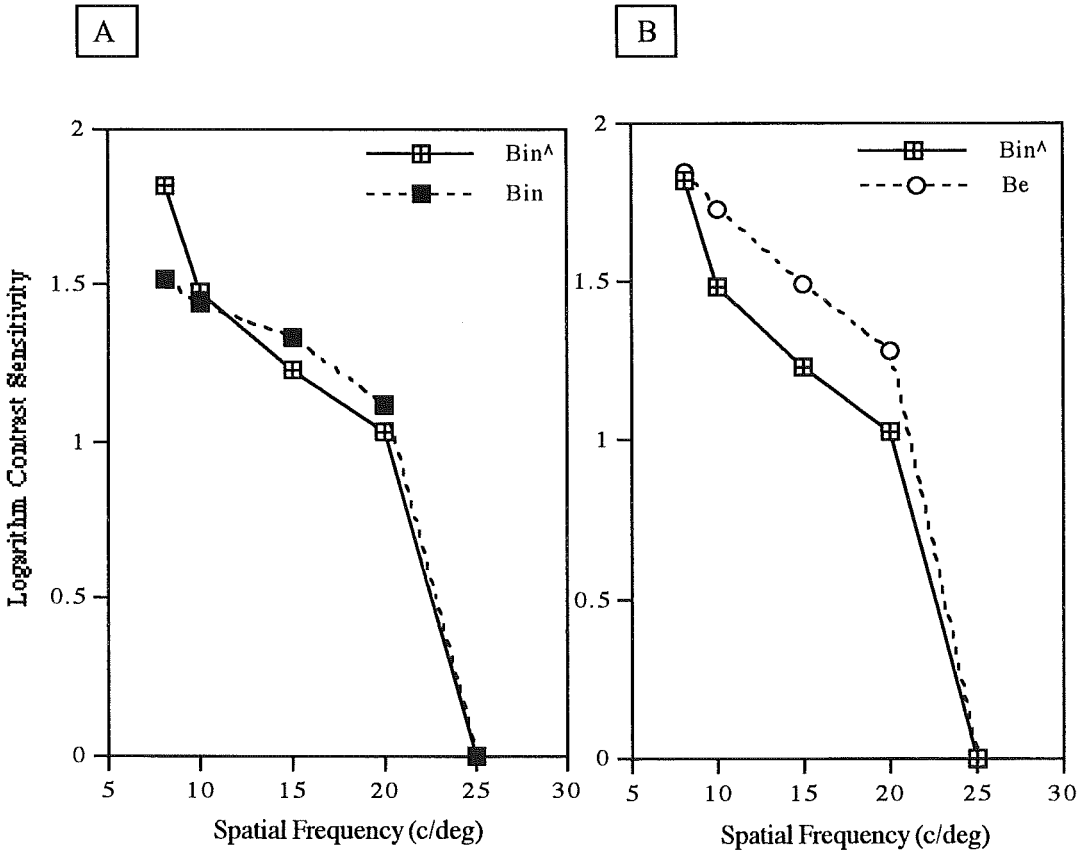


Figure 82. Logarithm contrast sensitivity against increasing spatial frequency for non-amblyopic exotrope without BSV, Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Binocular viewing (Bin) (same data as in Figure 55B) and under conditions of bifoveal stimulation (Bin^).
B. Monocular viewing through the better eye (Be) (same data as in Figure 55A) and under binocular conditions (Bin^) (same data as in **A**).

The bifoveal logarithm contrast sensitivities were reduced when compared with those for the better eye viewing (Be) (Figure 82B).

There was a mean increase of 0.035 log units under conditions of bifoveal stimulation (Bin^) over the range of spatial frequencies studied compared to that achieved binocularly (Bin) (Figure 82A). This represented a mean percentage increase of 8% (P = 0.1, paired t-test) (Figure 82A). This mean percentage increase is attributable to the bifoveal contrast sensitivity at 8c/deg which was 50% (0.30 log units) greater than that obtained under binocular conditions of viewing (Bin), and was not in keeping with the contrast sensitivity differences at the higher spatial frequencies (Figure 83). When the bifoveal logarithm contrast sensitivities (Bin^) were compared to those through the better eye (Be), there was a mean decrease of 0.20 log units over the range of spatial frequencies, representing a percentage reduction of 37% which was significant (P<0.05, t-test) (Figures 82B). The mean percentage reduction was 45% except at 8c/deg when it was considerably less at 7% (Figure 83).

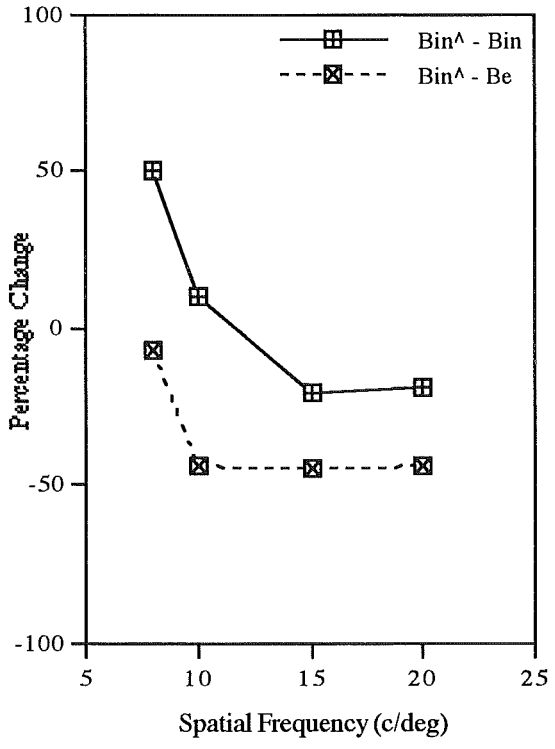


Figure 83. Mean percentage change in contrast sensitivity in non-amblyopic exotrope without BSV, Subject 1, at each spatial frequency under conditions of bifoveal stimulation (Bin^) compared with normal binocular viewing (Bin) and better eye viewing (Be).

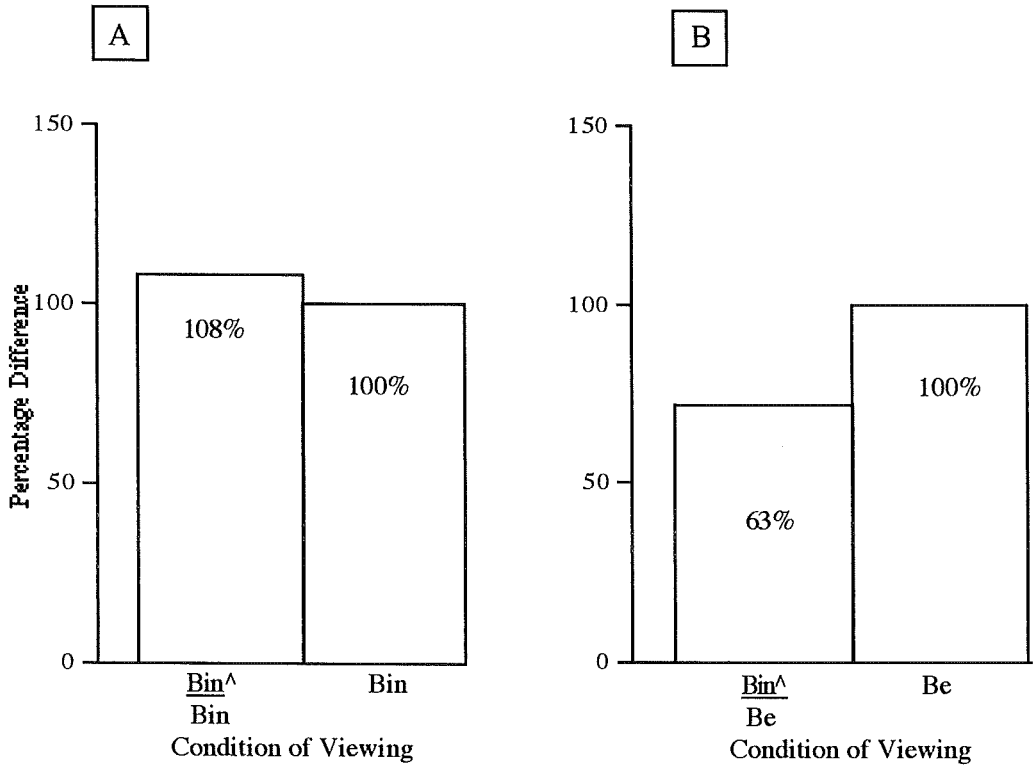


Figure 84. Contrast sensitivity changes in non-amblyopic exotrope without BSV, Subject 1
A. Percentage contrast sensitivity under conditions of bifoveal stimulation referenced to that under binocular conditions of viewing, taken as 100%, (Bin^/Bin) averaged over spatial frequencies 8c/deg to 20c/deg to give a single mean value ± SE.
B. The same data as in **A** (Bin^) referenced to the better eye (Be) taken as 100% (Bin^/Be) averaged over spatial frequencies 8c/deg to 20c/deg to give a single mean value ± SE.

Subject 2

There were no significant differences between the bifoveal logarithm contrast sensitivities (Bin^) and those under binocular conditions of viewing (Bin) for Subject 2. In this case, the bifoveal logarithm contrast sensitivities were only marginally less than the binocular findings (Figure 85A). Although this subject recorded a visual acuity of 6/4, the spatial frequencies above 20c/deg could not be detected. There was a slightly greater loss of bifoveal logarithm contrast sensitivities when compared to those obtained through the better eye and again, the grating pattern could not be resolved above 20c/deg (Figure 85B).

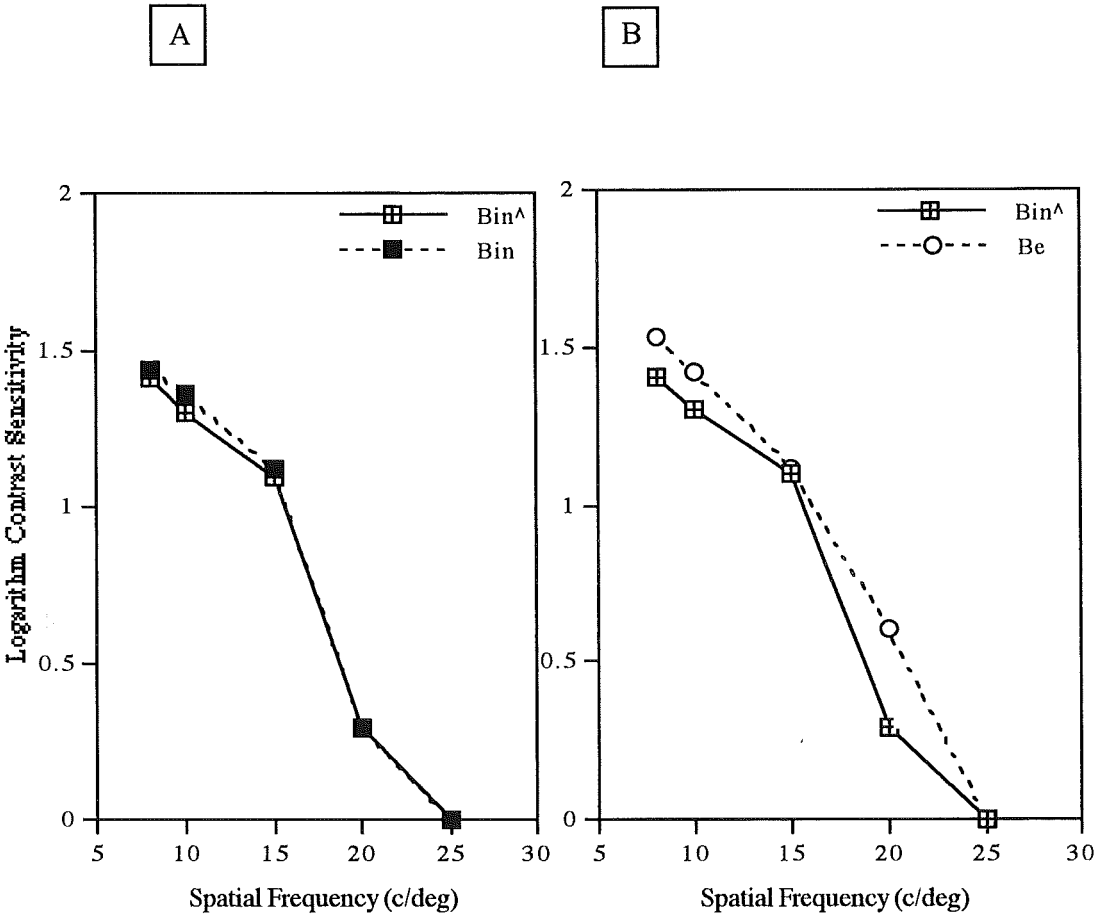


Figure 85. Logarithm contrast sensitivity against increasing spatial frequency for non-amblyopic exotrope without BSV, Subject 2. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Binocular viewing (Bin) (same data as in Figure 56B) and under conditions of bifoveal stimulation (Bin^).
B. Monocular viewing through the better eye (Be) (same data as in Figure 56A) and under binocular conditions (Bin^) (same data as in **A**).

The mean percentage decrease of 6% (0.028 log units) averaged over the range of spatial frequencies (Figures 85A) under conditions of bifoveal viewing was not significant (P = 0.5, paired t-test). However, when the logarithm contrast sensitivities under conditions of bifoveal stimulation (Bin^) were then compared to those through the better eye (Be), there was a mean loss of 0.14 log units representing a percentage reduction of 28% ± 9% SE but this, once more, was not significant (P = 0.2, paired t-test) (Figures 85B; 87B).

When the angle of deviation was corrected (Bin^), the percentage change in contrast sensitivity at each of the spatial frequencies examined varied from 0% at the highest spatial frequency (20c/deg) to -13% at 10c/deg when calculated against that for binocular viewing (Bin) (Figure 86). When compared with the better eye (Be), the mean percentage reduction in contrast sensitivity was not uniform and ranged from 19% at 8c/deg, to 0% at 15c/deg, and 51% at 20c/deg (Figure 86).

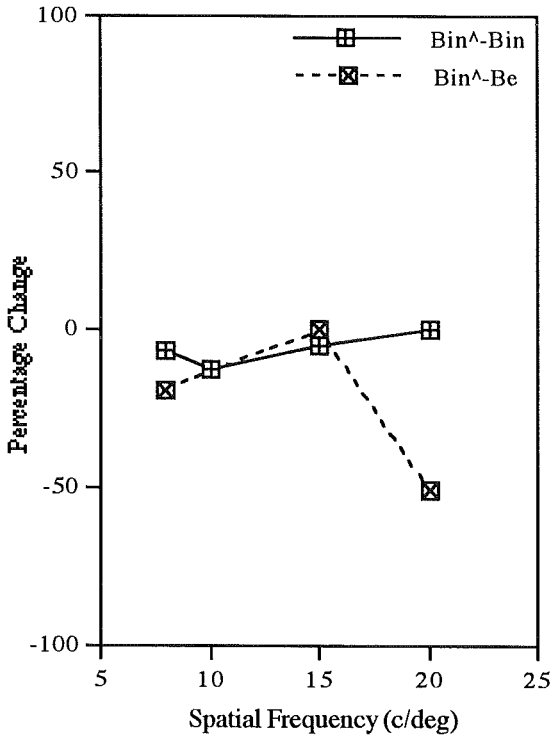


Figure 86. Mean percentage change in contrast sensitivity in non-amblyopic exotrope without BSV, Subject 2, at each spatial frequency under conditions of bifoveal stimulation (Bin^) compared with normal binocular viewing and with the better eye.

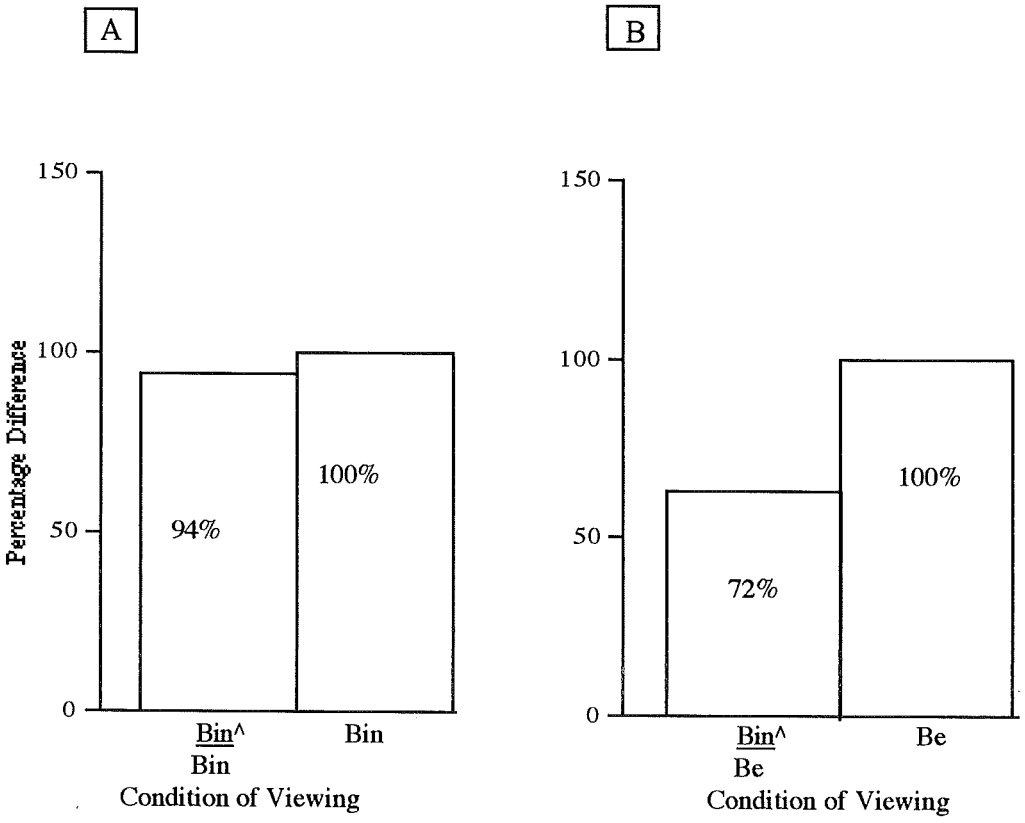


Figure 87. Contrast sensitivity changes in non-amblyopic exotrope without BSV, Subject 2.

A. Percentage contrast sensitivity under conditions of bifoveal stimulation referenced to that under binocular conditions of viewing, taken as 100%, (Bin^/Bin) averaged over spatial frequencies 8c/deg to 20c/deg to give a single mean value ± SE.

B. The same data as in **A** (Bin^) referenced to the better eye (Be) taken as 100% (Bin^/Be) averaged over spatial frequencies 8c/deg to 20c/deg to give a single mean value ± SE.

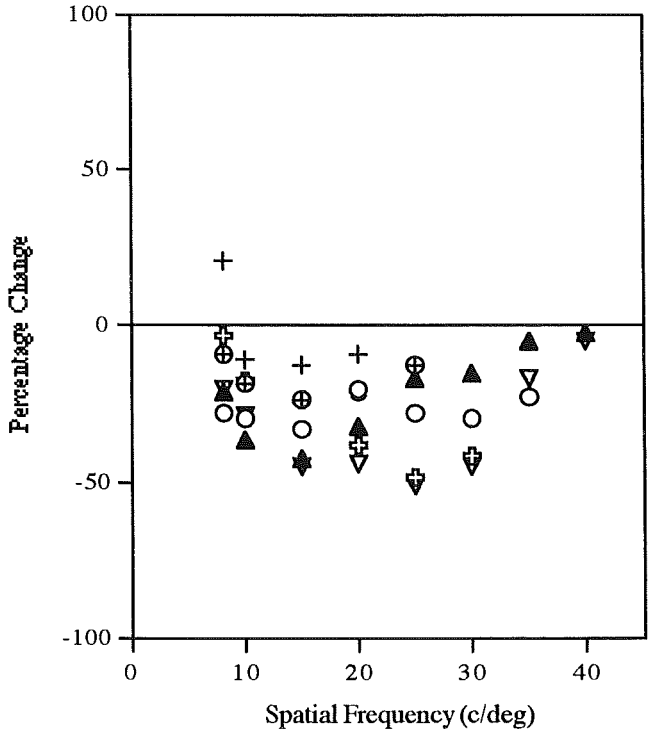
3.2.7 Summary

In all groups in which bifoveal contrast sensitivity (Bin^) was examined the contrast sensitivity was reduced in the presence of the prism.

Table 22 Percentage change in bifoveal contrast sensitivity averaged over spatial frequencies studied in strabismic groups with and without BSV.

Group	$\frac{(Bin^{\wedge} - Bin)}{Bin} \times 100\%$	Group	$\frac{(Bin^{\wedge} - Bin)}{Bin} \times 100\%$
Micro-esotropic Amblyopes with anomalous BSV	-26% ** {F = 183.96 **}	Esotropic Amblyopes without BSV	-24% * {F = 104.46 **}
Esotropic Amblyopes with anomalous BSV	-24% ns {F = 0.00 ns}	Non-Amblyopic Esotropes without BSV	-37% ** {F = 81.55 **}
		Exotropic Amblyopes without BSV	-31% (+) {F (+) }
		Non-Amblyopic Exotropes without BSV	+ 1% (+) {F (+) }
Mean	**- 25%**		**- 23%**

ns P > 0.05 P <0.05 * P<0.01 ** (+) not tested as n = 2.
{F - F factor obtained when analysis of data was undertaken using a 3 factor analysis of variance, the ANOVA statistical test}



○	Microtropic Amblyopes (Fig 61)	▽	Non-Amblyopic Esotropes without BSV (Fig 74)
⊕	Esotropic Amblyopes with Anomalous BSV (Fig 66)	✣	Exotropic Amblyopes without BSV (Mean of Fig 77 and 80)
▲	Esotropic Amblyopes without BSV (Fig 70)	+	Non-Amblyopic Exotropes without BSV (Mean of Fig 83 and 86)

Figure 88. Summary of mean percentage change in contrast sensitivity for bifoveal viewing compared with binocular viewing in all strabismic groups at each spatial frequency tested. $\frac{(Bin^{\wedge} - Bin)}{Bin}$ (given in parenthesis is the Figure number(s) from which data are taken).

3.3 Control Prism Experiments

It was important to determine the extent to which the prism(s) used to neutralise the deviation in strabismic subjects, to effect bifoveal stimulation, might have degraded the visual image, consequently affecting the measurements of contrast threshold for the eye(s) wearing the prism. Control experiments to test this possibility were therefore carried out in normal subjects. For monocular viewing, normal vision through the prism is possible since, although the prism deviates the incoming light rays, the eye is then translated in the appropriate direction to regain foveal fixation. If no degradation of contrast occurs, normal contrast sensitivities compared with direct viewing without the prism should be obtained.

Four individuals, 3 females and 1 male, with an age range of 22 years to 37 years underwent the experiment. One subject (Subject 1) had previously participated in the original experiments on normal subjects and the remaining 3 subjects were new to the study. The subjects consisted of 1 emmetrope, 1 low myope and 2 moderate myopes. Each had a visual acuity of 6/5 or better in each eye and all exhibited constant, normal BSV (Table 23).

Table 23 Clinical Data for Control Prism Group

Subject	Visual Acuity	Refractive Error
1	RE 6/5 ^ LE 6/5	Nil
2	RE 6/5 LE 6/5 ^	RE -1.00DS LE -1.00DS
3	RE 6/4 ^ LE 6/4	RE -5.25DS LE -4.00DS
4	RE 6/4 LE 6/4 ^	RE -5.00DS LE -5.50DS

Key: RE - Right Eye: LE - Left Eye: DS - Dioptre Sphere
DC. Dioptre Cylinder: - - Concave Lens: + - Convex Lens:
^ The eye wearing the prism.

Each subject underwent several practice runs at 5c/deg and 10c/deg to allow them to become familiar with the task which is described in the Methods, page

95. Control contrast sensitivities without the prism were obtained as before for 8, 10, 15, 20, 25, 30, 35, and 40c/deg *i.e.* one eye was occluded and the monocular contrast sensitivities obtained. Thereafter, a base-out (eso deviations) or a base-in (exo deviations) glass prism was placed in a trial frame or attached to the spectacle lens in front of one eye, while the companion eye was occluded and the contrast threshold measured. The direction of heterophoria (esophoria or exophoria) determined the base direction of the prism. Thus, in individuals with esophoria, a base-out prism was used and in exophoria, a base-in prism was worn in front of one eye. The prisms used ranged from 2^ to 12^ and were presented in random order (6^, 12^, 2^, 8^, 4^, 10^). The results obtained were then converted to the logarithm contrast sensitivity and plotted against spatial frequency.

3.3.1 Contrast Sensitivity: Individual Data

The effect of the prisms on logarithm contrast sensitivity in Subject 1, who was emmetropic, is shown in Figure 89. There was a remarkable similarity between the control logarithm contrast sensitivities and with the prism powers of 2^ to 8^ (Figures 89A, B, C and D). With the higher prism strengths of 10^ and 12^, a slight decrease in logarithm contrast sensitivity was present at the higher spatial frequencies, especially at 30c/deg to 40c/deg. (Figure 89E and F). There was a statistically significant mean decrease in contrast sensitivity when averaged over all the spatial frequencies examined of 10% ± 4% SE ($P < 0.05$, paired t-test) with a 10^ prism (Table 24). The reduction, however, was disproportionately greater at the higher spatial frequencies of 35c/deg and 40c/deg, with a mean percentage decrease in contrast sensitivity of 24% ± 5% which was significant ($P<0.05$, paired t-test). With the 12^ prism there was an overall mean percentage reduction across the range of spatial frequencies of 18% ± 5% SE ($P<0.05$, paired t-test) (Table 24). The reduction in contrast sensitivity extended over a wider range of spatial frequencies with the 12^ prism: for example, the mean percentage reduction at 30, 35 and 40 c/deg was 32% ± 8% SE ($P<0.05$, paired t-test) (Figure 89F).

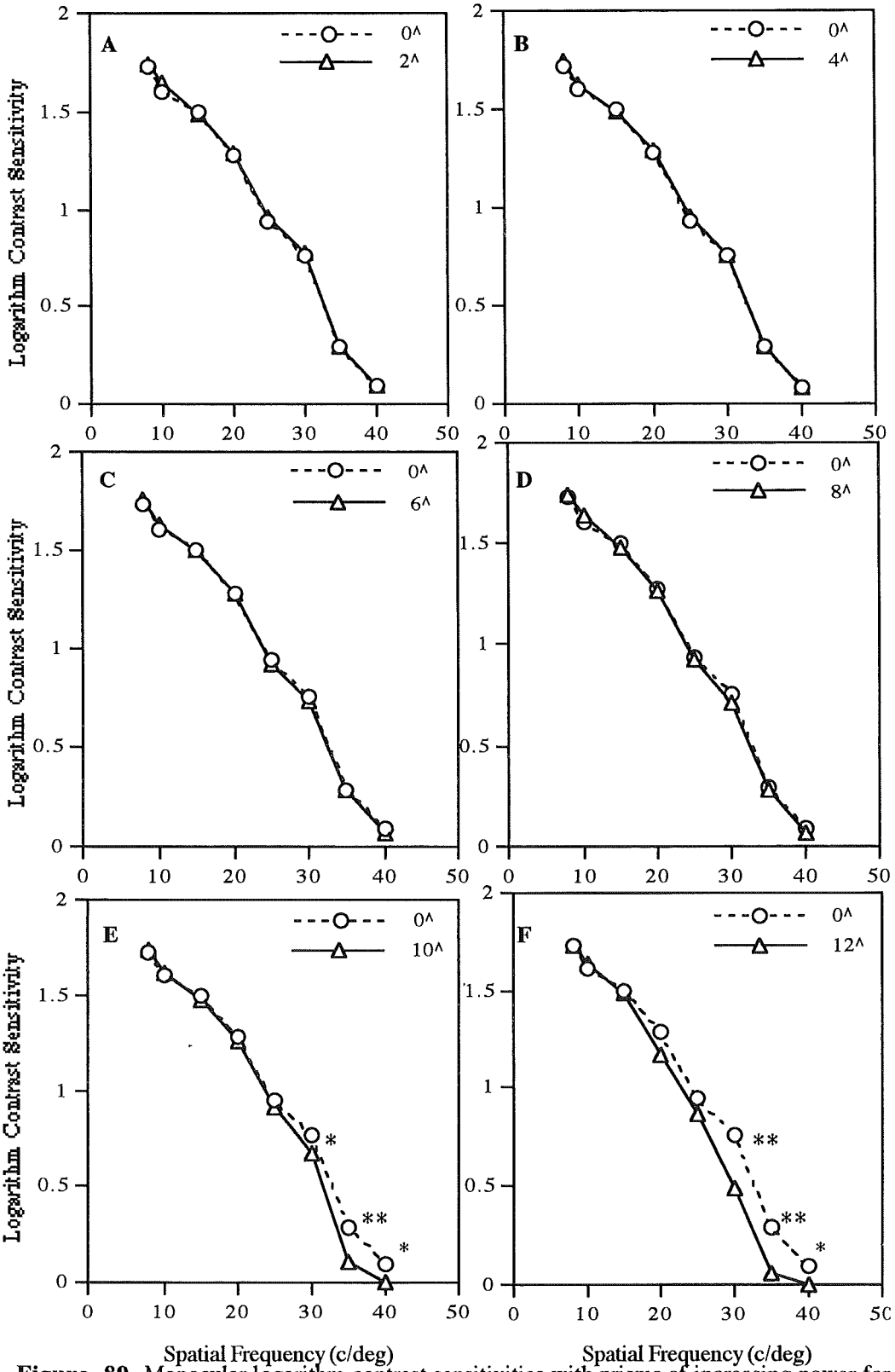


Figure 89. Monocular logarithm contrast sensitivities with prisms of increasing power for Subject 1. Each point is the mean of six determinations with standard error values of less than ± 0.05 which fall within the symbol size. Control contrast sensitivities are represented by open circles and broken lines, and those with the prism by open triangles and solid lines. **A**: 2^: **B**: 4^: **C**: 6^ **D**: 8^ **E** 10^: **F** 12^. (P<0.05 * P<0.01 **, paired t-test).

The next subject to be illustrated is the moderately severe myope in order to show whether the thickness of a spectacle lens also contributed to the degradation effect of the prisms described for Subject 1. The logarithm contrast sensitivities of Subject 4, a myope with a refractive correction of 5.50DS in the left eye, were similar with prism strengths of between 2^ and 8^ compared to those without the prism: there was almost exact superimposition at the spatial frequencies of 8c/deg to 25c/deg (Figure 90A, B, C and D). There was no statistically significant difference in contrast sensitivities over the range of spatial frequencies examined with prism powers of between 2^ - 8^ (Table 24). With the higher prism powers of 10^ and 12^ however, the logarithm contrast sensitivities were depressed compared to those measured without the prism. With the 10^ prism, a mean percentage reduction over all the spatial frequencies examined of 22% ± 9% SE was evident (Table 24). When the percentage reduction was averaged over 20c/deg to 40c/deg, the mean percentage reduction was 34% ± 12%, which was significant ($P<0.01$). A statistically significant reduction of 31% ± 11% SE ($P<0.05$, paired t-test) was present with the 12^ prism over all the spatial frequencies (Table 24). At the spatial frequencies of 20c/deg to 40c/deg, a greater mean percentage reduction of 46% ± 15% SE ($P<0.01$, paired t-test) was obtained.

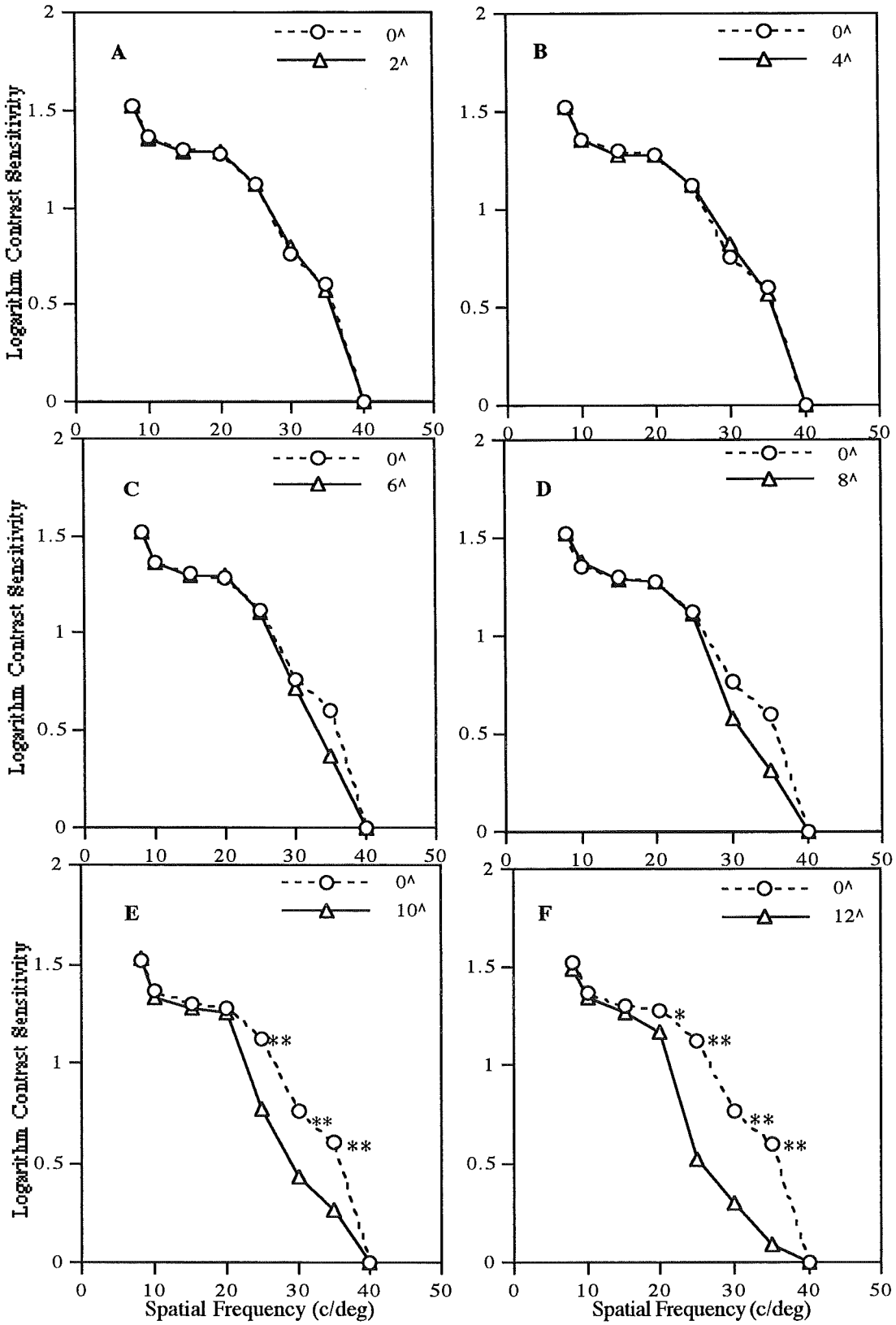


Figure 9 0. Monocular logarithm contrast sensitivities with prisms of increasing power for Subject 4. Each point is the mean of six determinations with standard error values of less than ± 0.05 which fall within the symbol size. Control contrast sensitivities are represented by open circles and broken lines, and those with the prism by open triangles and solid lines. **A**: 2^: **B**: 4^: **C**: 6^ **D**: 8^ **E** 10^: **F** 12^. (P<0.05* P<0.01**, paired t-test)

A reduction in contrast sensitivity at the higher spatial frequencies occurred in all four subjects with the higher prism powers of 10^ and 12^. While it appeared that the additional spectacle correction further added to the decrease caused by the prism powers of 10^ and 12^ in Subject 4, examination of the results for the other subjects (Table 24) did not support this premise.

In order to determine an approximate percentage reduction likely to have been caused by the spectacle lens, *per se*, the total percentage reduction with the 10^ and 12^ prism was obtained for the emmetrope (Subject 1) and the moderately severe myope (Subject 4). Thus, in Subject 1, the percentage reduction with 10^ was 10% and with the 12^ prism, 18%, giving a total of 28%; in Subject 4, the percentage reduction was 22% and 31% respectively, giving a total of 53% (Table 24). If the percentage reduction of Subject 1 is subtracted from Subject 4 and then divided by the refractive correction of the left eye in Subject 4, measured in dioptre spheres *i.e.* 5.50DS, an average reduction of 4.5% per 1.00DS is shown when the results of these 2 subjects are compared. However, if the percentage reduction with the higher prisms of all subjects in this group (n=4) are considered (Table 24), the refractive error does not seem to exert a systematic effect on the contrast sensitivities.

The reduction in contrast sensitivities with prism powers of 10^ and 12^ in Subjects 2, a low myope (1.00DS), and 3, a moderate myope (4.0DS), for example, is less than that for Subject 1, the emmetrope, not more as may have been expected in these ametropic subjects. Thus, the additional power of the spectacle correction did not contribute in a consistent way to the degradation caused by the prism.

3.3.2 Contrast Sensitivity: Group Data

The data for the 4 subjects were combined to give the mean values shown in Figure 91. These confirm the similarity of logarithm contrast sensitivity between control and prism powers of 2^ to 8^, and the reduction in contrast sensitivity with the higher prism power of 10^ and 12^ (Figure 91E and F).

When the changes in contrast sensitivities were averaged over all the spatial frequencies tested, for the four subjects, there was no significant change with 2^ to 10^. However, at 12^ there was a statistically significant reduction of 17% ± 5% (n = 4; t = 3.62; P = 0.036, one sample t-test).

Table 24 The Differences in Contrast Sensitivity with Prisms

Prism	Subject 1 0 DS	Subject 2 1.25DS	Subject 3 4.0DS	Subject 4 5.50DS	**Group Mean ± SE**
2^	+2% ± 1% ns	+5%±3% *	+1%±2% ns	+1% ±1% ns	**+ 2%±1% ns**
4^	+2% ± 1% ns	+7%±3% **	+5%±3% **	+1% ±2% ns	**+ 4%±1% ns**
6^	+1% ± 1% ns	+7%±3% **	+4%±5% **	- 6%±5% ns	**+ 1%±3% ns**
8^	+3% ± 2% ns	+5%±3% **	+11%±7% ns	-10%±7% ns	**+ 2%±4% ns**
10^	-10% ± 4% *	-2%±3% ns	- 7%±4% **	- 22%±9% **	**- 10%±4% ns**
12^	-18% ± 5% *	-10%±8% ns	-11%±4% *	- 31%±11% *	**- 17%±5% ***

Each value is mean ± SE averaged over the range of spatial frequencies examined:
DS - Dioptre Sphere ns - P>0.05 * - P<0.05 ** - P<0.01

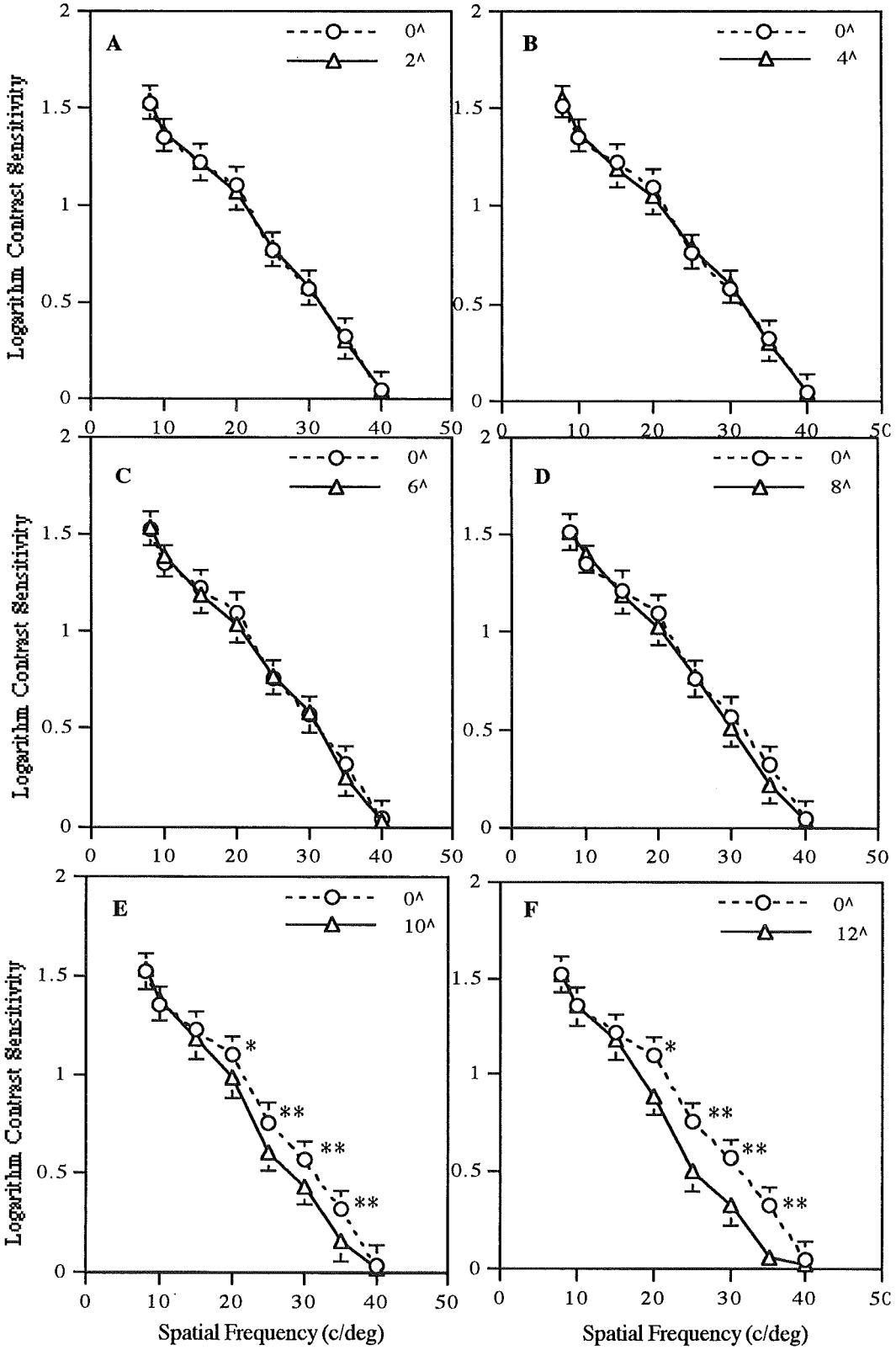


Figure 91. Group values (n=4) of monocular logarithm contrast sensitivities with prisms of increasing power (denoted by open triangle), compared with the control values obtained in the absence of a prism (denoted by open circle). The control value is repeated in each panel to allow comparison. Mean ± standard error (SE) is shown. **A**: 2^: **B**: 4^: **C**: 6^ **D**: 8^ **E** 10^: **F** 12^. (P>0.05. ns P<0.05 * P<0.01**, paired t-test).

3.4 Dichoptic Viewing Experiments

In strabismic subjects in whom there was an absence of BSV, prismatic correction of the squint so as to shift the image from the normal eccentric position on the retina back onto the fovea, which must now be considered to be a non-corresponding retinal point, consistently resulted in a reduction in binocular contrast sensitivity (Results, Section 3.2). It therefore had to be determined whether a similar shift of the retinal image in a normal subject, from the fovea to an eccentric, non-corresponding point, would likewise result in a reduction in binocular contrast sensitivity. While a prismatic correction was appropriate in causing translation of the image in strabismic subjects, this was not the case in normal subjects who would respond to placement of the prism in front of one eye with a compensatory movement of that eye in order to regain foveal fixation.

Therefore, the method adopted in normal subjects was as follows. A grating pattern was presented to the left eye which was thus viewed by the fovea of that eye. The monocular contrast sensitivities obtained were thus denoted Le. The grating pattern was also presented to the right eye (Re), the edge of which was located 2 deg from a green light emitting diode (Led), towards which the subject was instructed to direct the gaze of this eye (rather than the grating pattern). As a consequence, the image of the grating pattern was located 2 deg eccentric to the centre of the fovea of the right eye. Since the grating pattern thus fell nasally, it simulated a small esotropia.

With this stimulus arrangement, the subject would see the image of the grating pattern through the left eye, superimposed upon which was the image of the Led seen through the right eye, temporal to which was located the eccentric grating pattern (seen through the right eye (Re). The binocular contrast sensitivities thus obtained were denoted $Bin^{E.}$

For purposes of comparison of the binocular contrast sensitivities obtained for $Bin^{E.}$ viewing with the contrast sensitivities obtained for monocular viewing, it

was necessary to measure the contrast sensitivities with the image of the Led (seen through the Re) superimposed upon the image of the grating pattern (seen through the Le). These contrast sensitivities were denoted Le + Re Led. Thus, it would be possible to compare the effect of the additional eccentric right eye grating pattern on the left eye contrast sensitivities with superimposed Led (Le + Re Led). The latter, in turn, would allow a comparison with the monocular contrast sensitivities for the left eye only, to determine if the presence of the image of the Led (Re Led) interfered with these measurements.

3.4.1 The Normal Group

A normal group of 6 individuals was investigated. The subjects comprised females of between 27 years and 46 years of age. All achieved a visual acuity of 6/5 or better in both eyes (aided where applicable). Normal BSV was also evident in all subjects. 4 individuals exhibited exophoria, and 2 esophoria (Table 25). Two individuals (Subjects 1 and 5) had participated in the prism control experiments and Subject 3 had taken part in the main contrast sensitivity experiment.

Table 25 Clinical Data Under Conditions of Dichoptic Viewing in Normal Subjects

Subject	Visual Acuity	Refractive Error	Angle of Deviation	Accommodation (Amplitude)
1	RE 6/5 LE 6/5	RE -0.87DS LE -1.00DS	N: BI 4^: D:BI 4^	RE 8.00D LE 8.50D
2	RE 6/5 LE 6/5	RE -1.75DS LE -1.25DS	N: BI 4^: D:BI 4	RE 8.00D LE 8.00D
3	RE 6/4 LE 6/4	RE -3.12DS LE -3.25DS	N: BI 4^: D:BI 4^	RE 9.5D LE 8.5D
4	RE 6/5 LE 6/5	RE -5.00DS LE -5.00DS	N: BO 4^: D:BO2^	RE 6.00D LE 5.50D
5	RE 6/4 LE 6/4	RE -5.25DS LE -2.00DS	N: BO 4^: D:BO4^	RE 4.00D LE 4.25D
6	RE 6/5 LE 6/5	Nil Nil	N: BI 4^: D:BI 2^	RE 5.00D LE 6.00D

Key RE: Right Eye. LE: Left Eye. N+D: Near and Distance. BI: Base In. BO: Base Out. DS: Dioptre Sphere. DC: Dioptre Cylinder; ^: Prism Dioptre. +: Convex Lens. - : Concave Lens.

3.4.1.1 Contrast Sensitivity: Individual Data

For each subject, the contrast sensitivity expressed in logarithmic form at spatial frequencies 5, 8, 10, 15, 20, 25 and 30c/deg and at 35c/deg, if possible, was determined.

The subject viewed the grating pattern, which subtended 2 degrees by 2 degrees, through a dichoptic viewing apparatus (see Methods, Chapter 2, page 100), *i.e.* two paths were created for the sinusoidal grating pattern. The luminance was, of necessity, reduced compared with that in the previous experiments in which the grating pattern was viewed directly. Contrast thresholds were determined uniocularly and binocularly over the range of spatial frequencies, and six determinations of contrast threshold at each spatial frequency were made.

The monocular contrast sensitivities of the left eye (Le) alone were determined for each subject in response to the grating pattern. Then contrast sensitivities were obtained with the superimposition of the Led viewed through the right eye (Re Led) on the centre of the CRT display which was seen by the left eye (Le). Finally, the contrast sensitivities with the grating pattern viewed foveally by the left eye and eccentrically by the right eye (Bin^E) were determined.

Subject 1

The results for Subject 1 are shown in Figure 90. There was a close similarity between the logarithm contrast sensitivities for monocular viewing with the left eye in the presence and absence of the superimposed Led which was viewed by the right eye (Figure 92A). Furthermore, the presence of the eccentrically placed grating pattern viewed by the right eye (Bin^E) did not affect the logarithm contrast sensitivities when compared with those obtained by the left eye with the superimposed Led viewed through the right eye (Le + Re Led) (Figure 92B).

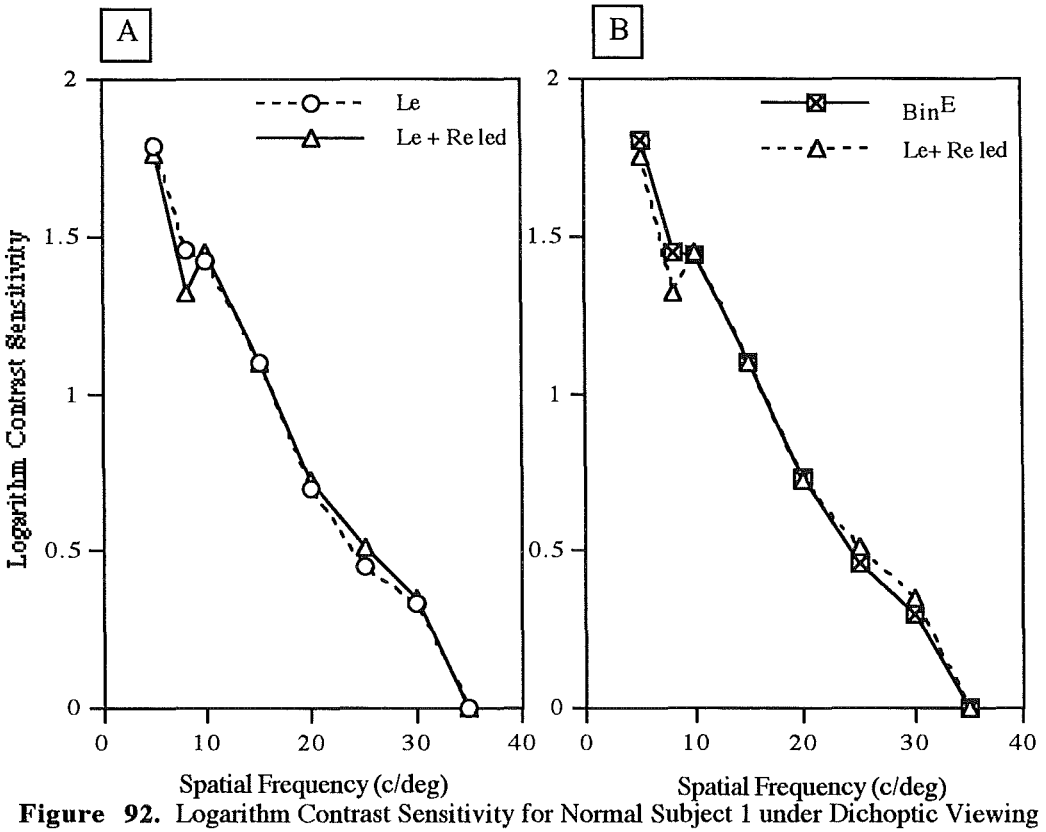


Figure 92. Logarithm Contrast Sensitivity for Normal Subject 1 under Dichoptic Viewing Conditions. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.

A. Comparison between left eye (Le) viewing grating pattern only and left eye viewing grating pattern and right eye viewing Led (Le + Re led)

B. Comparison between left eye viewing grating pattern and right eye viewing Led (Le+Re led) (same data as in **A**) and left eye viewing grating pattern and right eye viewing Led and eccentric grating pattern 2 degrees nasal to the centre of fovea (Bin^E)

The mean difference between contrast sensitivities at the spatial frequencies studied, averaged over the range of spatial frequencies, whilst viewing the grating pattern with the left eye (Le) and the Led with the right eye (Re Led) compared to that with the grating pattern alone viewed with the left eye (Le) was +0.05% ± 5% SE, which was not significant (P = 0.9, paired t-test). The overall mean percentage difference between contrast sensitivities with the addition of the eccentrically viewed grating pattern (Bin^E), *i.e.* when the grating pattern stimulated non-corresponding parts of the retina in the two eyes, and those obtained whilst viewing the grating pattern with the left eye and the

superimposed Led with the right eye (Le+Re Led) was +2% ± 5%, which was not statistically significant (P = 0.7, paired t-test) (Table 26).

3.4.1.2 Contrast Sensitivity: Group Data

When the monocular logarithm contrast sensitivities through the left eye which fixated the the grating pattern were compared with those of the right eye which fixated the Led (Le+Re Led), the logarithm contrast sensitivity values were almost exactly superimposed (Figure 93A) (Table 26).

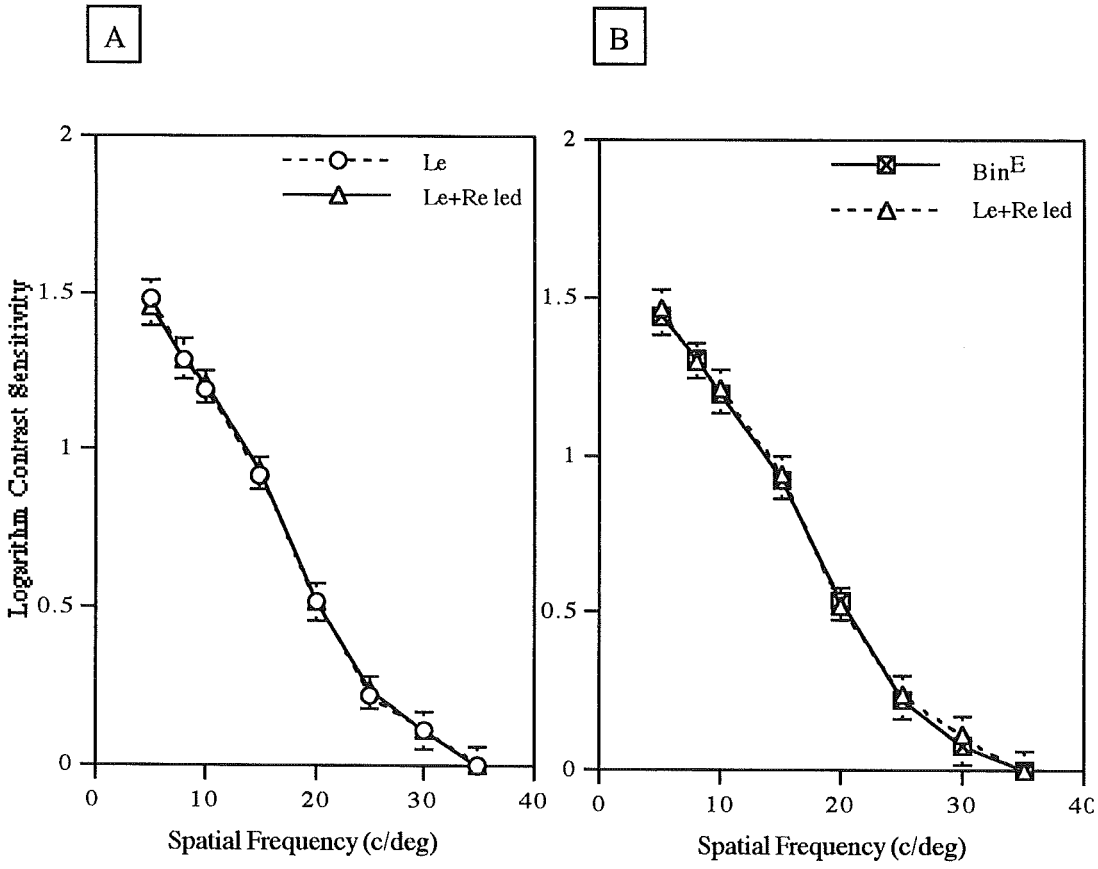


Figure 93. Logarithm Contrast Sensitivity for the Normal Group under Dichoptic Viewing Conditions. Mean ± SE is shown.
A. Comparison between left eye (Le) viewing grating pattern only and left eye viewing grating pattern and right eye viewing Led (Le + Re led)
B. Comparison between left eye viewing grating pattern and right eye viewing Led (Le+Re led) (same data as in **A**) and left eye viewing grating pattern and right eye viewing Led and eccentric grating pattern 2 degrees nasal to the centre of fovea (Bin^E)

A similar pattern emerged when the the binocular logarithm contrast sensitivities (Bin^E) were compared to the monocular logarithm contrast sensitivities (Le+Re

led) (Figure 91B). There was mean percentage decrease in the binocular contrast sensitivity (Bin^E) of 1% ± 1% ns compared to that obtained monocularly (Le+Re Led) which was not significant (n = 6; t = 1.58; P = 0.17; one sample t-test). This lack of statistical significance was also confirmed by the ANOVA test (F = 0.61; P = 0.43).

Table 26 Change in contrast sensitivity averaged over spatial frequencies studied between left eye and right eye viewing (Le + Re led) and left eye viewing (Le) and between left and right eye viewing (Le+Re led) and binocular viewing (Bin^E) under dichoptic conditions in normal subjects

Subject	$\frac{(Le + Re\ led) - Le}{Le} \times 100\%$	$\frac{Bin^E - (Le + Re\ led)}{(Le + Re\ led)} \times 100\%$
1	+0.5% ± 5% ns	+2% ± 5% ns
2	0% ± 1% ns	-2% ± 1% ns
3	-2% ± 4% ns	-2% ± 7% ns
4	-1% ± 2% ns	-2% ± 3% ns
5	+5% ± 4% ns	-4% ± 3% ns
6	+3% ± 2% ns	0% ± 2% ns
Mean	**+1%**	**-1%**

Each value is mean for the spatial frequencies tested in each subject.
Le - Left eye Re led - Right eye light emitting diode Bin^E - eccentrically placed grating
ns - not significant

Thus, in this group of normal subjects, the presence of a superimposed light emitting diode did not adversely affect the monocular contrast sensitivities. Further, the eccentrically viewed grating pattern presented to one eye did not affect the monocular contrast sensitivities obtained through the other eye.

3.4.2 Simple Anisometropic Amblyopes

There was also the opportunity to determine the effect of stimulation of non-corresponding retinal points in the simple anisometropic amblyopes who have, in effect, been treated as an extension of the normal group. As with the normal group, the direction of gaze of one eye had to be controlled in order that an eccentrically positioned grating pattern could be viewed.

The protocol was altered to take account of the eye which was amblyopic so that the directly viewed grating pattern was presented to the better, non-amblyopic eye (Be). The eccentric grating was, thus, presented to the amblyopic eye (Pe). For each subject, the contrast sensitivities expressed in logarithmic form at spatial frequencies 5c/deg to 40c/deg were obtained in the sequence previously applied to the normal group. Two simple anisometropic amblyopes were examined under dichoptic conditions of viewing. Both subjects had previously participated in the initial experiments (Subject 1 and Subject 7) and were thus experienced participants.

3.4.2.1 Contrast Sensitivity: Individual Data

Subject 1

The results for Subject 1 are shown in Figure 94. The logarithm contrast sensitivities for monocular viewing with the better eye (Be) alone and those in the presence of the superimposed Led viewed by the poorer eye (Be+Pe Led) were again very similar (Figure 94A). The mean percentage difference in contrast sensitivity, averaged over the range of spatial frequencies, for the better eye with the superimposed Led viewed by the poorer eye (Be+Pe Led) compared with monocular viewing by the better eye alone was -5% ± 3%, which was not significant (P = 0.1, paired t-test).

Furthermore, the logarithm contrast sensitivities obtained in the presence of an eccentrically placed grating pattern viewed by the poorer eye, (Bin^E) did not affect those obtained viewing with the better eye (Be + Pe led). The contrast sensitivity values were almost superimposed under the two conditions of viewing (Figure 94B).

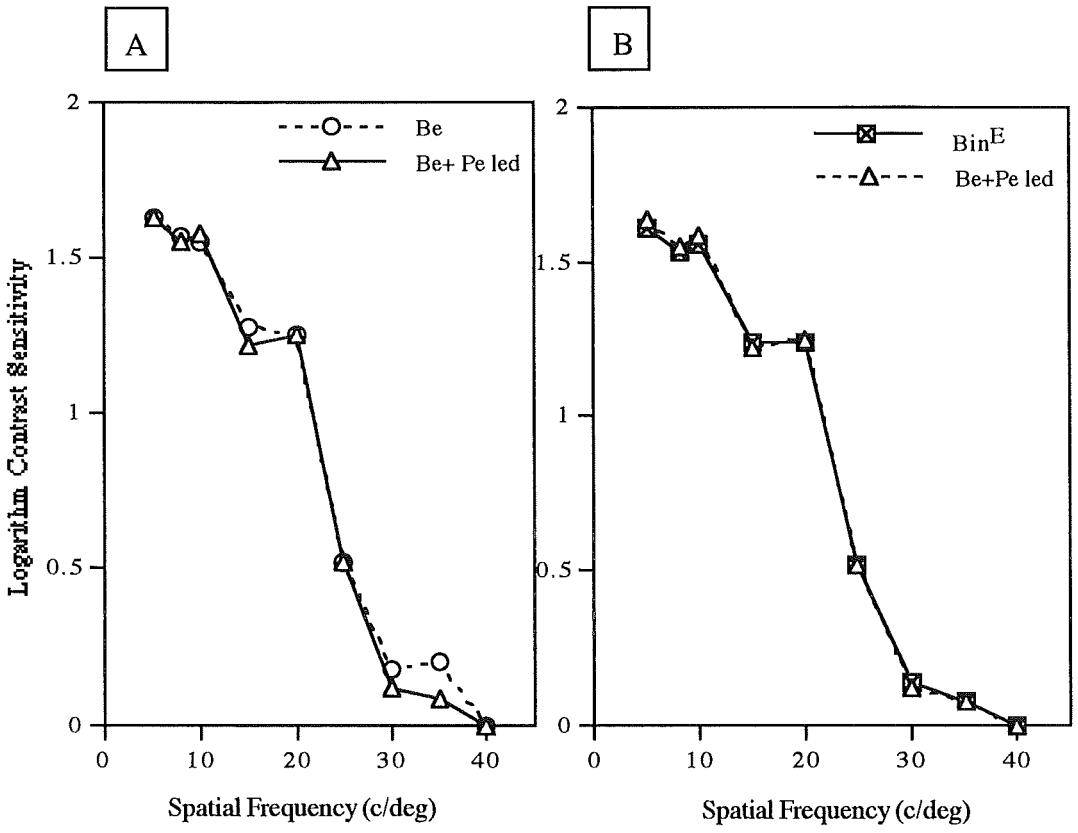


Figure 94. Logarithm Contrast Sensitivity for Simple Anisometropic Amblyope, Subject 1, under Dichoptic Viewing Conditions. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Comparison between better eye (Be) viewing grating pattern only and better eye viewing grating pattern and poorer eye viewing Led (Be + Pe led)
B. Comparison between better eye viewing grating pattern and poorer eye viewing Led (Be+Pe led) (same data as in **A**) and better eye viewing grating pattern and poorer eye viewing Led and eccentric grating pattern 2 degrees nasal to the centre of fovea (Bin^E).

Subject 2

In the second simple anisometrope (Subject 7), the monocular logarithm contrast sensitivities, obtained in the presence of the Led (Be + Pe Led) were similar to those for the better eye alone (Fig 95A). The mean percentage contrast sensitivity, averaged over the range of spatial frequencies, of the better eye with the superimposed Led (Be+Pe led) was greater than that of the better eye alone (Be) by 5% ± 6% SE, which was not significant (P = 0.4, paired t-test). The mean percentage binocular contrast sensitivities (Bin^E), averaged over the range of spatial frequencies tested, when compared to those obtained through the better eye with the superimposed Led (Be+Pe Led) were less by 2% ± 4% SE (P = 0.7, paired t-test), which was not significant (Figure 95B).

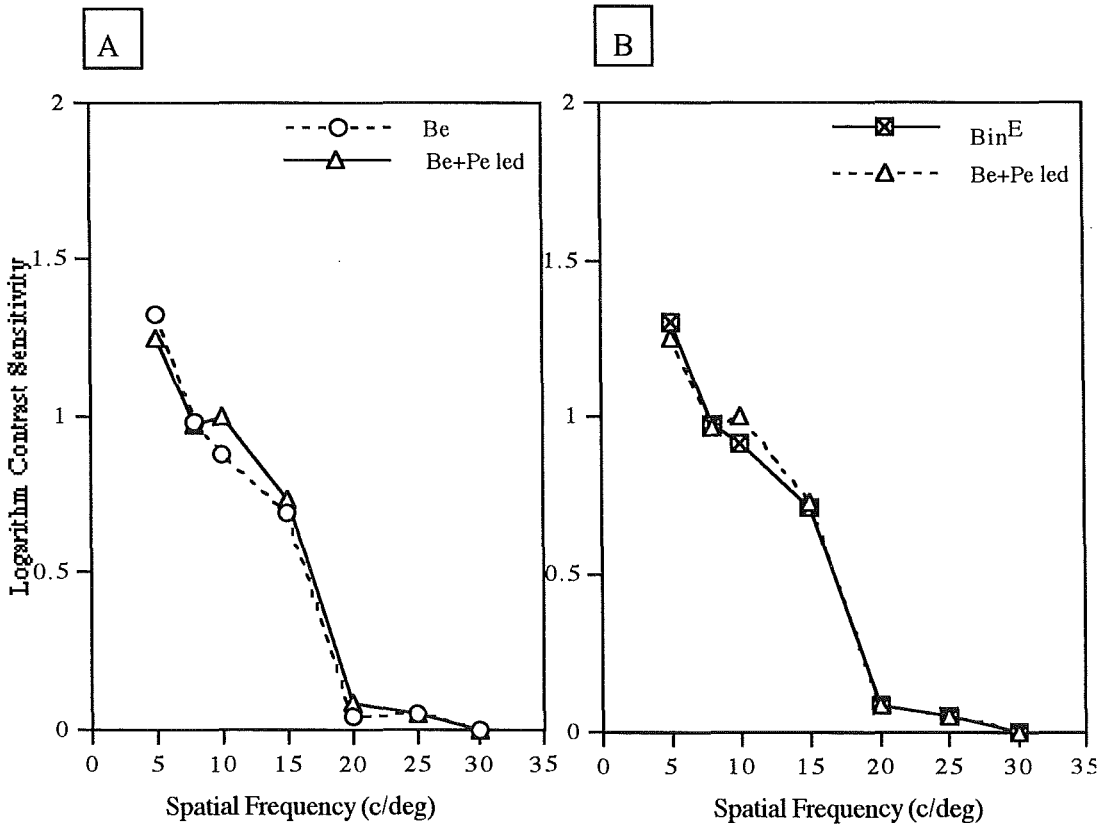


Figure 95. Logarithm Contrast Sensitivity for Simple Anisometropic Amblyope, Subject 7, under Dichoptic Viewing Conditions. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Comparison between better eye (Be) viewing grating pattern only and better eye viewing grating pattern and poorer eye viewing Led (Be + Pe led)
B. Comparison between better eye viewing grating pattern and poorer eye viewing Led (Be+Pe led) (same data as in **A**) and better eye viewing grating pattern and poorer eye viewing Led and eccentric grating pattern 2 degrees nasal to the centre of fovea (Bin^E).

Thus, in these 2 simple anisometropic amblyopes, there was no significant difference between the monocular contrast sensitivities with the superimposed Led (Be+Pe led) and those of the better eye (Be), nor was there any significant difference between the binocular contrast sensitivities (Bin^E) and those obtained by the better eye with the superimposed Led (Be + Pe Led).

It is therefore evident that in both non-squinting groups, the normal group and the simple anisometropic amblyopes, stimulation of non-corresponding retina with the presence of an eccentric grating pattern (Bin^E), did not significantly affect the contrast sensitivities obtained with foveal fixation by the companion eye.

3.4.3 Strabismic Subjects

In the previous prism experiments (Results, Section 3.2), it was possible to determine the effect of stimulation of non-corresponding retinal points in amblyopic and non-amblyopic strabismic groups by effecting bifoveal stimulation with the aid of prisms of suitable power and base direction. In order to test the validity of the results of these experiments in which bifoveal stimulation resulted in a reduction in contrast sensitivity, the dichoptic viewing experiments were also carried out in a number of strabismic subjects. The better eye (Be) viewed the grating pattern foveally, and the apparatus was adjusted so that the second grating pattern was also viewed foveally by the poorer, squinting eye (Pe), so as to effect bifoveal stimulation (Bin^F).

However, the dichoptic apparatus presented new problems in that the strabismic eye was resistant to attempts to change the direction of gaze towards the Led, which resulted in its use being discontinued. The monocular contrast sensitivities were therefore measured, in all cases, in response to the grating pattern alone for the better eye (Be) and the poorer eye (Pe). In addition, the contrast sensitivities obtained through the better eye (Be) were then compared to those obtained under bifoveal conditions of viewing (Bin^F).

3.4.3.1 Micro -esotropic Amblyopes

Two individuals comprised this group. Both were experienced observers who had participated in the earlier experiments (Subjects 1 and 5). The clinical findings were as previously stated, i.e. microtropia without identity of 3 degrees or less, amblyopia in the squinting eye, para-foveal fixation in the squinting eye and anomalous BSV.

Contrast Sensitivity: Individual Data

For each subject (1 and 5), the contrast sensitivities expressed in logarithmic form at spatial frequencies 5, 8, 10, 15, 20, 25, and when possible 30 and 35c/deg were obtained for monocular viewing of the grating pattern through the better eye (Be) and the poorer eye (Pe). Thereafter, logarithm contrast

sensitivities were then obtained for binocular viewing of the grating pattern, which was aligned so that it stimulated the fovea of the better eye and the pseudo fovea of the microtropic eye. Although this is not strictly bifoveal stimulation (Bin^F), for convenience, it will be referred to as such in this microtropic group.

Subject 1

For monocular viewing, the logarithm contrast sensitivities of the poorer eye (Pe) were markedly less than those obtained through the better eye (Be) (Figure 96A) to the extent that, when averaged over the range of spatial frequencies, they were reduced by 88% ± 7%, which was statistically significant ($P<0.01$, paired t-test) (Table 27).

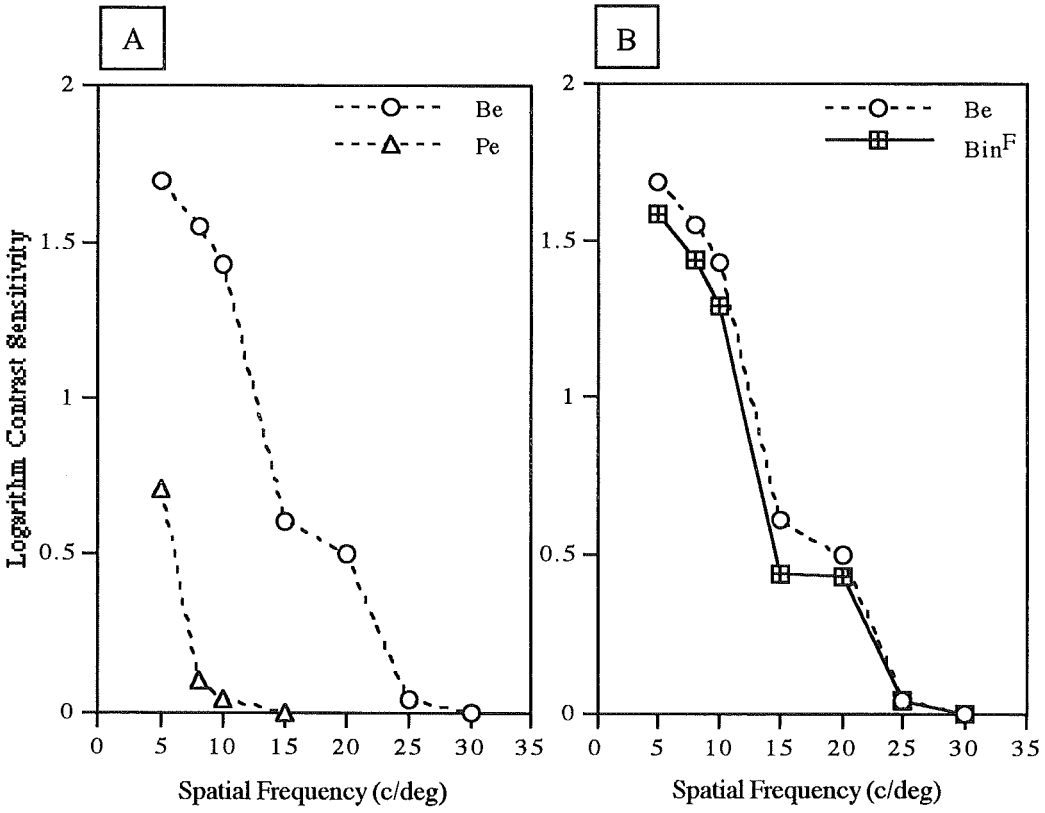


Figure 96. Logarithm Contrast Sensitivity for Micro-esotropic Amblyope, Subject 1, under Dichoptic Viewing Conditions. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Comparison of monocular contrast sensitivities obtained with the better eye (Be) and the poorer eye (Pe).
B: Comparison between contrast sensitivities obtained under conditions of bifoveal stimulation (Bin^F) with those of the better eye (Be) viewing the grating pattern only (same data as in **A**).

Under conditions of bifoveal stimulation (Bin^F), logarithm contrast sensitivities were slightly reduced compared to those of the better eye (Be) (Figure 96B), with a mean percentage reduction, averaged over the range of spatial frequencies, of 23% ± 8% SE ($P<0.05$, paired t-test) (Table 27).

Subject 5

In Subject 5, there was again a marked reduction in the logarithm contrast sensitivities obtained through the poorer eye (Pe) when they were compared to those in the better eye (Be) (Figure 97A). The mean percentage reduction in contrast sensitivity, averaged over the range of spatial frequencies tested, through the poorer eye was 76% ± 4% SE and this was statistically significant ($P<0.01$, paired t-test) (Table 27).

Under bifoveal conditions of viewing (Bin^F), a consistent reduction in contrast sensitivity was evident when compared with viewing through the better eye (Be) (Figure 97B). The reduction in the mean percentage bifoveal contrast sensitivity (Bin^F), averaged over the range of spatial frequencies, compared with that obtained through the better eye (Be) was 25% ± 4% SE, which was also significant ($P<0.01$, paired t-test) (Table 27).

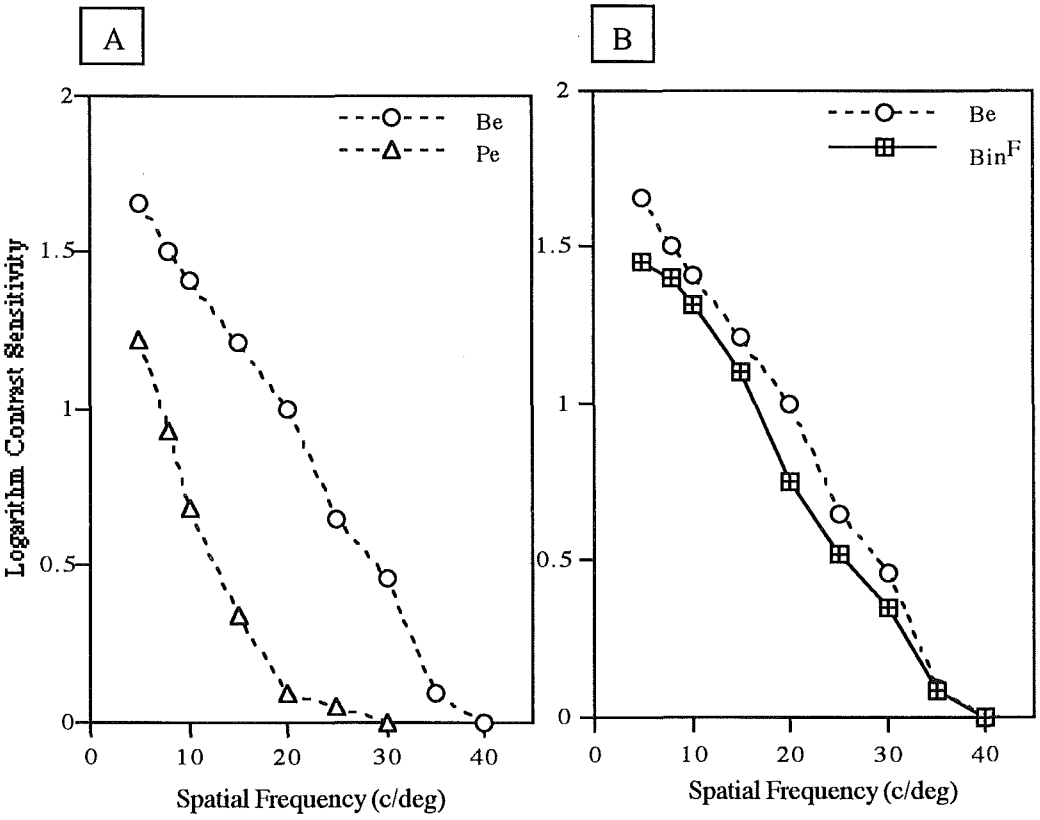


Figure 97. Logarithm Contrast Sensitivity for Micro-esotropic Amblyope, Subject 5, under Dichoptic Viewing Conditions. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Comparison of monocular contrast sensitivities obtained with the better eye (Be) and poorer eye (Pe).
B: Comparison between contrast sensitivities obtained under conditions of bifoveal stimulation (Bin^F) with those of the better eye (Be) viewing the grating pattern only (same data as in **A**).

Table 27 Percentage Change in Contrast Sensitivity, Averaged Over the Range of Spatial Frequencies, in Micro-esotropic Amblyopes

Subject	$\frac{(Pe - Be)}{Be} \times 100\%$	$\frac{(Bin^F - Be)}{Be} \times 100\%$
1	- 88% ± 7% **	- 23% ± 8% *
5	- 76% ± 4% **	- 25% ± 4% **
Mean	**- 82%**	**- 24%**

Each value is mean ± SE for the spatial frequencies tested in each subject.
Be - Better Eye Pe - Poorer Eye Bin^F - bifoveal viewing
* - P<0.05 ** - P<0.01.

Therefore, in these two microtropic amblyopes, the mean percentage reduction in contrast sensitivity was 82% when the contrast sensitivity through the squinting amblyopic eye (Pe) was compared to that of the better eye (Table 27). When the bifoveal contrast sensitivities (Bin^F) were compared with those through the better eye (Be) alone, the mean percentage reduction, averaged over the range of spatial frequencies tested, was 24%.

3.4.3.2 Esotropic Amblyopes without BSV

Three esotropic amblyopes with an absence of BSV took part in the dichoptic viewing experiments. All individuals exhibited a constant esotropia, amblyopia in the squinting eye, peripheral and central suppression. All subjects had taken part in the earlier experiments (3, 4 and 5) (Table 10) .

Contrast Sensitivity: Individual Data

For each subject, contrast sensitivity expressed in logarithmic form at spatial frequencies 5, 8, 10, 15, 20, 25, and if possible 30c/deg was obtained for monocular and binocular viewing.

Subject 3

The logarithm contrast sensitivities of the esotropic eye (Pe) were depressed at all spatial frequencies compared with those of the normal eye (Be) (Figure 98A). The mean percentage reduction in contrast sensitivity through the poorer eye (Pe) compared to that obtained by the better eye, averaged over the range of spatial frequencies, was 35% ± 4% SE ($P<0.01$, paired t-test) (Table 28).

The bifoveal logarithm contrast sensitivities (Bin^F) were also reduced compared to those obtained through the better eye (Be): the grating pattern could not be discerned above 25c/deg under bifoveal conditions of viewing, although through the better eye alone, 30c/deg could be resolved (Figure 98B).

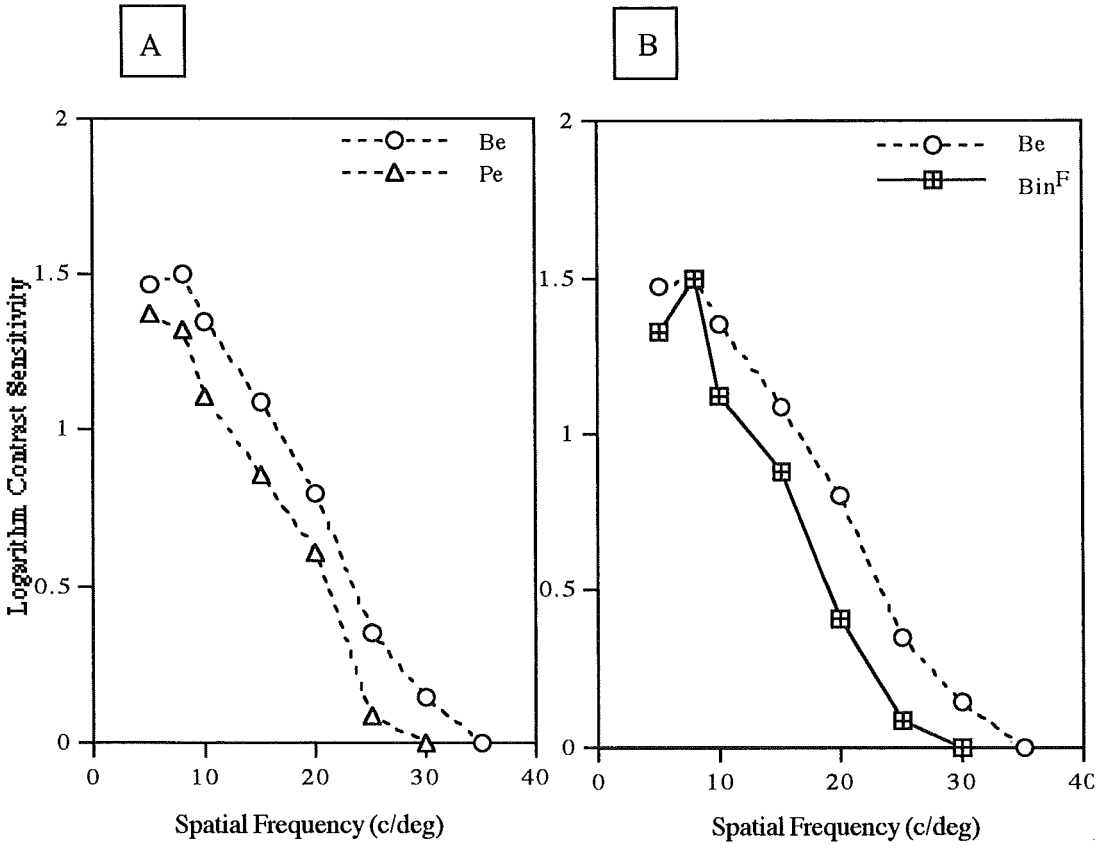


Figure 98. Logarithm Contrast Sensitivity for Esotropic Amblyope without BSV, Subject 3, under Dichoptic Viewing Conditions. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Comparison of monocular contrast sensitivities obtained with the better eye (Be) and poorer eye (Pe).
B: Comparison between contrast sensitivities obtained under conditions of bifoveal stimulation (Bin^F) with those of the better eye (Be) viewing the grating pattern only (same data as in **A**).

The mean percentage reduction in the bifoveal contrast sensitivity, averaged over the range of spatial frequencies tested, was 33% ± 7% SE (Table 28) when compared to viewing with the better eye, and this was significant ($P<0.01$, paired t-test) .

Subject 4

In this individual, vision was severely compromised for monocular viewing with the amblyopic eye (Pe) compared with the better eye (Be) (Figure 99A). It should also be noted that, while vision through the normal eye was 6/5, contrast sensitivities were recorded only up to 20c/deg, which indicated that vision through this eye was not entirely normal. The contrast sensitivities when averaged over the range of spatial frequencies showed a reduction of 78% ± 7% SE, which was significant (P<0.01, paired t-test) (Table 28).

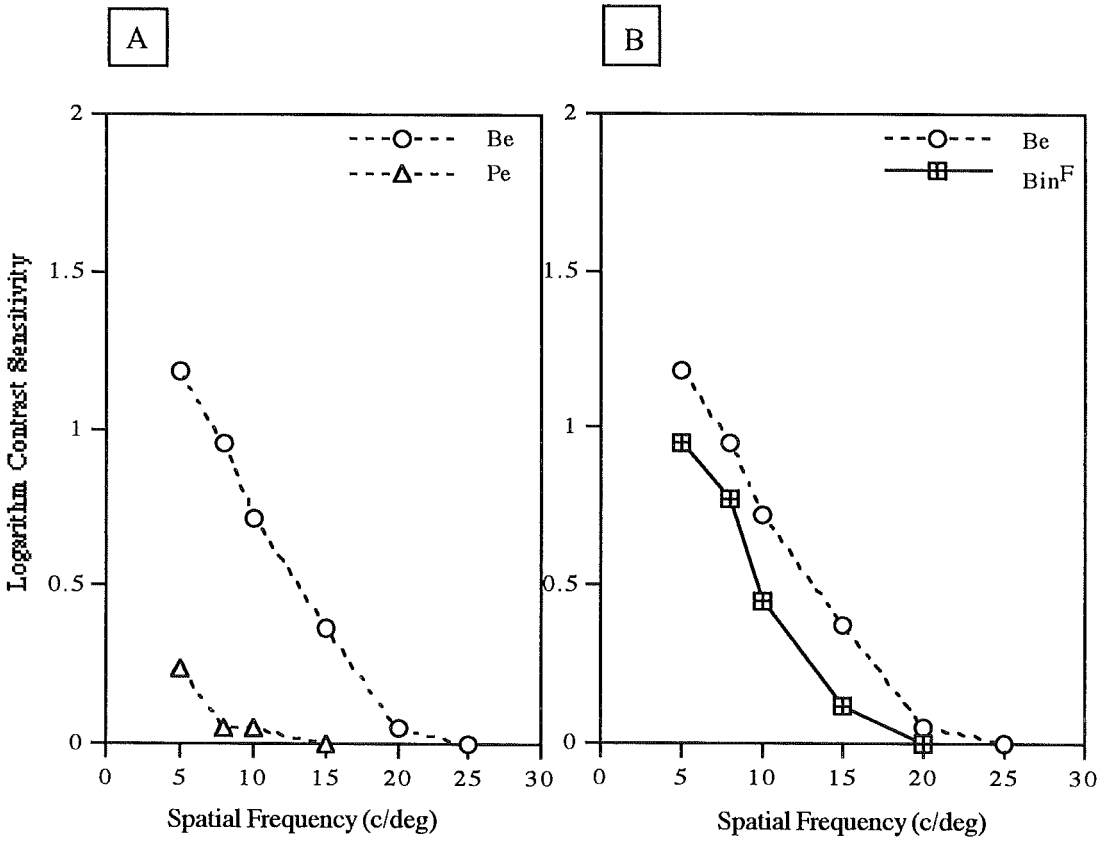


Figure 99. Logarithm Contrast Sensitivity for Esotropic Amblyope without BSV, Subject 4 under Dichoptic Viewing Conditions. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Comparison of monocular contrast sensitivities obtained with the better eye (Be) and poorer eye (Pe).
B: Comparison between contrast sensitivities obtained under conditions of bifoveal stimulation (Bin^F) with those of the better eye (Be) viewing the grating pattern only (same data as in **A**).

The bifoveal contrast sensitivities (Bin^F) were reduced at all spatial frequencies compared to those obtained by the better eye (Be) (Figure 99B). A statistically

significant decrease of 33% ± 8% SE (P<0.05, paired t-test), averaged over the range of spatial frequencies, was found when compared to that of the better eye (Be) alone (Table 28).

Subject 5

In subject 5, the logarithm contrast sensitivities in the poorer eye (Pe) were again depressed compared to those through the better eye (Be) (Figure 100A). The mean percentage reduction in contrast sensitivity, over the range of spatial frequencies examined, was 52% ± 8% SE (P<0.01, paired t-test) through the poorer eye (Pe) compared with viewing through the better eye (Be) (Table 28).

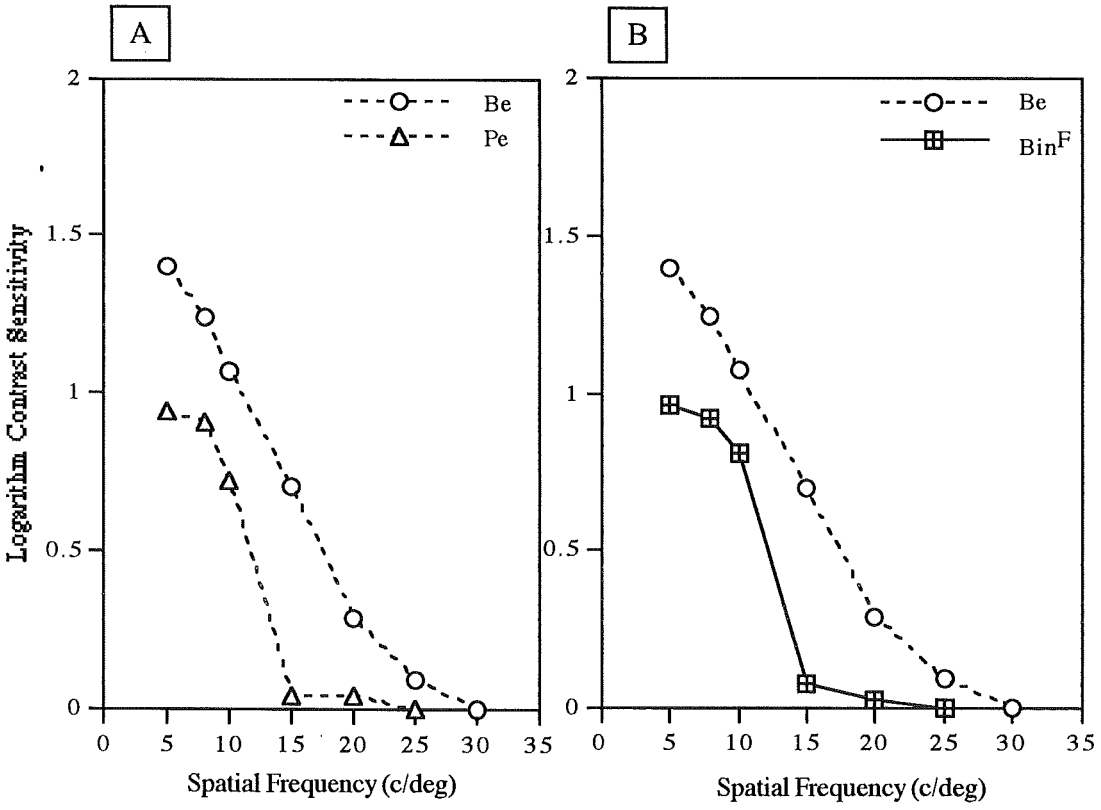


Figure 100. Logarithm Contrast Sensitivity for Esotropic Amblyope without BSV, Subject 5, under Dichoptic Viewing Conditions. Each point is the mean of six determinations with standard error values of less than ± 0.05, which fall within the symbol size.
A. Comparison of monocular contrast sensitivities obtained with the better eye (Be) and poorer eye (Pe).
B: Comparison between contrast sensitivities obtained under conditions of bifoveal stimulation (Bin^F) with those of the better eye (Be) viewing the grating pattern only (same data as in **A**).

There was also a reduction in contrast sensitivities under bifoveal conditions of viewing (Bin^F) compared to those obtained by the better eye (Be) (Figure 100B). The mean percentage decrease in bifoveal contrast sensitivity, over the range of spatial frequencies tested, was 50% ± 8% SE which was significant ($P < 0.01$, paired t-test) (Table 28).

Table 28 Percentage Reduction in Contrast Sensitivity, Averaged over the Range of Spatial Frequencies, in Esotropic Amblyopes without BSV

Subject	$\frac{(Pe - Be)}{Be} \times 100\%$	$\frac{(Bin^F - Be)}{Be} \times 100\%$
3	-35% ± 4% **	-33% ± 7% **
4	-78% ± 7% **	-33% ± 8% *
5	-52% ± 8% **	-50% ± 8% **
Mean	**-55%**	**-39%**

Each value is mean ± SE for the spatial frequencies tested in teach subject tested.
Be - Better Eye Pe - Poorer Eye Bin^F - bifoveal viewing
* - $P<0.05$ ** - $P<0.01$)

Thus, in the 3 esotropic amblyopes without BSV, bifoveal contrast sensitivities (Bin^F) were reduced by a mean of 39%, averaged over the range of spatial frequencies, compared with those of the better eye (Be) (Table 28).

3.4.4 Summary

In the non-strabismic groups in which stimulation of non-corresponding retinal points was effected (Bin^E) (the normal group and the simple anisometropic amblyopes), the contrast sensitivities across the range of spatial frequencies tested were not significantly affected by the presence of the eccentric grating pattern. In the strabismic groups, however, stimulation of non-corresponding retinal points (Bin^F) (microtropic anisometropic amblyopes with anomalous BSV and esotropic amblyopes without BSV) did result in a significant loss of bifoveal contrast sensitivity. These results are summarised as linear differences

against spatial frequency in Figure 101 and Table 29 which also shows the results from the previous experiments in which the angle of deviation was neutralised with a prism.

Table 29 Comparison of the percentage change in contrast sensitivity, averaged over the range of spatial frequencies, in non-strabismic and strabismic groups for dichoptic viewing and viewing with prismatic correction (where appropriate) and for monocular viewing.

Group	Subject	Bin* - Be / Be	Bin^ - Be / Be	Pe-Be / Be	(previous) Pe-Be / Be
Normals with BSV		-1% ns {F = 0.61 ns}	-	-	-
Simple Anisometropic Amblyopes with anomalous BSV	1	-1% ± 2% ns	-	-	-
	7	-2% ± 4% ns	-	-	-
Micro-esotropic Amblyopes with anomalous BSV	1	-23% ± 8% *	-26% ± 7% **	-88%±7%**	-87% ± 3% **
	5	-25% ± 4% **	-39% ±16%ns	-76%±4%**	-42% ± 8% **
Esotropic Amblyopes without BSV	3	-33% ± 7% **	-45% ± 4%**	-35%±4%**	-75% ± 3% **
	4	-33% ± 8% *	-19% ± 6% *	-78%±7%**	-68% ± 10%**
	5	-50% ± 8% **	-21% ± 5% **	-52%±8%**	-31% ± 2% **

Bin* - Bin^E or Bin^F: Bin - Binocular: Be - Better Eye: Pe - Poorer Eye
(Previous) - data from another experiment;
micro-esotropic data is from Table 6 (previous Pe - Be) and Table 18 (Bin^- Be);
esotropic amblyope data is from Table 10 (Pe-Be) and Table 20 (Bin^- Be).
microtropic data is from Table 27 (Pe-Be)

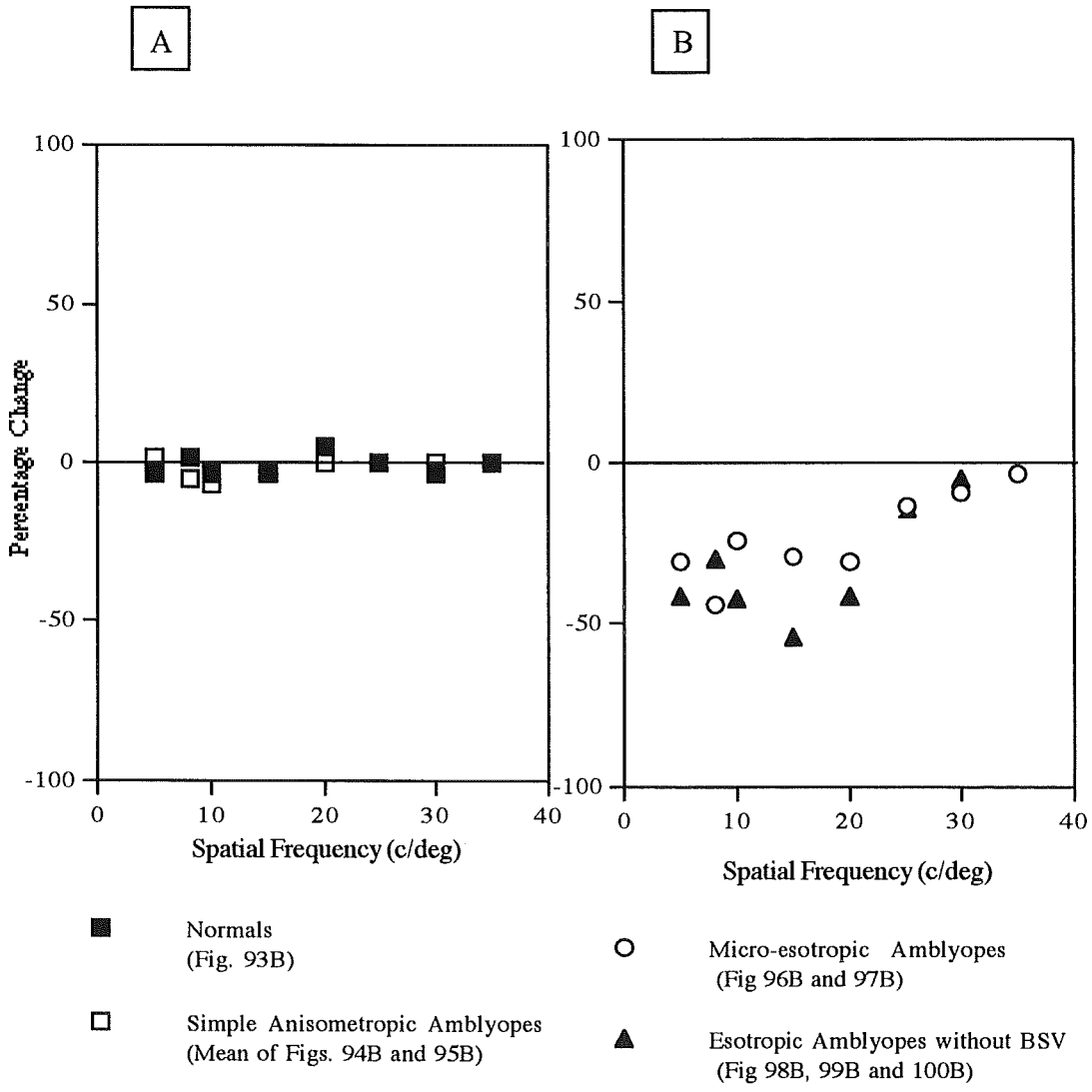


Figure 101. Summary of mean percentage change in contrast sensitivity for binocular viewing with eccentrically placed grating pattern at each spatial frequency tested.

A: Groups showing a change in contrast sensitivity
B: Groups showing a decrease in contrast sensitivity.

(given in parenthesis is the Figure number(s) from which data are taken)

4.0 DISCUSSION

In the present study, a series of comparisons has been made of the contrast sensitivities obtained under different conditions of viewing in normal subjects, in amblyopic subjects and in non-amblyopic strabismic subjects. These comparisons were made between:

1. Left and right eye monocular viewing, which demonstrated that viewing through one eye, denoted the better eye, had higher contrast sensitivities than the companion eye.

2 Binocular viewing and better eye monocular viewing, which demonstrated that binocular enhancement occurred in the presence of normal or anomalous BSV, but that binocular depression occurred when BSV was absent.

3 Binocular viewing under normal conditions and with neutralisation of the angle of deviation in strabismics, which resulted in a reduction of contrast sensitivity in the majority of individuals.

4.1 Monocular Contrast Sensitivities

4.1.1 The Normal Group

The mean reduction, across the range of spatial frequencies examined, between the contrast sensitivities of the poorer eye compared with those of the better eye ranged from 6% to 43% with a mean value of 22% in this group who had been designated normal on the basis of their Snellen acuity (Table 30).

The relatively high reduction in contrast sensitivity between the two eyes, found in this study, may be a reflection of the time taken to complete the experimental protocols which, in the majority of cases, took between three to four hours. Thus, fatigue may indeed have contributed to the percentage contrast sensitivity difference between the eyes. In addition, lack of randomisation in the order to eye testing, thus contributing to a "learned effect" could conceivably have also influenced the contrast sensitivity findings. However, as 5 individuals exhibited poorer contrast sensitivities in the right eye, and 6 subjects exhibited poorer

contrast sensitivity in the left eye, it reasonable to suggest that the lack of randomisation of presentation did not unduly influence the contrast sensitivity outcomes. If the reduction in contrast sensitivity between the two eyes is a true loss, then it would be a reflection of diminished vision at spatial frequencies lower than the highest spatial frequency detectable. On the basis that inter-ocular contrast sensitivity difference between the eyes is a true reflection of visual performance a substantial difference between the eyes in an individual cannot be viewed as normal; it is therefore necessary to arrive at a cut off point for normality. This must of necessity be arbitrary unless a very conservatively narrow difference is to be adopted, in which case very few subjects would meet the criteria for normality. However, the distribution in the histogram in Figure 102, shows nine individuals with differences below 30% and two individuals above 35%, which suggests a separation point of 30%. Thus, with respect to the present study, differences of 30% or less are deemed to be normal while those with differences greater than 30% are not considered to be normal. This leads to the exclusion of two subjects classified as normal on the basis of their Snellen acuity (Subjects 5 and 10).

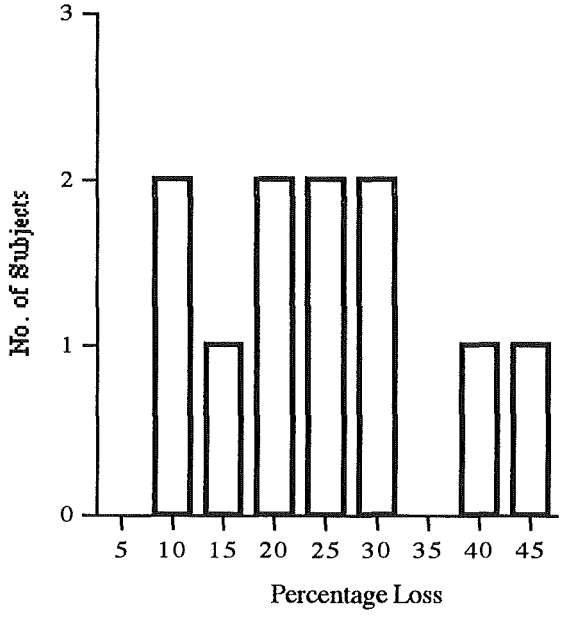


Figure 102 Histogram of the percentage loss in subjects comprising the normal group. The number of subjects were placed in 5% bins centred on the values shown on the abscissa.

Table 30 Recapitulation of Mean Percentage Reduction in Contrast Sensitivities of the Poorer Eye Compared with the Better Eye, together with Snellen Acuities in Groups with and without BSV

Subject No.	Normals			Simple Anisometropic Anisometropes			Micro-esotropic Amblyopes			Esotropes with ABSV		
	CS	VA Re	Le	CS	VA Re	Le	CS	VA Re	Le	CS	VA Re	Le
1	-29%	4	4	- 83%	4	36	- 87%	12	5	- 44%	9	5
2	-27%	5	5	- 30%	18	5	- 43%	12	5	- 85%	18	5
3	-22%	4	4	- 13%	9	6	- 70%	4	12	- 44%	9	6
4	-17%	5	5	- 65%	12	4	- 40%	6	12			
5	-43%	5	5	- 8%	18	5	- 42%	9	5			
6	-19%	5	5	- 27%	4	9	- 26%	4	9			
7	-6%	4	4	- 50%	9	4						
8	-7%	4	4	- 79%	5	24						
9	-11%	4	5	- 50%	12	5						
10	- 40%	5	5									
11	- 23%	4	5									
Mean	**-22%**			**-45%**			**-51%**			**-58%**		
Subject No.	Esotropic Amblyopes without BSV			Non-Amblyopic Esotropes without BSV			Exotropic Amblyopes without BSV			Non-Amblyopic Exotropes without BSV		
	CS	VA Re	Le	CS	VA Re	Le	CS	VA Re	Le	CS	VA Re	Le
1	- 73%	24	5	- 44%	6	6	- 87%	6	36	- 44%	5	5
2	- 79%	18	5	- 22%	5	5	- 56%	9	6	- 41%	4	4
3	- 75%	5	18	- 51%	5	5						
4	- 68%	60	5	- 18%	4	4						
5	- 31%	6	9									
Mean	**-65%**			**-34%**			**-72%**			**-42%**		

CS: Contrast Sensitivity VA: The number represents the denominator of Snellen fraction
Re: Right Eye. Le: Left Eye BSV: Binocular Single Vision. ABSV: Anomalous BSV.

In addition, in the context of defining what is normal or abnormal vision, the value of the Snellen acuity and the highest spatial frequency of a sinusoidal grating pattern detected cannot be disregarded. These are not necessarily inter-changeable since the determination of Snellen acuity contains an element of letter recognition which is not a feature of the highest spatial frequency detected. It is conceivable that an individual might have a normal high spatial frequency cut off but with a subnormal Snellen acuity due to abnormal letter recognition. Thus, for the purposes of the present study, *under our conditions of test*, the following set of criteria were required to be met in its entirety for the individual to be considered normal:

- visual acuity of 6/5 or better in each eye.
- a high spatial frequency cut off of at least 35c/deg in each eye.
- a contrast sensitivity difference averaged over the spatial frequency range of no more than 30% between the two eyes.

A set of requirements for the diagnosis of amblyopia must also be arrived at. *Under our conditions of test*, an individual is classified as amblyopic if at least one of the following criteria is met.

- visual acuity of 6/6 or worse in one eye:
- a high spatial frequency cut off of 30c/deg or less in one eye:
- a contrast sensitivity difference averaged over the spatial frequency range of greater than 30% between the two eyes:

Thus, Subjects 5 and 10 may now be considered to be "covert amblyopes" and have been removed from the normal group. The mean overall difference in contrast sensitivity between the two eyes shown in the results have been restated in Table 31 in which the exclusion criteria for normality and the inclusion criteria for amblyopia have been applied.

Table 31 Application of New Criteria to Data in Table 30. Percentage Reduction in Mean Contrast Sensitivities and Snellen Acuity between the Poorer and the Better Eyes.

Subject No.	Normals			Simple Anisometropic Amblyopes			Micro-esotropic Anisometropes			Esotropes with ABSV		
	CS	VA Re	Le	CS	VA Re	Le	CS	VA Re	Le	CS	VA Re	Le
1	-29%	4	4	- 83%	4	36	- 87%	12	5	- 44%	9	5
2	-27%	5	5	- 30%	18	5	- 43%	12	5	- 85%	18	5
3	-22%	4	4	- 13%	9	6	- 70%	4	12	- 44%	9	6
4	-17%	5	5	- 65%	12	4	- 40%	6	12			
5	-	-	-	- 8%	18	5	- 42%	9	5			
6	-19%	5	5	- 27%	4	9	- 26%	4	9			
7	- 6%	4	4	- 50%	9	4						
8	- 7%	4	4	- 79%	5	24						
9	-11%	4	5	- 50%	12	5						
10	-	-	-									
11	-23%	4	5									
Mean	**- 18%**			**- 45%**			**- 51%**			**-58%**		

Subject No.	Esotropic Amblyopes without BSV			Non-Amblyopic Esotropes without BSV			Exotropic Amblyopes without BSV			Non-Amblyopic Exotropes without BSV		
	CS	VA Re	Le	CS	VA Re	Le	CS	VA Re	Le	CS	VA Re	Le
1	- 73%	24	5	-	-	-	- 87%	6	36	-	-	-
2	- 79%	18	5	- 22%	5	5	- 56%	9	6	-	-	-
3	- 75%	5	18	-	-	-	- 44%	5	5			
4	- 68%	60	5	- 18%	4	4	- 41%	4	4			
5	- 31%	6	9									
6	- 44%	6	6									
7	- 51%	5	5									
Mean	**-60%**			**-20%**			**- 57%**					

CS: Contrast Sensitivity VA: The number represents the denominator of Snellen fraction Re: Right Eye. Le: Left Eye. BSV: Binocular Single Vision. ABSV: Anomalous Binocular Single Vision.

The inter-ocular difference, in the revised group of 9 normal subjects, ranged between 6% and 29% and, in all cases, the monocular visual acuities were 6/5 or better. Where unequal Snellen acuity existed (subjects 9 and 11), the lower Snellen acuity was, in both instances, recorded by the eye with the poorer contrast sensitivity. Overall, the mean percentage reduction in contrast sensitivity between the poorer eye compared with the better eye now becomes 18% (Table 31).

4.1.2 The Reclassified Amblyopic Groups

In order to be designated as an amblyope, individuals were required, as stated above, to exhibit one or more of the following; reduced visual acuity in one eye (6/6 or worse); a high spatial frequency cut off of 30c/deg or less; an inter-ocular reduction in contrast sensitivity in excess of 30%. Consequently, when the inclusion criteria for amblyopia was applied to the subjects comprising the amblyopic groups, there was a redistribution of individuals between the groups (Table 31).

With regard to the simple anisometropic amblyopic amblyopes and micro-esotropic amblyopes, the original groupings were adhered to even although 5 individuals exhibited an inter-ocular difference of 30% or less. They were designated amblyopic on the basis of their reduced Snellen acuity. The esotropic amblyopes also remained unaltered (Table 31).

However, the number of subjects comprising the remaining groups, *viz.* esotropic and exotropic amblyopes without BSV was changed (Table 30). Two individuals originally designated non-amblyopic esotropes without BSV (Subjects 1 and 3) recorded an inter-ocular difference in contrast sensitivity of greater than 30% and were thus included in the group of esotropic amblyopes without BSV. The two non-amblyopic exotropes without BSV also showed an inter-ocular contrast sensitivity difference of greater than 30% and were therefore included in the group of exotropic amblyopes without BSV (Table 31).

In amblyopes, the visual acuity in the squinting and/or anisometropic eye is reduced when compared with that achieved by the companion eye which is assumed to be normal. However, by examination of contrast sensitivity measures, Lequire, Rogers and Bremer (1990) reported that the contrast sensitivities were reduced not only in the amblyopic eye but also in the companion eye of their subjects. They concluded that, in amblyopes, "the normal eye was not normal" and that the amblyopic eye was exerting a detrimental effect on the other dominant eye. They postulated that this may be due to inhibition at the level of the visual cortex.

Thus, in order to determine if the non-amblyopic eye of amblyopes was "normal", the contrast sensitivity values (log values) of the better eye of subjects comprising the amblyopic groups were compared to the logarithm contrast sensitivity values for the better eye of subjects comprising the normal group. A three factor analysis of variance was applied. The first factor comprised the normal/abnormal eye, the second factor, the spatial frequencies (10c/deg to 40c/deg[2]) and the third factor comprised the subjects within each group.

The results showed that there was a statistically significant difference between the better eyes of the regrouped nine normal individuals and the better eyes of the nine simple anisometropic amblyopes ($F = 61.31$; $P<0.01$). This trend was also evident when the better eyes of the individuals comprising the normal group were compared to the better eyes of the nine subjects comprising the amblyopes with anomalous BSV ($F = 25.38$; $P <0.01$) and those of the eleven, regrouped esotropic amblyopes without BSV[3] ($F = 48.67$; $P<0.01$). Thus, the results of this study confirm the earlier findings of Lequire, Rodgers and Bremer (1990) *i.e.* in amblyopes "the normal eye is not normal".

[2] The three factor analysis of variance included the logarithm contrast sensitivity findings from 10c/deg, not 8c/deg as no such data was available from the normal group.

[3] GLM analysis was used in this instance to take account of the unequal group sizes.

4.1.2.1 Micro-esotropic Amblyopes with Anomalous BSV

The maximum spatial frequency which could be discriminated by the amblyopic eye of these microtropic individuals ranged from 25c/deg down to 15c/deg, in keeping with acuities of 6/9 to 6/12. All the subjects comprising this group exhibited eccentric fixation under uniocular conditions of viewing and this point possessed a reduced visual acuity value. It is possible that the Snellen acuity in the squinting eye may actually be normal for the particular eccentric location. In this case, an inverse relationship might be expected if the Snellen acuity were indeed normal for that point of eccentricity. A Spearman' Rank Test confirmed that there was no correlation between the two variables, decimal acuity and the angle of manifest deviation (SPCT).

In the group of microtropes there was one main difference in the clinical characteristics of these individuals compared with the simple anisometropic amblyopes *viz.* the presence of esotropia. However, a two sample t-test of the mean percentage reduction in contrast sensitivity in the poorer eye when compared with the better eye showed that there was no significant difference in the percentage contrast sensitivity loss between these two groups ($df = 12$; $t = 0.49$; $P = 0.63$;). Thus, the state of uniocular fixation in the amblyopic eye, i.e. whether foveal, as in the simple anisometropic amblyopes or parafoveal as found in the microtropes, did not significantly influence the contrast sensitivity outcome.

4.1.2.2 Esotropic Amblyopes with Anomalous BSV

No reclassification of the esotropic amblyopes with anomalous BSV occurred as a consequence of the revised criteria for amblyopia. However, in one esotropic amblyope with anomalous BSV (Subject 1) anisometropia was evident. In addition, the angle of deviation in this group was small and anomalous BSV was present; thus, the only difference between the individuals comprising this esotropic group and those comprising the microtropic amblyopes was the state of fixation. Therefore, these two groups have been amalgamated and redesignated esotropic amblyopes with anomalous BSV (n=9)

Table 32 . There was a mean percentage loss of 53% ± 7%SE (n = 9; t = 7.41; P = 0.00) when the poorer eye was compared with the better eye.

The 3-factor ANOVA also showed a significant difference in the logarithm contrast sensitivity between the eyes with the poorer eye being significantly different from the better eye (F = 443.09; P<0.001). There was also considerable variation amongst subjects (F = 142.31; P<0.001) and across the range of spatial frequencies examined (F = 360.12; P<0.001).

Table 32 Percentage reduction in mean contrast sensitivities and Snellen acuity between the poorer and the better eye in the reclassified group of esotropic amblyopes with anomalous BSV.

Subject No	CS	VA Re	VA Le
1	- 87%	12	5
2	- 43%	12	5
3	- 70%	4	12
4	- 40%	6	12
5	- 42%	9	5
6	- 26%	4	9
7	- 44%	9	5
8	- 85%	18	5
9	- 44%	9	6
Mean	**-53% ****		

CS: Contrast Sensitivity VA: The number represents the denominator of Snellen fraction Re: Right Eye. Le: Left Eye.

As a consequence of the amalgamation between the two groups (micro-esotropic amblyopes with anomalous BSV and esotropic amblyopes with anomalous BSV), there are now nine individuals comprising strabismic amblyopes with anomalous BSV and nine non-strabismic amblyopes with normal BSV i.e. simple anisometropic amblyopes. A two sample t-test of the

mean percentage loss in contrast sensitivity in the poorer eye when compared with the better eye showed that there was no significant difference in the percentage contrast sensitivity loss between these two groups (df = 15; t = 0.73; P = 0.48;).

4.1.2.3 Esotropic Amblyopes without BSV

A regrouping of the esotropic amblyopes without BSV was necessary as a consequence of the revised inclusion criteria for the amblyopic groups

The esotropes without BSV now consist of 5 original subjects plus 2 individuals who had previously been designated as non-amblyopic esotropes without BSV since their contrast sensitivity loss was greater than 30% (Table 30). In this reclassified group, the poorer eye was significantly reduced when compared to the better eye. The mean percentage reduction was 60% ± 7% (n = 7; t = 8.72; P = 0.0001). Analysis of the data using a 3-factor ANOVA also showed evidence of a significant difference between the poorer and the better eyes of subjects comprising this group (F = 550.85; P <0.001). There was also a significant variation amongst subjects (F = 38.41; P<0.001) and spatial frequencies (F = 156.52; P <0.001).

Comparison of the mean percentage loss in contrast sensitivity between the poorer and the better eyes of individuals comprising this group of esotropic amblyopes without BSV with the reclassified esotropic amblyopes with anomalous BSV (Table 32) showed no significant difference between the two groups (df = 13; t = 0.67; P = 0.51;).

4.1.2.4 Exotropic Amblyopes without BSV

The four exotropic amblyopes, after the inclusion criteria for amblyopia were applied, fell into two distinct subgroups. First, 2 individuals who exhibited reduced visual acuity and a significant inter-ocular difference in contrast sensitivities, and 2 amblyopic exotropes in whom Snellen acuities were normal

but who were designated amblyopes because the inter-ocular difference in contrast sensitivity was greater than 30% (Table 31). In the latter two cases, the high spatial frequency cut off was much lower than might reasonably be expected when compared with Snellen acuity. Both individuals failed to resolve the grating pattern at 25c/deg, the equivalent to ~6/9, though both achieved 6/5 or better in this eye. The contrast sensitivity in the poorer eyes of subjects comprising this group was significantly reduced when compared with that obtained through the better eyes. The mean percentage reduction was 57% ± 10%SE ($P<0.05$).

The 3-factor ANOVA also showed that the poorer eye was significantly different from the better eye ($F= 171.60$; $P<0.001$); that there was a considerable variation amongst subjects ($F= 78.28$: $P<0.001$) and spatial frequencies ($F = 196.14$; $P<0.001$).

A two sample t-test between these exotropic amblyopes and the esotropic amblyopes without BSV showed that there was no significant difference between the groups ($df = 5$; $t = 0.25$; $P = 0.81$).

The two exotropic amblyopes who recorded large inter-ocular differences in contrast sensitivity and reduced Snellen acuity had originally been esotropic in childhood. However, because of the very small number of individuals, it was not possible to determine if these cases were significantly similar to the esotropic amblyopes without BSV, *i.e.* to consider if they were actually covert esotropes.

4.1.3 The Reclassified Non-Amblyopic Group

4.1.3.1 Non-Amblyopic Esotropes without BSV

Only 2 subjects remained in the non-amblyopic category after the inclusion criteria were applied under our conditions of test; both recorded a percentage contrast sensitivity difference between the eyes of less than 30%. In this

reclassified group, there was an insufficient number of subjects to undertake a meaningful statistical analysis of any possible relationship between the variables.

4.1.4 Summary

The mean percentage reduction in contrast sensitivity between the poorer and the better eyes of non amblyopic subjects (normals and non amblyopic esotropes without BSV) and amblyopic subjects in the reclassified groups is shown in Table 33.

Table 33 The Mean Percentage Reduction in Contrast Sensitivity between the Poorer Eye and the Better Eye in the Reclassified Non-Amblyopic and Amblyopic Groups.

Group	Mean % Reduction	Group	Mean % Reduction
Normals (n=9)	18% ** {F = 63.88 **}	Simple Anisometropic Amblyopes (n=9)	45% ** {F = 531.57 **}
Non Amblyopic Esotropes without BSV (n=2)	20% (+) {F - (+))	Esotropic Amblyopes with Anomalous BSV (n=9)	53% ** {F = 443.09 **}
		Esotropic Amblyopes without BSV (n=7)	60% ** {F = 550.85 **}
		Exotropic Amblyopes without BSV (n=4)	57% * {F = 171.60 **}
Mean	**19%**		**54%**

P. ns - not significant. * P<0.05. ** P <0.01. (+) not tested as n =2.
{F - F factor obtained when analysis of data was undertaken using the 3 factor analysis of variance, the ANOVA statistical test).

4.2 Binocular Contrast Sensitivity in the Reclassified Groups with BSV

4.2.1 Normal Group

In binocular vision, binocular enhancement of contrast sensitivity is normally demonstrable *i.e.* the binocular contrast sensitivities are increased compared with those of the better eye. In the reclassified normal group (n=9), the mean contrast sensitivity, averaged over the range of spatial frequencies, was enhanced by 13% (n=9; t = 2.8; P= 0.02; one sample t-test). The 3-factor ANOVA showed evidence of significant binocular enhancement (F = 68.34; P<0.001) with significant variation amongst subjects (F = 155.42; P<0.001) and across the range of spatial frequencies (2210.35; P<0.001)

Pirenne (1943) explained the higher binocular performance on purely probabilistic grounds, and he showed that binocular luminance detection would exceed the monocular luminance detection by 12%. However, Campbell and Green (1965) showed that there was an enhancement of 41% in the binocular contrast sensitivities compared with those obtained monocularly in two experienced subjects. Ross, Clarke and Bron (1985) showed that binocular contrast sensitivities were greater than the monocular contrast sensitivities by 37%. However, when Ross *et al* compared the binocular contrast sensitivities to those obtained monocularly, they did not determine whether these were related to the better eye. Likewise, Pardhan and Gilchrist (1990), who showed an overall increase of 42%, also did not indicate that the monocular contrast sensitivities were obtained with the better eye. Thus, in none of the earlier work was it determined that the monocular determinations were made with the better eye. In our study, if the comparison had been made with the better eye, in the reclassified normal group (n=9), the binocular increment would have been 13% plus 22%, *i.e.* 35%, which is similar to the earlier studies cited.

4.2.2 Simple Anisometropic Amblyopes

Enhanced binocular contrast sensitivities were evident in all 9 simple anisometropic amblyopes. The mean percentage binocular enhancement was

35% ± 7% (P <0.01) compared with the better eye. This was not spatial frequency dependent. This significant difference in the binocular contrast sensitivity was also shown when analysis of data was undertaken using the ANOVA (F = 29.50; P <0.001).

The binocular enhancement is this group was significantly greater than the 13% increase shown by the reclassified normal group when the result of the two groups were compared (df = 13; t = 2.40; P = 0.03; two sample t-test). In addition, there was no consistent relationship between the percentage increase in binocular contrast sensitivity and the inter ocular contrast sensitivity differences (R^2 = 12%; P = 0.4). The Spearman's rank correlation test confirmed the lack of correlation between these two variables (0.27; P>0.05).

4.2.3 Esotropic Amblyopes with Anomalous BSV

Binocular contrast sensitivities were enhanced in the reclassified esotropic group in which anomalous BSV was evident (n=9). Binocular enhancement of 38% ± 11% (P<0.01) was shown. The 3-factor ANOVA showed evidence of a significant enhancement in binocular contrast sensitivity when compared to that obtained by the better eye in the subjects comprising this group (F = 107.86; P<0.001) with considerable variation evident amongst subjects (F = 206.49; P<0.001) and across the range of spatial frequencies (F = 729.43; P,0.001). There was no relationship between the percentage increase in binocular contrast sensitivity and the inter ocular contrast sensitivity differences (R^2 = 21%; P = 0.2; Spearman's rank correlation - 0.5; P>0.05).

Comparison between the two amblyopic groups with BSV, viz. simple anisometropic amblyopes (n=9) and esotropic amblyopes with anomalous BSV (n=9) showed that there was no significant difference in the mean percentage binocular enhancement between these groups (df = 13; t = 0.24; P = 0.8, two sample t-test).

4.2.4 Summary

The reclassified normal group and the amblyopic groups in which BSV was present showed binocular summation when the binocular contrast sensitivities were compared with those obtained through the better eye (Table 34) (Figure 103).

Table 34 Percentage Change in Binocular Mean Contrast Sensitivities when compared to the Better Eye in The Reclassified Normal Group and Amblyopes with BSV.

Mean Percentage Binocular Contrast Sensitivity			
Subject	Normals	Simple Anisometropic Amblyopes with Normal BSV	Esotropic Amblyopes with Anomalous BSV
1	+16%	+29%	+15%
2	+49%	+47%	+67%
3	+ 7%	+ 6%	+25%
4	+11%	+28%	+37%
5	--	+77%	-26%
6	+ 6%	+37%	+90%
7	+19%	+55%	+48%
8	+ 3%	+22%	+26%
9	+ 7%	+11%	+59%
10	–		
11	+ 3%		
Mean	**+13% ****	**+35% ****	**+ 38% ****

Normals: data from Table 2: Simple Anisometropic Amblyopes: data from Table 4 Esotropic Amblyopes with Anomalous BSV: data from Table 6 (microtropic amblyopes) and Table 8 (esotropic amblyopes with anomalous BSV). ns - $P>0.05$ ** $P<0.01$ * $P<0.05$.

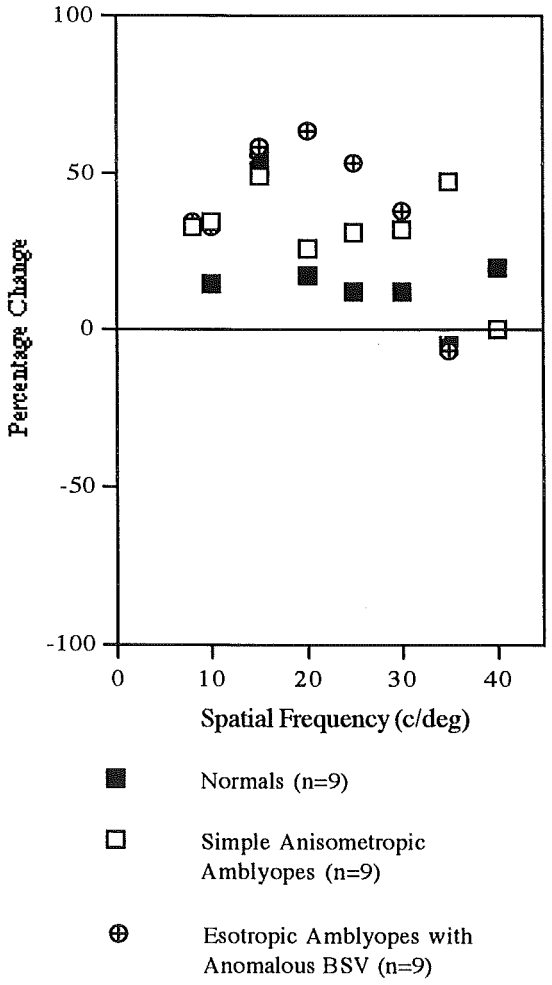


Figure 103 Summary of the mean percentage change in contrast sensitivity for binocular viewing compared with monocular viewing through the better eye across the range of spatial frequencies in the reclassified groups with BSV. (No value for normal subjects is shown at 8c/deg).

4.2.5 Binocular Contrast Sensitivity in the Reclassified Groups without BSV

In the reclassified amblyopic and non-amblyopic groups without BSV, binocular contrast sensitivities were reduced compared with the monocular sensitivities of the better eyes.

4.2.2.1 Esotropic Amblyopes without BSV

The binocular contrast sensitivity findings in this group of individuals, classified under our conditions of test, were very different from those exhibited by the groups in which BSV was present. Esotropic amblyopes without BSV (n=7) exhibited a statistically significant mean percentage reduction of 14% ± 3% ($t = 5.17$; $P = 0.002$; one sample t-test; $F = 23.19$; $P<0.001$, ANOVA) in the binocular contrast sensitivity compared with that obtained through the better eye. This was a considerable difference from the reclassified amblyopic groups with BSV which exhibited an enhancement in binocular contrast sensitivities of 35% and 38% (Table 34). The attenuation of binocular contrast sensitivity was relatively uniform across the spatial frequencies examined (Figure 104).

4.2.2.2 Non-Amblyopic Esotropes without BSV

No binocular enhancement of contrast sensitivity occurred in this reclassified group of 2 non-amblyopic esotropes without BSV (Table 35).

4.2.2.3 Exotropic Amblyopes without BSV.

In the revised group of amblyopic exotropes without BSV (n=4), binocular contrast sensitivities were reduced mirroring the results of the esotropes without BSV. The mean binocular contrast sensitivity, averaged over the range of spatial frequencies, was reduced by 26% ($t = 4.09$; $P= 0.026$). The ANOVA also showed that the binocular contrast sensitivity was significantly reduced ($F =9.01$; $P=0.003$). When the percentage reduction in binocular contrast sensitivities was compared to the inter-ocular percentage difference in contrast sensitivities, there was an inverse, relationship between the two variables ($R^2 = 54\%$; $P = 0.3$) which was not significant.

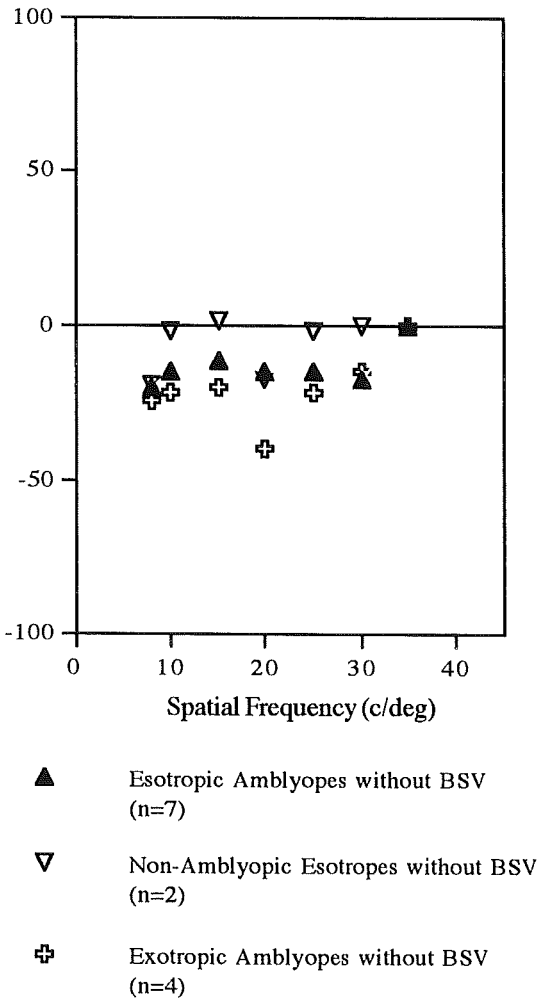


Figure 104 Summary of the mean percentage change in contrast sensitivity for binocular viewing compared with monocular viewing through the better eye across the range of spatial frequencies in the reclassified groups without BSV.
Groups showing a general decrease in binocular contrast sensitivity. (There is no value for the non-amblyopic esotropes without BSV at 35c/deg).

Table 35. Mean Percentage Binocular Contrast Sensitivity Deficit in Amblyopic and Non-amblyopic Strabismics without BSV compared with those of the Better Eye.

Subject	Mean Percentage Binocular Contrast Sensitivity		
	Esotropic Amblyopes without BSV	Non-Amblyopic Esotropes without BSV	Exotropic Amblyopes without BSV
1	-11%	+ 2%	-11%
2	-18%	-14%	-29%
3	-14%		-41%
4	- 7%		-22%
5	-17%		
6	-26%		
7	- 5%		
Mean	**-14% ****	**- 6% ns**	**-26% ***

Esotropic Amblyopes without BSV: data from Table 10 and Table 12: Non-amblyopic esotropes without BSV: data from Table 12. Exotropic Amblyopes without BSV: data from Table 14 and Table 16 ns - $P>0.05$ ** $P<0.01$ * $P<0.05$.

4.2.3 Summary.

All amblyopic groups in which normal or anomalous BSV was evident exhibited enhanced contrast sensitivities on binocular viewing. Thus, the assertion that binocular contrast sensitivities, in the presence of amblyopia, would not exceed that of the better eye (Blake, Martens and DiGianfilippo 1980) is refuted.

The binocular enhancement present in the simple anisometropic amblyopes and in the reclassified esotropic amblyopes with anomalous BSV was significantly greater than that in the normal group of subjects.

In addition, the magnitude of binocular summation in simple anisometropic amblyopes and in the esotropic amblyopes with anomalous BSV was not related to the inter-ocular contrast sensitivity difference between the eyes. Thus, the

assertion that "a balanced or equal contrast threshold is necessary for binocular summation" (Legge, 1979) has not been confirmed in this study. Therefore, it is suggested that it is not a balanced or equal input which is required for binocular summation of spatial information but that it is the state of BSV, *i.e* its presence or absence, which is the significant factor in the difference in the binocular contrast sensitivity outcomes between the groups examined.

Table 36 The Mean Percentage Change in Contrast Sensitivity under Binocular Conditions of Viewing compared with Better Eye Viewing in the Reclassified Groups with and without BSV.

Group	Mean % Binocular Enhancement	Group	Mean % Binocular Reduction
Normals (n=9)	13% * {F = 68.34 **}	Esotropic Amblyopes without BSV (n=7)	14% ** {F = 23.19 **}
Simple Anisometropic Amblyopes (n=9)	35% ** {F = 29.50 **}	Non Amblyopic Esotropes without BSV (n=2)	6% ns {F = (+) }
Esotropic Amblyopes with Anomalous BSV (n=9)	38% ** {F = 107.86 **}	Exotropic Amblyopes without BSV (n=4)	26% * {F = 9.01 **}
Mean	**+ 29%**		**-15 %**

P. ns - not significant. * P<0.05. ** P <0.01. (+) not tested as n =2.
{F - F factor obtained when analysis of data was undertaken using the 3 factor analysis of variance, the ANOVA statistical test).

4.3 Neutralisation of the Angle of Strabismus

The binocular contrast sensitivity results under the stated binocular conditions of viewing for each individual in the reclassified groups are shown in Table 36.

4.3.1 Esotropes

In the three esotropic groups, neutralisation of the angle of strabismus so as to effect bifoveal stimulation resulted in a consistent reduction in binocular contrast sensitivity across the range of spatial frequencies studied (Figure 105). One difficulty, specifically in individuals with anomalous BSV, is that when a prism is applied motor fusion may be disrupted and the angle deviation increases to the pre-prismatic angle. However, all individuals were regularly checked during the test procedure to determine if a change in the angle of deviation with the prism had occurred. In no individual was this detected.

A mean reduction of 25% ± 4% ($t = 6.36$; $P = 0.0002$, one sample t-test) in the esotropic amblyopes with anomalous BSV, and 27% ± 5% ($t = 4.96$; $P = 0.003$, one sample t-test) in the esotropic amblyopes without BSV was present (Table 37). A higher value of 43% ± 10% ($t = 4.30$; $P = 0.15$, one sample t-test) was obtained from the two non-amblyopic esotropes without BSV, while the result in exotropes was not so clear cut with a mean percentage reduction in contrast sensitivity of 15% ± 11% ($t = 1.38$; $P = 0.26$, one sample t-test), which included a small increase of 5% at 15 c/deg (Figure 105).

The 3-factor ANOVA confirmed a significant difference, *viz* a significant reduction in bifoveal contrast sensitivities when compared with those obtained through the better eye (Table 37).

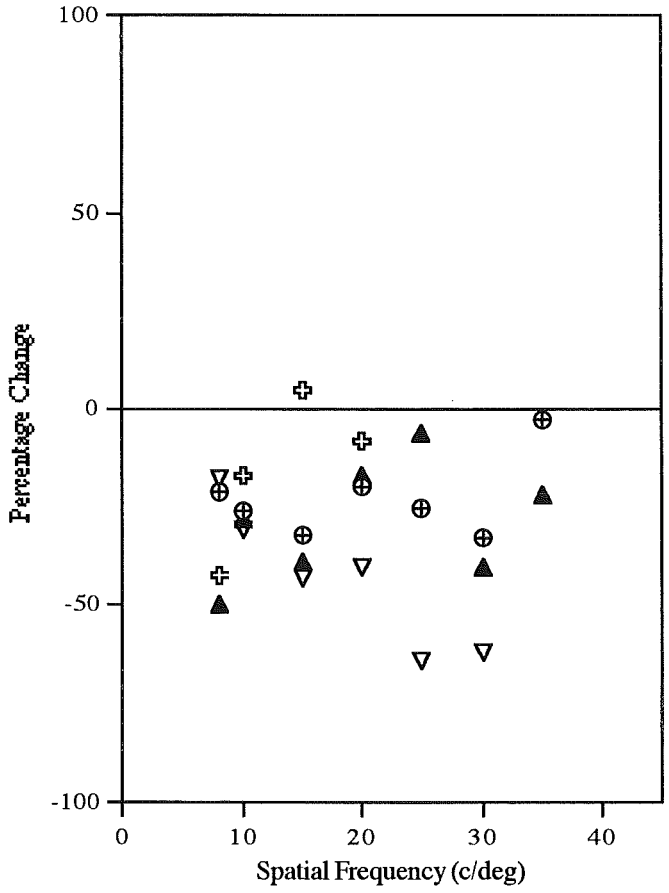


Figure 105 Summary of the mean percentage change in contrast sensitivity for bifoveal viewing compared with binocular viewing at each spatial frequency tested in the reclassified groups.
(There is no value for the exotropic amblyopes without BSV at 25c/deg to 40c/deg; there is no value for the non-amblyopic esotropes without BSV at 35c/deg; there is no value for any of the groups at 40c/deg).

Table 37 General Reduction in contrast sensitivity averaged over spatial frequencies studied under bifoveal conditions of viewing compared with binocular viewing.

Subject	Esotropic Amblyopes with ABSV	Esotropic Amblyopes without BSV	Non-Amblyopic Esotropes without BSV	Exotropic Amblyopes without BSV
1	-37%	-44%	- -	-44%
2	-23%	-29%	-33%	-19%
3	-21%	-34%	- -	+ 8%
4	- 8%	-13%	-53%	- 6%
5	-26%	- 4%		
6	-39%	-24%		
7	-37%	-39%		
8	-29%			
9	- 7%			
Mean	**-25% ****	**-27% ****	**-43% ns**	**-15% ns**
ANOVA	**F = 190.14 ****	**F = 158.42 ****	**F- (+)**	**F = 27.62 ****

Esotropic Amblyopes with Anomalous BSV: data from Table 18 and Table 19: Esotropic amblyopes without BSV: data from Table 20 and Table 21. Non-amblyopic Esotropes without BSV: data from Table 21. Exotropic Amblyopes without BSV: data from Text pages. 174; 177; 181' 183; ns - P>0.05 ** P<0.01 * P<0.05.
{F - F factor obtained when analysis of data was undertaken using the 3 factor analysis of variance, the ANOVA statistical test).

There was no significant difference in the mean percentage reduction in bifoveal contrast sensitivity between the esotropic amblyopes with anomalous BSV and the esotropic amblyopes without BSV (P = 0.83, two sample t-test) and between the esotropic amblyopes without BSV and the exotropic amblyopes without BSV (P = 0.4, two sample t-test).

Thus, in all groups in which bifoveal contrast sensitivity was effected, there was a further decrease in binocular contrast sensitivities compared with normal viewing with both eyes open for those subjects.

4.3.2 Prismatic Degradation

The possibility existed that the prism itself actually degraded the visual image and consequently adversely affected the contrast thresholds in the eye wearing the prism. No significant degradation occurred over the range of spatial frequencies with prism strengths of between 2^ and 8^ in a group of normal subjects. The higher strengths of 10^ and 12^ did, however, cause a reduction in the contrast sensitivities at the higher spatial frequencies of 20c/deg to 40c/deg (Results, page 194).

The prismatic corrections used in the strabismic groups have been tabulated below (Table 38).

Table 38 Prism Strengths used to Neutralise the Angle of Deviation in the Reclassified Strabismic Groups

Subject	Esotropic Amblyopes with ABSV		Esotropic Amblyopes without BSV		Non-Amblyopic Esotropes without BSV		Exotropic Amblyopes without BSV	
	Re	Le	Re	Le	Re	Le	Re	Le
1	6^	-	12^	12^	-	-	8^	16^
2	6^	-	10^	20^	25^	16^	8^	10^
3	-	4^	10^	4^	-	-	8^	10^
4	-	4^	2^	4^	8^	10^	4^	8^
5	6^	-	5^	3^				
6	-	4^	4^	8^				
7	2^	4^	4^	8^				
8	1^	3^						
9	2^	4^						

^ - Prism dioptre Re - Right eye Le - Left eye.

Degradation of the visual stimulus was thus only likely in those individuals who required a prismatic correction of 10^ or more and in amblyopes who were able to detect the grating pattern at the higher spatial frequencies.

The individuals comprising the esotropic amblyopes with anomalous BSV did not require prism strengths of greater than 6^. This suggests that any degradation of the grating stimulus was so small as not to adversely affect the bifoveal contrast sensitivity outcomes. In this group a reduction in bifoveal contrast sensitivities of 25% occurred (Table 37).

In the reclassified esotropic amblyopes without BSV only 3 subjects (Subjects 1, 2, and 3) required prism strengths of 10^ or greater (Table 38). Since these three subjects could not discern the grating pattern above 25c/deg with normal viewing, i.e. with both eyes open, substantial prismatic degradation would seem to be unlikely. A mean reduction in bifoveal contrast sensitivity of 27% occurred (Table 37).

4.3.3 Exotropes

In the reclassified exotropic amblyopes, 3 individuals required a prismatic correction of 10^ or greater (subjects 1, 2, and 3) and could discern the grating stimulus with both eyes open up to 30c/deg. There, thus, is the possibility of an adverse contribution of the prism to the mean reduction of 15% which was recorded in this reclassified group of exotropic amblyopes without BSV.

Thus, the balance of evidence is that the contrast sensitivity loss occurring with bifoveal stimulation could not, in any substantial measure, be attributed to the degradative effects of the prism. In other words, the reduction in contrast sensitivity arose as a consequence of bifoveal stimulation.

As it was not possible to carry out the prism experiment with the non-strabismics, the use of dichoptic viewing was the only way in which investigation of the consequences of stimulation of non-corresponding retinal

points in non- strabismics could be determined. Thus, in these individuals comprising the normal group and the simple anisometropic amblyopes, stimulation of the fovea of one eye and an extra-macular point in the companion eye was effected by dichoptic viewing. This also provided an opportunity to validate the prism experiments which had been under taken on the strabismics.

4.4 Dichoptic Viewing Experiments

In normal and simple anisometropic amblyopes, the monocular contrast sensitivities of the better eye were not adversely affected by the superimposition of the image of the light emitting diode. When non-corresponding retinal points were stimulated dichoptically with the same grating display, no inhibition of the contrast sensitivities was shown, *i.e.* the monocular contrast sensitivities remained unchanged in the presence of two images of the grating stimulus (Figure 106 ; Table 39).

This was not the case, however, in strabismic groups. In all individuals examined, there was a significant reduction in the monocular contrast sensitivities of the better eye when bifoveal stimulation was effected (Figure 107; Table 39).

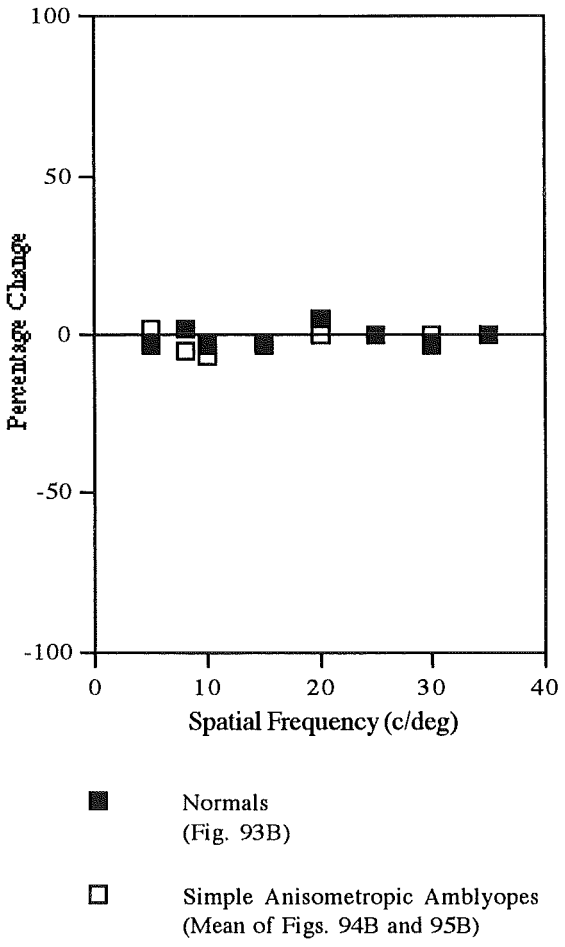
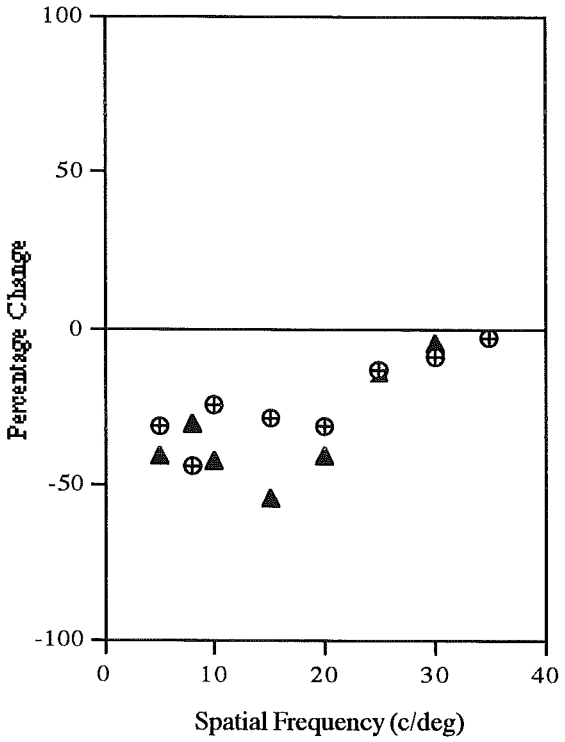


Figure 106 Summary of mean percentage change in contrast sensitivity for binocular viewing with eccentrically placed grating pattern at each spatial frequency tested against the better eye. (Given in parenthesis is the Figure number(s) from which data are taken)



⊕ Esotropic Amblyopes with Anomalous BSV (previously designated microtropic anisometropic Amblyopes (n=2) (Fig 96B and 97B)

▲ Esotropic Amblyopes without BSV (n=3) (Fig 98B, 99B and 100B)

Figure 107 Summary of mean percentage decrease in contrast sensitivity in strabismic groups for binocular viewing with eccentrically placed grating pattern at each spatial frequency tested against the better eye. (There is no value for esotropic amblyopes without BSV above 30c/deg and no value for the esotropic amblyopes with anomalous BSV above 35c/deg (nb. esotropic amblyopes with anomalous BSV were, in the original classification, micro-esotropic amblyopes). (Given in parenthesis is the Figure number(s) from which data are taken)

Table 39 Comparison of the percentage change in contrast sensitivity, averaged over the range of spatial frequencies, in non-strabismic and strabismic individuals for dichoptic viewing with previous results with prismatic correction (where appropriate).

Group	Subject	Dichoptic Viewing (Mean ± SE) Bin* - Be / Be	Bifoveal Stimulation effected with prism(s) (Mean ± SE Bin^ - Be / Be
Normals with BSV		-1% ± 2% ns	-
Simple Anisometropic Amblyopes with normal BSV	1	-1% ± 2% ns	-
	7	-2% ± 4% ns	-
Mean		**1.5%**	
Esotropic Amblyopes with anomalous BSV (previously classified as micro-esotropic amblyopes)	1	-23% ± 8% *	-26% ± 7% **
	5	-25% ± 4% **	-39% ±16% ns
Mean		**24%**	**32%**
Esotropic Amblyopes without BSV	3	-33% ± 7% **	-45% ± 4% **
	4	-33% ± 8% *	-19% ± 6% *
	5	-50% ± 8% **	-21% ± 5% **
Mean		**39%**	**28%**

Bin* - Bin^E or Bin^F Be - Better Eye: (Bin^ is recapitulated data from tables 18 and 20)
((Bin* for the normal group is the mean ± SE of data from Table 25; data for the microtropic anisometropic amblyopes are from Table 27; data for the esotropic amblyopes without BSV are from Table 28)
(Bin^E represents the dichoptic viewing presentation in the non-strabismic subjects, *i.e* the grating pattern stimulated the fovea of the better eye and an eccentric point of the retina in the poorer eye; Bin^F represents the dichoptic viewing presentation in the strabismic subjects *i.e.* the grating pattern stimulated the fovea of the better eye and the fovea of the poorer eye. Thus, Bin * under dichoptic viewing conditions represents either Bin^E or Bin^F depending on the group.)

In these strabismics, the light emitting diode had to be discontinued as all subjects were unable to fixate the grating when the LED was presented to the amblyopic eye.

The three esotropic amblyopes without BSV showed numerically greater mean reductions in contrast sensitivity than the esotropic amblyopes with anomalous BSV (Table 39).

On comparison with the results from the prismatic experiments, which are also shown in Table 39, broadly there was qualitative agreement in that all individuals showed a statistically significant reduction on bifoveal stimulation whether caused by prismatic correction or by dichoptic viewing. There was some variation in the actual magnitude of the reduction in contrast sensitivities between the two tests. While no specific reason can be offered, the experimental methods were substantially different in term of the dimensions and luminance of the display. Nevertheless, these results confirm the previous findings in which contrast sensitivity loss occurred with stimulation of non corresponding retinal points effected by prismatic correction.

Thus, it would appear that in individuals with and without BSV inhibition of contrast sensitivity is the rule rather than the exception when non-corresponding retinal points are stimulated.

4.5 Visual Deficit in Amblyopia

Two mechanisms have been invoked to account for the visual deficit in the amblyopic eye (Harrad, 1996). These consist of dichoptic masking and binocular rivalry.

4.5.1 Dichoptic Masking

It is has been demonstrated in man that prolonged viewing of a high contrast grating pattern causes a temporary rise in contrast threshold for that grating pattern. This is termed adaptation (Blakemore and Campbell, 1969). Further, Blakemore and Campbell, showed that presentation of the adapting display to one eye caused a definite rise in contrast threshold for viewing through the other eye. While the rise in contrast threshold was not as great as for the same eye viewing, it did demonstrate that inter-ocular transfer of spatial information must have taken place.

In 1979, Legge applied the technique of dichoptic masking in which he measured contrast thresholds with one eye while the other eye viewed an

adapting grating. He showed that binocular summation was dependent upon a balance of contrast sensitivity between the two eyes and that an imbalance led to reduced vision in one eye due to the greater transfer of adaptation from the other, better eye. This explanation was invoked to explain the loss of vision in the affected eye of amblyopes.

Harrad and Hess (1992) tested this proposal in several types of amblyopes. While a substantial proportion displayed normal physiological dichoptic masking, conforming to Legge's prediction, many did not. The most general result was that there was a reduced effectiveness of the presence of the mask in the amblyopic eye on the contrast threshold of the normal eye. The effects of adaptation of the normal eye on the contrast thresholds of the amblyopic eye were quite variable showing either no change, increased contrast threshold or decreased contrast threshold. Thus, there was a substantial number of cases, particularly in the slightly larger angled esotropes, in whom there was a deviation from Legge's prediction for the operation of physiological dichoptic masking. Furthermore, there was no consistent relationship between the results and the level of amblyopia, *i.e.* whether it was mild or severe; nor was there any consistent relationship between the type of amblyopia, *i.e.* strabismic or anisometropic, or whether BSV was present or absent.

4.5.2 Binocular Rivalry

In strabismics, the fovea of the squinting eye may be stimulated by a different image to that falling on the fovea of the fixating eye. This would give rise to a phenomenon called binocular rivalry which occurs when corresponding retinal points are stimulated by dissimilar images (Lyle and Wybar, 1967).

Smith, Levi, Manny, Harwerth and White (1983) expressed the view that it was this rivalry which could be responsible for initiating the suppression response in strabismus, ultimately leading to the development of amblyopia. This is contrary to the view of Worth (1903) (refer to Introduction, page 27) who postulated that amblyopia represented and "arrest of development" of visual acuity due to the presence of a "sensory obstacle" such as strabismus.

4.6 Proposed Model

In the present study, in order to determine a possible explanation for the results presented, consideration has been given to the stages involved in the determination of binocular contrast sensitivity.

In normal individuals, foveal viewing of the grating stimulus would occur in the presence of normal fixation eye movements. This, and the presence of a 1-2 degree strip of bilateral projection from the retina down the vertical meridian (Bunt, Minckler and Johanson, 1977) may be surmised to result in a bilateral projection and thus representation of the stimulus in both the right and left hemispheres.

It is proposed that the lateral geniculate nucleus does not have a role in binocularity (reviewed by Harrad, 1996), and for clarity it has been omitted from the following schematic representations. In addition, the two eyes are represented twice in order to avoid the confusion of the crossed and uncrossed pathways. The crossed pathway comprises the projection from the right eye to the left hemisphere and the left eye to the right hemisphere. The uncrossed pathway comprises projection from the right eye to the right hemisphere and from the left eye to the left hemisphere.

Within each hemisphere, the inputs from the left and the right eyes converge on a neuronal pool at which binocular integration occurs. Once the hemispheres have summated the right and left eye inputs, there must then be some process of "unification" or "fusion" of the activities within the two hemispheres to create a single perception of the stimulus. Thus, when BSV occurs, binocular perception also results and in the absence of BSV, no binocular perception is appreciated. Although the following diagrams suggest that BSV occurs at the first site of binocular integration, i.e. the visual cortex, no suggestion is offered as to the actual site at which BSV occurs.

4.6.1 The Normal Group

The proposed scheme for normal subjects is shown in Figure 108. While a binocular enhancement of 13% occurred in the revised normal group, an even greater enhancement of ~36% occurred in the amblyopes with BSV (Table 34) which was significantly better than that obtained by the normal group (df = 24; t = 2.82; P = 0.009; , two sample t-test).

The limited increase in the normal group cannot be ascribed entirely to non-linear binocular summation for the reason that a much larger increase occurred in amblyopes with BSV, even with a reduced contribution from the amblyopic eye, which was appreciably less than that from the poorer eye in normal subjects. This implies that in the normal individuals an inhibitory process was recruited on binocular viewing but that it was not recruited to the same extent in the amblyopes. This gives rise to the possibility that the inhibitory mechanisms had a diminished sensitivity compared with the excitatory mechanisms, *i.e.* the inhibitory mechanisms had a higher threshold than the excitatory mechanisms. Therefore, in normal subjects, both excitatory and inhibitory processes were activated, leading to a relatively small enhancement of binocular contrast sensitivities. In Figure 108, and subsequent Figures, this inhibition is shown as a direct projection onto the neuronal pool within the hemisphere, though it is more likely that the actual neuronal arrangement is through an inhibitory interneurone.

The Normal Group

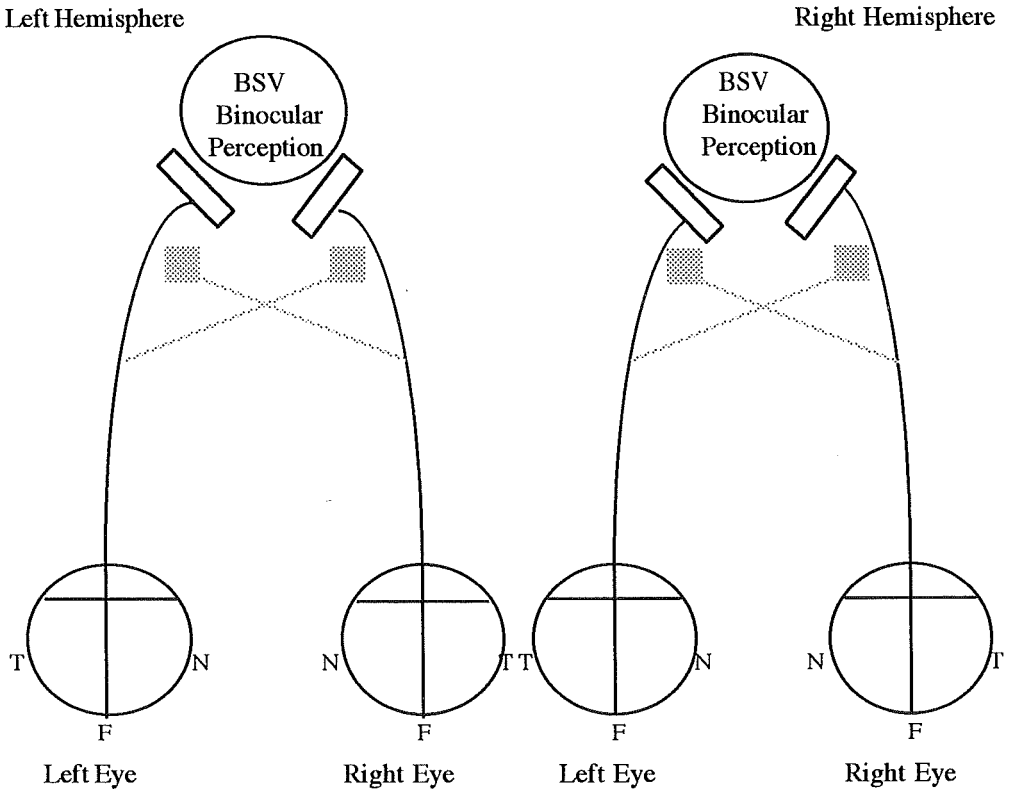


Figure 108 Schematic representation of the combination of activity in the left and right hemispheres for bifoveal viewing to produce a single perception. Within the circle representing each eye the horizontal line represents the cornea and thus gives the direction of gaze. At the level of the right and left hemispheres, the circles represent the neuronal pool subserving binocular integration.
T - temporal retina N - nasal retina F - fovea ☐- excitatory pathway.
▒ - inhibitory pathway BSV - binocular single vision.

4.6.2 The Simple Anisometropic Amblyopes

In the anisometropic group, a similar arrangement is proposed but with one major difference. Due to the impaired visual input from the amblyopic eye, inhibition arising in the amblyopic eye is proposed to be subthreshold and consequently there is reduced inhibition of the companion eye pathway. It is proposed that this leads to greater contrast sensitivity summation under binocular conditions of viewing (Figure 109).

The Simple Anisometropic Amblyopes

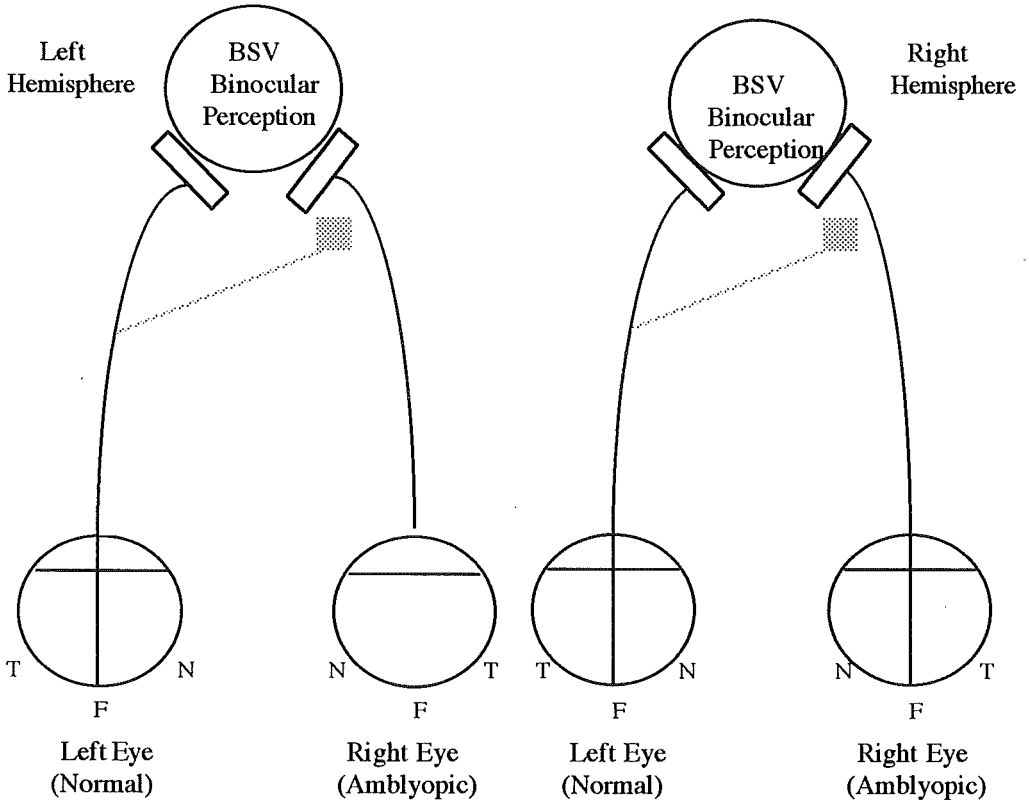


Figure 109 Schematic representation of the combination of activity in the left and right hemispheres for bifoveal viewing to produce a single perception in simple anisometropic amblyopes. The inhibitory projection in the right eye pathway has been omitted since it is proposed to be subthreshold. Further explanation of diagram is given in Figure 108.
T - temporal retina N - nasal retina F - fovea ☐ - excitatory pathway.
▒ - inhibitory pathway BSV - binocular single vision.

4.6.3 . The Strabismic Groups

4.6.3.1 Esotropic Amblyopes with Anomalous BSV

A greater mean binocular enhancement in contrast sensitivity compared with that of the normal group was also present in the esotropic amblyopes with anomalous BSV. However, the binocular state differed from the normal group and the simple anisometropic amblyopes in that there was a correspondence between the fovea of the fixating eye and an extra-macular point in the nasal retina of the squinting eye. The latter projection must be contralateral since it would be highly improbable for there to have been an anatomical redirection of the nasal fibres from the retina of the squinting eye. The generation of BSV must be the consequence of a functional rewiring involving the centre responsible for BSV. The fovea of the esotropic eye will thus project to a different neuronal pool from that which receives the foveal projection from the normal eye.

It is proposed that the level of input from the extra-macular point of the amblyopic eye is reduced compared to that which would normally arise from a foveal point by virtue of its eccentricity and, hence, the reduced density of retinal neurones. It is proposed that as well as a reduced excitatory input, the inhibitory input arising from the amblyopic eye is subthreshold with the result that there is reduced inhibition of the companion eye pathway (Figure 110). Therefore, in this group of esotropic amblyopes with anomalous BSV, it is proposed that the "BSV mechanism" has accepted the binocular input from the left hemisphere in which binocular enhancement has occurred. The perceptual image must, likewise, be binocularly enhanced.

Esotropic Amblyopes with Anomalous BSV

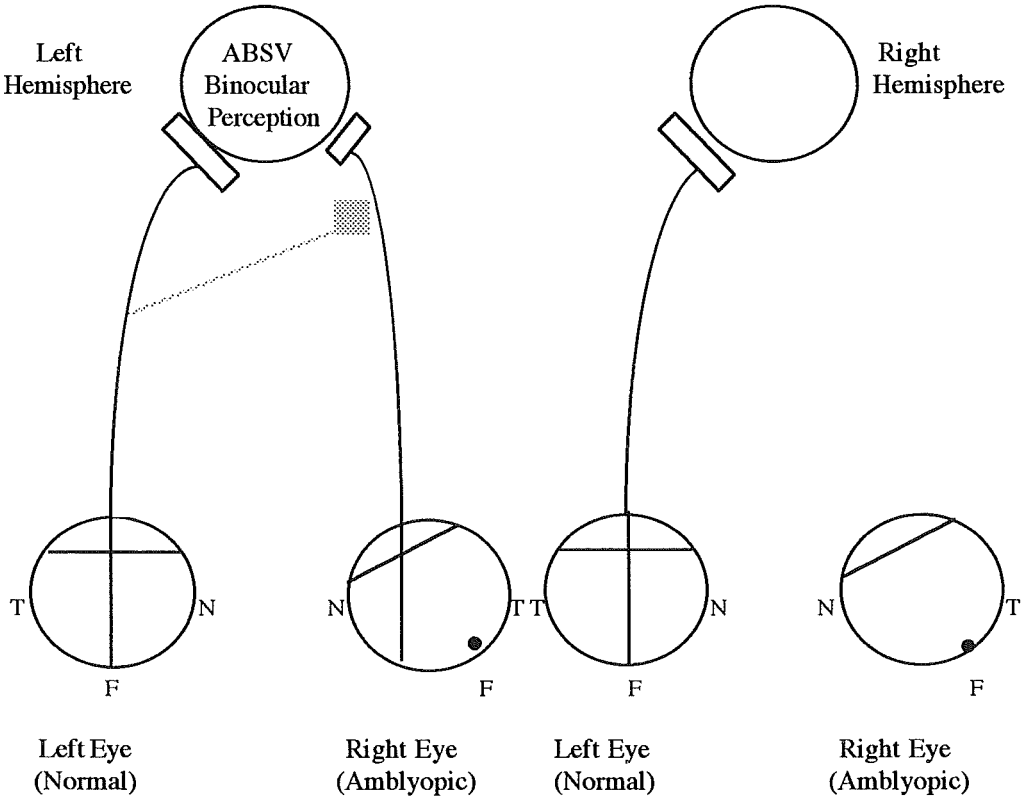


Figure 110 Schematic representation of the combination of activity in the left and right hemispheres to produce a single perception in right esotropic amblyopes with anomalous BSV. There is no input from the nasal retina of the squinting right eye to the ipsilateral hemisphere. Further explanation of diagram is given in Figure 108.
T - temporal retina N - nasal retina F - fovea ▭ excitatory pathway.
▒ - inhibitory pathway ABSV - anomalous binocular single vision.

4.6.3.1 Esotropic Amblyopes without BSV

A very different result was obtained in the esotropic amblyopes without BSV with regard to the binocular contrast sensitivity outcomes. In these subjects, binocular contrast sensitivities were actually reduced compared to those obtained through the better eye alone.

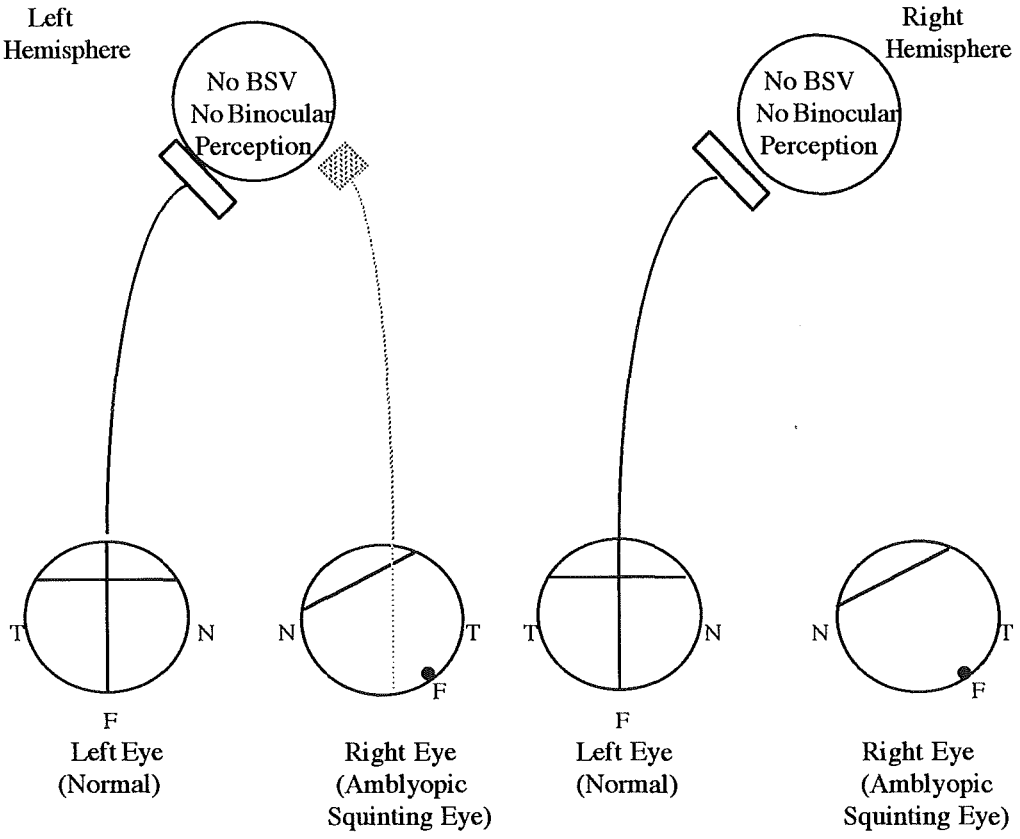


Figure 111 Schematic representation in right eye esotropic amblyopes without BSV of the combination of activity in the left and right hemispheres resulting in reduction of the better eye contrast sensitivities. There is no input from the nasal retina of the squinting right eye. Further explanation of diagram is given in Figure 108.
T - temporal retina N - nasal retina F - fovea ▭ - excitatory pathway.
▒ - inhibitory pathway

It is proposed that in these cases as shown in the example in Figure 111, the left hemisphere receives a binocular input but exhibits reduced excitation due to inhibition arising from the nasal retina of the esotropic eye. While this projection to the left hemisphere is shown in Figure 111 as a direct inhibitory

pathway, it is likely that an inhibitory inter neurone may be involved in the pathway. It is proposed that the perceptual mechanism accepts the binocular activity of the left hemisphere rather than that of the right hemisphere which has no binocular input (Figure 111). Consequently, this leads to a diminished binocular contrast sensitivity.

It is proposed that the same mechanism operates in exotropic amblyopes without BSV, with the difference that temporal retina is stimulated in these cases.

4.3.3 Bifoveal Stimulation

When bifoveal stimulation was effected in strabismic amblyopes with anomalous BSV by shifting the image prismatically from the extra-macular point onto the fovea of the amblyopic eye, a significant reduction in contrast sensitivity occurred. Under normal conditions of viewing in these subjects, there is a correspondence between the fovea of the fixating eye and an extra-macular point in the nasal retina of the squinting eye the projection of which is contra-lateral. As the result of the shift of retinal correspondence, it is proposed that the foveae, which now constitute non-corresponding retinal points, project to different neuronal pools. It is proposed that both hemispheres are stimulated in this way. However, the relationship between the foveal projection of the esotropic eye is such that it inhibits the neuronal pool which receives excitation from the fovea of the normal eye (Figure 112). This neuronal pool, thus, has a reduced level of activity compared with when stimulated by the normal eye alone. Both hemispheres are proposed to be symmetrical in this respect and the BSV mechanism accepts these inputs resulting in diminished binocular contrast sensitivity. The perception of the image which is directed onto the fovea of the squinting eye would be expected, through stimulation of its own separate neuronal pool, to lead to a double image of the grating pattern. It is proposed that this does not arise due to suppression of the perception of this second image by the mechanism responsible for the perception of the image falling on the normal eye.

Bifoveal Stimulation in Esotropic Amblyopes with Anomalous BSV

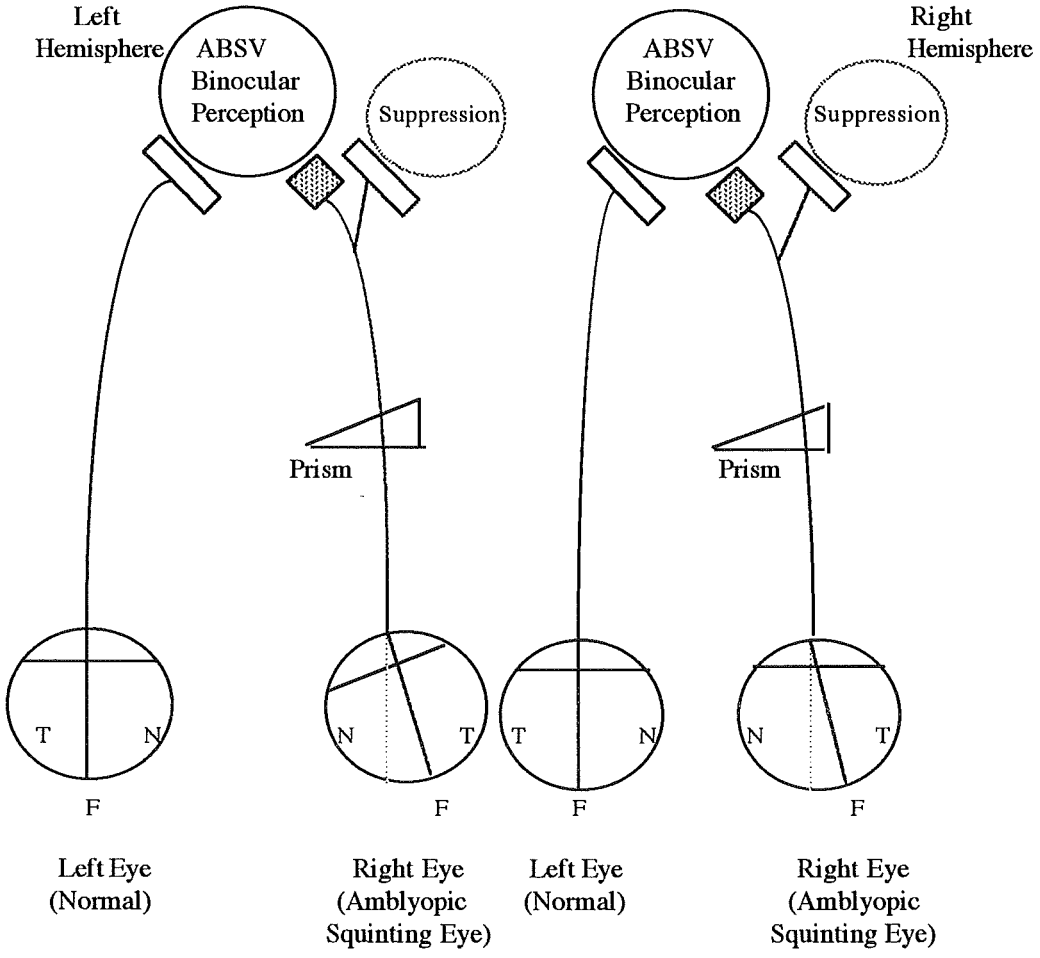


Figure 112 Schematic representation, under conditions of bifoveal stimulation, in a right esotropic amblyope with anomalous BSV, of the combination of activity in the left and right hemispheres. Non-corresponding retinal points (the foveae) are stimulated, and an inhibitory interaction occurs. Further explanation is given in the text.
T - temporal retina N - nasal retina F - fovea ☐ - excitatory pathway.
▒ - inhibitory pathway ▨ bifoveal pathway (non-corresponding retinal points shown by the dark grey solid lines and dotted grey lines). ABSV - abnormal BSV

Esotropic Amblyopes without BSV

It is proposed that, in strabismics without BSV, a similar mechanism under conditions of bifoveal viewing, will exist.

Both hemispheres receive a binocular input but exhibit reduced excitation due to inhibition arising from the foveal input from the esotropic eye. It is proposed that the perceptual mechanism accepts the binocular activity of both hemispheres which is now reduced and, consequently, this leads to diminished binocular contrast sensitivities. The excitatory input from the fovea of the esotropic eye to another neuronal pool may be expected to give rise to another perceptual image, *i.e.* diplopia, but it is proposed that this is suppressed by the mechanism which accepts the input from the left eye.

Esotropic Amblyopes without BSV

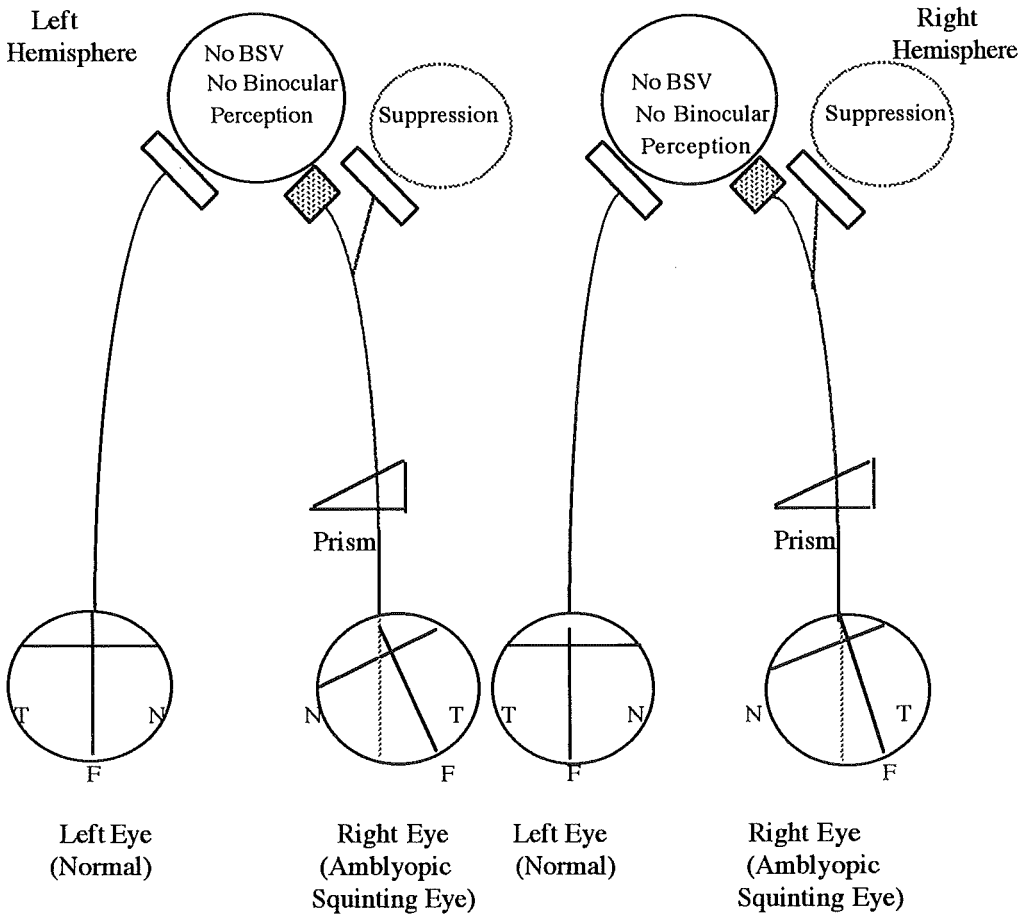


Figure 113 Schematic representation, under conditions of bifoveal stimulation in a right eye esotropic amblyope without BSV, of the combination of activity in the left and right hemispheres. Non-corresponding retinal points, (the foveae) are stimulated, and an inhibitory interaction occurs. Further explanation is given in the text.
T - temporal retina N - nasal retina F - fovea ☐- excitatory pathway.
▒- inhibitory pathway ▒-bifoveal pathway shown by the dark grey lines and boxes

Normal and Simple Anisometropic Amblyopes

The results of bifoveal stimulation on binocular viewing in normals and in simple anisometropic amblyopes were very different when compared to those of the strabismic groups. The normal and simple anisometropic groups did not exhibit a reduction in the contrast sensitivities of the better eye.

The left hemisphere is proposed to show activation of two neuronal pools through the foveal input from the left eye and through the nasal input from the right eye. It is proposed, since the left eye contrast sensitivities are unaffected by simultaneous projection of the grating pattern onto the nasal retina of the right eye, that the latter does not have an inhibitory action on the neuronal pool stimulated by the fovea of the left eye. The reason for this may be that either, inhibitory interactions are not present or, and perhaps more likely, any inhibitory projection is subthreshold. This may arise since the level of excitation emanating from an eccentric region of the nasal retina is appreciably less than that emanating from the fovea, and thus any inhibitory projections arising from this nasal projection may be comparably reduced to become subthreshold.

Since, under these conditions of dichoptic viewing, the normal subjects were aware of both the foveal and nasal images of the grating pattern, this implies that the BSV mechanism had accepted both images. However, foveal contrast sensitivities were unaffected by the presence of the additional nasal image (Figure 114).

Normal Subjects and Simple Anisometropic Amblyopes

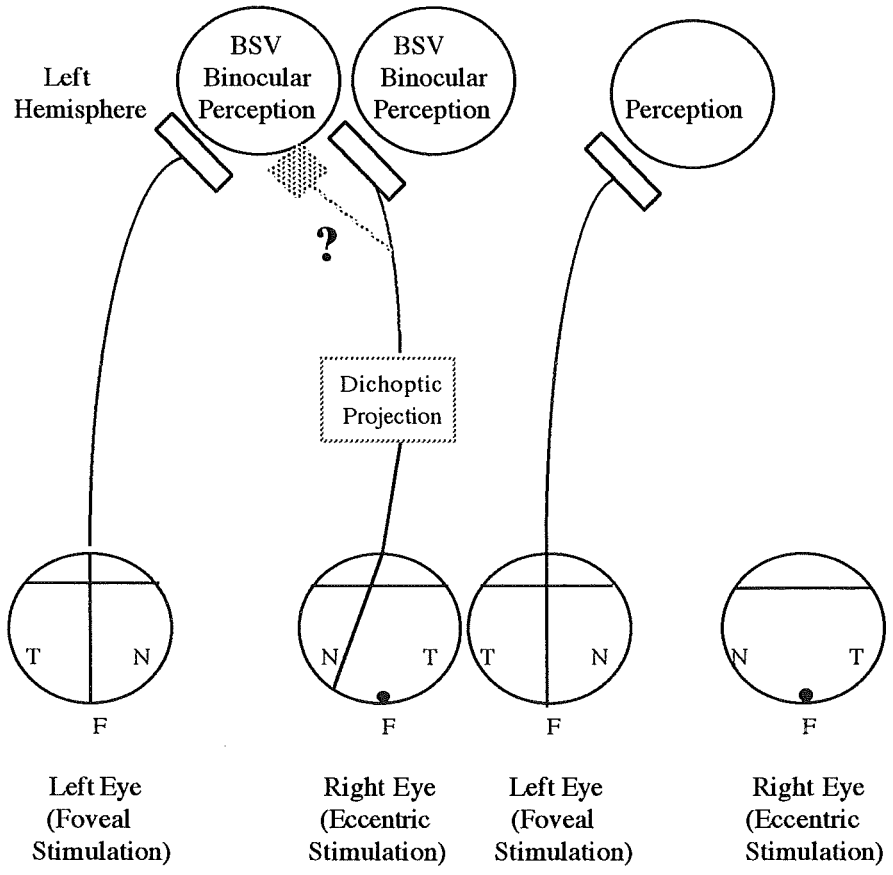


Figure 114 Schematic representation, under dichoptic viewing conditions in normals and simple anisometropic amblyopes, of the combination of activity in the left and right hemispheres.
T - temporal retina N - nasal retina F - fovea ☐ - excitatory pathway.
▒ - inhibitory projection BSV - binocular single vision

The level of the neuronal pool at which integration of inputs from the two eyes occurs can be considered to be the binocular neurones of the primary visual cortex. In normal animals, stimulation of the retina at corresponding points, by targets of the same orientation leads to facilitation of the response. However, presentation of a stimulus of different orientation to one eye at the

corresponding points resulted in inhibition of the response. In an esotropic monkey, binocular stimulation also led to inhibition of the response in the majority of neurones tested (9/11) (Sengpiel and Blakemore, 1996). The neurones were located in layers 4B, 4Cα and layer 6 of the primary visual cortex indicating the importance of the M pathway. Sengpiel and Blakemore proposed a model for amblyopia based on lateral interactions within the primary visual cortex. In the normal cortex ocular dominance columns are proposed to be linked by excitatory connections as are columns of the same orientation preference. Columns of different orientation preference are linked by long-range diffuse inhibitory connections. They proposed that, in strabismus, the excitatory connections between the ocular dominance columns were lost, leaving only the inhibitory connections, and these lead to a diminished response on binocular viewing.

The outcome of the dichoptic viewing experiments in these normals and simple anisometropic amblyopes has shown that the diplopia induced by the dichoptic viewing apparatus did not cause a reduction in monocular foveal contrast sensitivity. As well as the mechanism proposed in Figure 114, there may have been a contribution from the effects of directed attention. Evidence for this comes from the studies of primate V4 neurones where the response to a stimulus presented within the receptive field was enhanced if attention was directed towards the stimulus. The response was reduced if attention was directed away from the stimulus although it was still located in the receptive field (Conner, Gallant, Preddie and Van Essen, 1996). Thus, normal subjects may be able to affect the efficacy of the neural inputs by shifts of attention.

This did not seem to arise in strabismics since the effect of the prismatic shift of the image on to the fovea of the squinting eye always caused inhibition, *i.e.* it was not ignored. Therefore, the eccentric grating pattern may have been disregarded by the normal and simple anisometropic amblyopes as attention was not directed towards it.

4.7 Summary:

This study has investigated contrast sensitivity in normal subjects, simple anisometropic amblyopes, strabismic amblyopes and non-amblyopic strabismics and the following has been shown.

In the reclassified amblyopes with BSV (simple anisometropic amblyopes and esotropic amblyopes with anomalous BSV) and without BSV, diminished contrast sensitivity was present in the amblyopic eye. The companion eye was also found to be abnormal which confirms the assertion by Lequire *et al* (1990) that the "normal eye is not normal" in amblyopic subjects.

On binocular viewing, contrast sensitivities, averaged over the range of spatial frequencies examined in the 18 amblyopes with BSV increased by 36%, indicating that the amblyopic eye contributed to the enhancement in binocular contrast sensitivities. This is contrary to Blake, Martens and DiGianfilippo (1980) who asserted that the amblyopic eye makes no contribution to binocular contrast sensitivities.

The binocular enhancement in contrast sensitivity was not dependent on the contrast sensitivity difference between the normal and the amblyopic eye *i.e.* enhancement occurred whether the difference was small or large. This finding argues against the assertion that binocular summation depends upon balanced or equal contrast sensitivities through the two eyes (Legge, 1979).

Binocular contrast sensitivities were reduced in the reclassified strabismic subjects comprising the groups in which BSV was absent (esotropic amblyopes, non-amblyopic esotropes, exotropic amblyopes).

Bifoveal contrast sensitivities were also reduced compared with those obtained under binocular conditions of viewing in the group with anomalous BSV (esotropic amblyopes) and without BSV (esotropic amblyopes, non-amblyopic esotropes, exotropic amblyopes).

4.8 Conclusions

The results of this study have shown that:-

- there is an inter-ocular difference in monocular contrast sensitivities in the normal population, in non-strabmismic amblyopes and in strabismic amblyopes.

- the non-amblyopic eye of amblyopes is abnormal, a finding which is in agreement to that of previous studies.

- binocular contrast sensitivity is enhanced by the presence of normal or anomalous BSV.

- the inter-ocular difference in contrast sensitivities, regardless of the magnitude of this difference, does not prevent enhancement of binocular contrast sensitivities in individuals in whom normal or anomalous BSV is present.

- in subjects in whom BSV is absent binocular contrast sensitivities are reduced compared with the monocular contrast sensitivities of the better eye.

- neutralisation of the angle of deviation in strabismics with and without BSV, i.e. under conditions of bifoveal stimulation, results in a further reduction in binocular contrast sensitivities.

These findings suggest that visual function, i.e. binocular contrast sensitivity, is enhanced by the presence of normal or anomalous BSV and that re-alignment of the visual axes gives rise to attenuation of binocular contrast sensitivity and thus, is disadvantageous to visual performance.

5.0 REFERENCES

Albright, T.D., Desimone, R. and Gross, C.G. (1984) Columnar Organisation of Directionally Selective Cells in Visual Area MT of the Macaque. J. Neurophysiol. **51:** 16-31.

Albus, K. and Wolf, W. (1984) Early Post-Natal Development of Neuronal Functions In The Kitten's Visual Cortex: A Laminar Analysis. J. Physiol. (Lond) **348:** 153-185.

Arden, G.B., Barnard, W.M. and Mushin, A.S. (1974) Visually evoked responses in amblyopia. Br. J. Ophthalmol. **58:** 183-195.

Arden, G.B., Vaegan and Hogg, C.R. (1982) Clinical and Experimental Evidence that the Pattern Electroretinogram (PERG) is Generated in More Proximal Retinal Layers Than The Focal Electroretinogram (FERG). Ann. New York Acad. Sci. **388:** 580-607.

Arden, G.B., Vaegan and Hogg, C.R., Powell, D.J. and Carter, R.M (1980) Pattern ERGs are Abnormal in Many Amblyopes. Trans. Ophthalmol. Soc. U.K. **100:** (4) 453-460.

Atkinson, J. and Braddick, O. (1981) In Scientific Foundations of Paediatrics, 2nd. ed. Edit. Davies, J.A. and Dobbing, J. 865-877. Heineman Medical. London.

Bagolini, B. (1974) Is Amblyopia due to Inappropriate Stimulation of the "Sustained Pathway" during Development? Br. J. Ophthalmol. **58**: 173-175.

Barlow, H.B., Blakemore, C. and Pettigrew, J.D. (1967) The Neural Mechanism of Binocular Depth Discrimination. J. Physiol. (Lond) **193:** 327-342.

Bergen, J.R. and Julesz, B. (1983) Parallel versus Serial Processing in Rapid Pattern Discrimination. Nature **303:** 696-698.

Bielschowsky, A. (1934) Divergence Excess. Arch. Ophthalmol. **12**: 157-159.

Blake, R., Martens, W.L. and DiGianfilippo, A. (1980) Reaction Time as a Measure of Binocular Interaction in Human Vision. Invest. Ophthalmol. Vis. Sci. **19:** 930-941.

Blakemore, C., and Cooper, G.F. (1970) Development of the Brain Depending on the Visual Environment. Nature **228:** 477-478.

Blakemore, C. and Campbell, F.W. (1969) On the Existence of Neurones in the Human Visual System Selectively Sensitive to the Orientation and Size of Retinal Images. J. Physiol. (Lond) **203**: 237-260.

Blakemore, C, Fiorentini, A and Maffei, L. (1972) A Second Neural Mechanism of Binocular Depth Discrimination. J. Physiol.(Lond) **226**: 725-739.

Blakemore, C. and Vital-Durand, F. (1986) Effects of Visual Deprivation on the Development of the Monkey's Lateral Geniculate Nucleus. J. Physiol. (Lond) **380:** 493-511.

Blakemore, C., Vital-Durand, F., and Garey, L.J. (1981) Recovery from Monocular Deprivation in the Monkey. I. Reversal of Physiological Effects in the Visual Cortex. Proc. Roy. Soc. (Lond) **B213**: 399-423.

Blodi, V.C. and Van Allan, M. (1962) Electromyography in Intermittent Esotropia: recordings before, during and after corrective operation. Doc. Ophthalmol. **26**: 21-23.

Bowmaker, J. K. and Dartnall, H.J. H. (1980) Visual Pigments of Rods and Cones in a Human Retina. J. Physiol.(Lond) **298:** 501-511.

Bradley, A. and Freeman, R.D. (1981) Contrast Sensitivity in Anisometropic Amblyopia. Invest. Ophthalmol. Vis. Sci. **21:** 267-276.

British Orthoptic Society (1980) Glossary of Terminology 1-21. The British Orthoptic Society, Manchester, England.

Breinin, G.M. (1957) The Nature of Vergence Revealed by Electromyography. Arch. Ophthalmol. **58**: 623-625.

Breinin, G.M. and Moldaver, J. (1955) Electromyography of the Human Extra-Ocular Muscles. Arch. Ophthalmol. **54**: 200-202.

Bunt, A.H., Minckler, D.S. and Johanson, G.W. (1977) Demonstration of Bilateral Projection of the Central Retina of the Monkey with Horseradish Peroxidase Neuronography. J. Comp. Neurol. **171:** 619-630.

Burian, H.M. (1966) Occlusion Amblyopia and the Development of Eccentric Fixation in Occluded Eyes. Am. J. Ophthalmol. **62:** 853-856.

Burian, H.M. and Lawwill, T. (1966) Electro-retinographic Studies in Strabismic Amblyopia. Am. J. Ophthalmol. **61**: 422-430.

Burian, H.M. and von Noorden, G.K. (1981) Binocular Vision and Ocular Motility: Theory and Management of Strabismus. 3rd. ed. The C.V. Mosby Company, St Louis.

Burkhalter, A. and Van Essen, D.C. (1986) Processing of Color, Form, and Disparity Information in Visual Areas VP and V2 of Ventral Extrastriate Cortex in Macaque Monkey. J. Neurosci. **8:** 2327-2351.

Callaway, E.M. (1998) Local Circuits in Primary Visual Cortex of the Macaque Monkey. Ann. Rev. Neurosci. **21:** 47-74.

Campbell, F.W. and Green, D.G. (1965) Optical and Retinal Factors Affecting Visual Resolution. J. Physiol.(Lond) **18:** 576-593.

Campbell, F.W. and Robson, J.G. (1968) Application of Fourier Analysis to the Visability of Gratings. J. Physiol.(Lond) **197:** 551-566.

Campbell, F.W., Robson, J.G. and Westheimer, G. (1959) Fluctuation of Accommodation Under Steady Viewing Conditions. J. Physiol. (Lond) **145:** 579-594.

Campos, E.C. and Chiesi, C. (1983) Binocularity in comitant strabismus: II. Objective evaluation with visual evoked responses. Doc. Ophthalmol. **55**: 277-293.

Carroll, E.W. and Wong-Riley, M.T. (1984) Quantitative Light and Electron Microscopic Analysis of Cytochrome Oxidase-Rich Zones in the Striate Cortex of the Squirrel Monkey. J. Comp. Neurol. **222** (1): 1-17.

Casegrande, V.A. (1999) The Mystery of the Visual System K Pathway. J. Physiol.(Lond) **517**: 630-630.

Cleland, B.G., Dubin, M.W., and Levick, W.R. (1971) Sustained and Transient Neurones in Cat's Retina and Lateral Geniculate Nucleus. J. Physiol. (Lond) **217:** 473-496.

Connor, C.E., Gallant, J.L., Preddie, D.C. and Van Essen, D.C. (1996) Responses in Area V4 Depending on the Spatial Relationship between Stimulus and Attention. J. Neurophysiol. **75:** 1306-1308.

Costenbader, F.D. (1950) The Physiology and Management of Divergent Strabismus. Strabismic Ophthalmic Symposium I. Ed: Allen, J.H. The C.V. Mosby Company, St. Louis.

Cowley, A. and Porter, J. (1979) Brain Damage and Global Stereopsis. Proc. Roy. Soc. (Lond) **B 204:** 399-407

Crawford, M.L.J., Harwerth, R.S., Chino, Y.M., and Smith III, E. L. (1996) Binocularlity in Prism-Reared Monkeys. Eye **10:** 161-166.

Daniel, P.M. and Whitteridge, D. (1961) The Representation of the Visual Field on the Cerebral Cortex in Monkeys. J. Physiol. (Lond) **159:** 203-221.

Dale, R.T. (1982) Fundamentals of Ocular Motility and Strabismus. Grune and Stratton, Inc. New York.

Dawson, W.W. and Maida, T.M. (1984) Relations between the Human Retinal Cone and Ganglion Cell Distribution. Ophthalmologica, Basel **188:** 216-221.

De Valois, R.L. and De Valois, K.K. (1988) In: Spatial Vision, Ch. 1: 18-19. Oxford Science Publication, Oxford University Press Inc., New York.

De Monasterio, F.M. (1978a) Properties of Concentrically Organized X and Y Ganglion Cells of macaque Retina. J. Neurophysiol. **41**(6): 1394-1417.

De Monasterio, F.M. (1978b) Properties of Ganglion Cells with Atypical Receptive Field Organization in Retina of Macaques. J. Neurophysiol. **41**(6): 1435-1449.

De Vries, J. (1985) Anisometropia in Children: Analysis of a Hospital Population. Br. J. Ophthalmol. **69:** 504-507.

De Yoe, E.A. and Van Essen, D.C. (1985) Segregation of Efferent Connections and Receptive Field Properties in Visual Area V2 of the Macaque. Nature **317:** 58-61.

Desimone, R. and Schein, S.J. (1987) Visual Properties of Neurones in Area V4 of the Macaque: Sensitivity to Stimulus Form. J. Neurophysiol. **57** (3): 835-867.

Devlin, M.L., Jay, J.L. and Morrison, J.D. (1989) Abnormality of the pattern electroretinogram and pattern visually evoked cortical response in esotropic cats. Doc. Ophthalmol. **73:** 53-69.

Dreher, B. (1972) Hypercomplex cells in the cat's striate cortex. Invest. Ophthalmol. **11:** 355-356.

Duane, A. (1896) A New Classification of the Motor Anomalies of the Eyes Based Upon Physiological Principles, together with their Symptoms, Diagnosis and Treatment. Ann. Ophthalmol., Otolarangol., 5: 969: In: Noorden, von G.K. (1996) Binocular Vision and Ocular Motility; Theory and Management of Strabismus. 4th. ed. The C.V. Mosby Company, St Louis.

Duke Elder, S. (1969) The Practice of Refraction J.A. Churchill Ltd., London.

Duke Elder, S. (1973) System of Ophthalmology. Ocular Motility and Strabismus. **Vol. VI.** Henry Kimpton, London.

Enroth-Cugell, C. and Robson, J.G. (1966) The Contrast Sensitivity of Retinal Ganglion Cells of the Cat. J. Physiol. (Lond) **187:** 517-52.

Famigliettie, E.V. Jr. and Kolb, H. (1976) Structural Basis of "ON" and "OFF" Centre Responses in Retinal Ganglion Cells. Science. **194:** 193-15.

Fellman, D.J. and Van Essen, D.C. (1987) Receptive Field Properties of Neurones in Area V3 of Macaque Monkey Extrastriate Cortex. J. Neurophysiol. **57** (4): 889-920.

Ferster, D., Chung, S., and Wheat, H. (1996) Orientation Selectivity of Thalamic Input to Simple Cells of Cat Visual Cortex. Nature. **380**: 249-252.

Fielder, A.R., Irwin, M., Auld, R., Cocker, KD., Jones, H.S. and Moseley, M.J. (1995) Compliance in Amblyopia Therapy: Objective Monitoring of Occlusion. Br. J. Ophthalmol. **76** (6): 585-589.

Fisher, N.F. (1986) The Optic Chiasm and the Corpus Callosum: Their Relationship to Binocular Vision in Humans. J. Ped. Ophthalmol. Strab. **23:** 126-131.

Fitzpatrick, D., Itoh, K., and Diamond, I.T. (1983) The Laminar Organization of the Lateral Geniculate Body and the Striate Cortex in the Squirrel Monkey (*Saimiri sciurells*). J. Neurosci. **3:** 673-702.

Gallant, J.L, Connor, C.C., Rakshit, S., Lewis, J.W. and Van Essen, D.C. (1996) Neural Responses to Polar, Hyperbolic, and Cartesian Gratings in Area V4 of the Macaque Monkey. J. Neurosci. **76** (4): 2718-2739.

Garey, L.J. and Vital-Durand, F. (1981) Recovery from Monocular Deprivation in the Monkey II. Reversal of Morphological Effects in the Lateral Geniculate Nucleus. Proc. Roy. Soc. Lond. **B 213**: 425-433.

Hall, I.B. (1961) Primary Divergent Strabismus. Analysis of Aetiological Factors. Br. Orth. J. **18:** 106-109.

Harcourt, R.B. (1981) Dissociated Vertical Divergence (DVD) And Its Treatment. Trans. Ophthalmol. Soc. UK. **101**: 271-272.

Harrad, R. and Hess, R.F (1992) Binocular Integration of Contrast Information in Amblyopia. Vision Res. **32:** 2135-2150.

Harrad, R. and Hess, R.F. (1992) A Model for Suppression in Amblyopia. Transactions of the 20th Meeting of the European Strabismological Association 113-118.

Harrad, R., Sengpiel, F. and Blakemore, C. (1996) Physiology of Suppression in Strabismic Amblyopia. Br. J. Ophthalmol. **80:** 373-377.

Hendrickson, A.E., Movshon, J.A., Eggers, H.M., Gizzi, M.S. Boothe, R.G. and Kiorpes, L. (1987) Effects of Early Unilateral Blur on Macques's Visual System II. Anatomical Observations. J. Neurosci. **7:** 1327-1339.

Hess, R.F. and Baker, C.L. (1984) Assessment of Retinal Function in Severely Amblyopic Individuals. Vision Res. **24:** 1367-1376.

Hess, R.F. and Howell, E.R. (1977) Threshold Contrast Sensitivity Function in Strabismic Amblyopia: Evidence for a Two Type Classification. Vision Res. **17:** 1049-1055.

Hess, R.F. and Pointer, J.G. (1985) Differences in the Neural Basis of Human Amblyopia. The Distribution of the Anomaly Across the Visual Field. Vision Res. **25:** 1577-1594.

Hilz R and Cavonius CR., (1974) Functional Organization of the Peripheral Retina; Sensitivity to Periodic Stimuli. Vision Res. **14:** 1333-1337.

Hirsch, H.V., Leventhal, A.G., McCall, M.A. and Tieman, D.G. (1983) Effects of Exposure to Lines of One or Two Orientations on Different Cell Types in the Striate Cortex of the Cat. J. Physiol. (Lond.) **337**: 241-255.

Hirsch, H.V. and Spinelli, D.N. (1971) Modification of the Distribution of Receptive Field Orientation in Cats by Selective Visual Exposure During Development. Brain Res. **13**: 509-527.

Holmes, G. (1918) In: Davson's Physiology of the Eye (1980) 4th. ed. Churchill Livingstone, London.

Holopigian, K., Blake, R. and Greenwald, M.J. (1986) Selective Losses in Binocular Vision in Anisometropic Amblyopes. Vision Res. **26** (4): 621-630.

Holopigian, K., Blake, R., and Greenwald, M.J. (1988) Clinical Suppression and Amblyopia. Invest. Ophthalmol. and Vis. Sci. **29** (3): 444-451.

Horton, J.C. and Hubel, D.H. (1981) Regular Patchy Distriubution of Cytochrome Oxidase Staining in Primary Visual Cortex of Macaque Monkey. Nature **292**: 762-764.

Hoyt, C.S., Stone, R.D., Fromer, C., Billdon, F.A. (1981) Monocular Axial Myopia Associated with Neonatal Eyelid Closure in Human Infants. Am. J. Ophthalmol. **91:** 197-200.

Hubel, D. H. and Livingstone, M.S. (1987) Segregation of Form, Colour and Stereopsis in Primate Area 18. J. Neurosci. **7:** 3378-3415.

Hubel, D.H. and Wiesel, T.M. (1962) Receptive Fields, Binocular Interaction and Functional Architecture in Cat's Visual Cortex. J. Physiol. (Lond) **160**: 106-154.

Hubel, D.H. and Wiesel, T.N. (1963) Receptive Fields of Cells in Striate Cortex of Very Young, Visually Inexperienced Kittens. J. Neurophysiol. **26:** 994-1002.

Hubel, D.H. and Wiesel, T.N. (1965) Receptive Fields and Functional Architecture in Two Nonstriate Visual Areas (18 and 19) of the Cat. J. Neurophysiol. **28:** 229-289.

Hubel, D.H. and Wiesel, T.N. (1965) Binocular Interaction in Striate Cortex of Kittens Reared with Artificial Squint. J. Neurophysiol. **28:** 1041-1059.

Hubel, D.H. and Wiesel, T.N. (1968) Receptive Fields and Functional Architecture of Monkey Striate Cortex. J. Physiol. (Lond) **195**: 215-243.

Hubel, D.H. and Wiesel, T.N. (1970) Cells Sensitive to Binocular Depth in Area 18 of the Macaque Monkey Cortex. Nature **225:** 41-42.

Hubel D.H. and Wiesel, T.N. (1972) Laminar and Columnar Distribution of Geniculate Cortical Fibres in the Macque Monkey. J. Comp. Neurol. **146:** 421-450.

Hubel, D.H. and Wiesel, T.N. (1973) A Re-examination of Stereoscopic Mechanisms in Area 17 of the Cat. J. Physiol. (Lond) **232**: 29-30.

Hubel, D.H. and Wiesel, T.N. and Le Vay, S. (1977) Plasticity of Ocular Dominance Columns in Monkey Striate Cortex. Phil. Trans. Soc. (Lond) **B 278:** 131-163.

Ikeda, H. and Wright, M. J. (1974) Is Amblyopia due to Inappropriate Stimulation of the "Sustained Pathway" during Development? Br. J. Ophthalmol. **58:** 165-173.

Ikeda, H. and Wright, M. (1976) Properties of LGN Cells in Kittens Raised with Convergent Squint; a Neurophysiological Demonstration of Amblyopia. Exp. Brain Res. **25**: 63-77.

Ikeda, H. and Tremain, K.E. (1979) Amblyopia Occurs in Retinal Ganglion Cells in Cats Reared with Convergent Squint without Alternating Fixation. Exp. Brain Res. **35:** 559-82.

Ingram, R.M. (1977) The Problem of Screening Children for Visual Defects. Br. J. Ophthalmol. **61**: 4-7.

Ingram, R.M. (1977) Refraction as a Basis for Screening Children for Squint and Amblyopia. Br. J. Ophthalmol. **61:** 8-15.

Ingram, R. and Barr, A. (1979) Changes in Refraction between the Ages of 1 and 3.5 Years. Br. J. Ophthalmol. **63:** 339-342.

Ingram, R., Traynor, M., Walker, C. and Wilson, J. M. (1979) Screening for Refractive Error at Age One Year; a Pilot Study. Br. J. Ophthalmol. **63:** 243-250.

Ingram, R, Walker, C., Billingham, B., Lucas, J. and Dally, S. (1990) Factors Relating to Visual Acuity in Children Who Have Been Treated for Convergent Squint. Br. J. Ophthalmol. **74:** 82-83.

Irvine, S.R. (1944) A Simple Test for Binocular Fixation: Clinical Application Useful in the Appraisal of Ocular Dominance, Amblyopia Exanopsia, Minimal Strabismus and Malingerers. Am. J. Ophthalmol. **27:** 740-744.

Jacobs, D.S. and Blakemore, C. (1988) Factors Limiting the Post Natal Development of Visual Acuity in the Monkey. Vision Res. **28**: 947-958.

Jampolsky, A. and Schlor, C.M. (1955) Characteristics of Suppression in Strabismus. Arch. Ophthalmol. **54**: 683-696.

Jampolsky, A., Flom, B.C., Weymouth, F.W. and Moses, L.E. (1955). Unequal Corrected Visual Acuity as Related to Anisometropia. Arch. Ophthalmol. **54**: 893-905.

Julesz, B. (1960) Foundations of Cyclopean Perception. University of Chicago Press, Chicago, USA.

Kay, C.D. and Morrison, J.D. (1987) A Quantitative Investigation into the Effects of Pupil Diameter and Defocus on Contrast Sensitivity for an Extended Range of Spatial Frequencies in Natural and in Homatropinised Eyes. Ophthal. Physiol. Opt. **7**: (1) 21-30.

Kervick, G. (1986) The Importance of Birth History in the Aetiology of Strabismus. Br. Orth. J. **43:** 68-71.

Kivlin, J.D. and Flynn, J.T. (1981) Therapy of Anisometropic Amblyopia. J. Ped. Ophthalmol. Strab. **18:** 47-56.

Kolb, H. (1970) Organisation of the outer plexiform Layer of the Primate Retina: Electron Microscopy of Golgi-impregnated Cells. Phil. Trans. Roy. Soc. (Lond). **B 258:** 261-283.

Kuffler, S.W. (1953) Discharge Patterns and Functional Organisation of Mammalian Retina. J. Neurophysiol. **16:** 37-68.

Krzystkowa, K and Pajakowa, J. (1972) The Sensorial State in Divergent Strabismus. In: Orthoptic Proceedings of the 2nd. International Orthoptic Congress, Amsterdam. Excerpta Medica Foundation, Holland.

Lang, J. Microtropia. (1984) Strabismus. Slack Inc. New Jersey, USA.

Lee, B.B. (1996) Receptive Field Structure in the Primate Retina. Vision Res. **36** (5): 631-644.

Legge, G.E. (1979) Spatial Frequency Masking in Human Vision: Binocular Interactions. J. Opt.Soc. Am. **69:** 838-874.

Leguire, L.E., Rogers, G.L., and Bremer, D.L. (1990) Amblyopia: The Normal Eye is Not Normal. J. Ped. Ophthalmol. Strab. **27** (1): 32-38.

Leguire, L.E., Rodgers, G.L., Bremer, D.L. and Wali, N. (1989) A Comparison of Contrast Sensitivity Functions (CSF) Between Strabismic and Anisometropic Amblyopia in Children. Binocular Vision Quarterly. **4** (4): 179-186.

Levi, D.M. and Harwerth, R. (1977) Spatio-Temporal Interactions in Anisometropic and Strabismic Amblyopia. Invest.Ophthalmol Visual Sci. **16:** 90-95.

Levi, D.M., Harwerth, R.S. and Smith, E.L. III (1979). Humans Deprived of Normal Binocular Vision have Binocular Interactions Tuned to Size and Orientation. Science. **206:** 852-854.

Lithander, J., and Sjöstrand, J. (1991) Anisometropic and Strabismic Amblyopia in the Age Group 2 years and Above: a prospective study of the results of treatment. Br. J. Ophthalmol. **75:** 111-116.

Livingstone, M.S., and Hubel, D.H. (1983) Specificity of cortico-cortical connections in monkey visual system. Nature. **304:** 531-534.

Livingstone, M.S., and Hubel, D.H. (1984) Anatomy and Physiology of a Colour System in the Primate Visual Cortex. J. Neurosci. **4:** 309-356.

Livingstone, M.S., and Hubel, D.H. (1987) Connections between Layer 4B of Area 17 and Thick Cytochrome Oxidase Stripes of Area 18 in the Squirrel Monkey. J. Neurosci. **7:** 3371-3377.

Luck,S.J., Chelazzi, L., Hillyard, S.A. and Desimone, R. (1997) Neural Mechanisms of Spatial Selective Attention in Areas V1, V2, and V4 of Macaque Visual Cortex. J. Neuophysiol. **77**: 24-42.

Lyle, T.K. and Wybar, K.C. (1967) Practical Orthoptics in the Treatment of Squint. 5th. ed. H.K. Lewis & Co., London.

Marshall, E.B. (1967) The Purpose and Significance of the Cover Test. The First International Congress of Orthoptics. Transactions of the Royal College of Surgeons, England. 99-103.

Maurer, D. and Lewis, T.L. (1993) Visual Outcomes after Infant Cataract. In Early Visual Development: Normal and Abnormal. Editor; K. Simmons. 454-484 Oxford University Press, New York.

Mein, J. and Harcourt, B. (1986) Diagnosis and Management of Ocular Motility Disorders. Blackwell Science Publications, London.

Mein, J. and Trimble, R. (1991) Diagnosis and Management of Ocular Motility Disorders. 2nd ed. Blackwell Science Publications, London.

Merigan, W.H. (1989) Chromatic and Achromatic Vision of Macaques: Role of the P Pathway. J. Neurosci. **9** (3): 776-783.

Merigan, W.H., Katz, L.M. and Maunsell, J.H.R. (1991) The Effects of Parvocellular Lateral Geniculate Lesions on the Acuity and Contrast Sensitivity of Macaque Monkeys. J. Neurosci. **11** (4): 994-1001.

Minkowsky, E. (1920) In: Davson's Physiology of the Eye 5th. ed Ed. Davson, H. McMillan Press, London.

Mitchell, D.E. (1966) Retinal Disparity and Diplopia. Vision Res. **6:** 441-451.

Mitchell, D.E. and Blakemore, C. (1970) Binocular Depth Perception and the Corpus Callosum. Vision Res. **10:** 49-54.

Morrison, J.D. and McGrath, C. (1985) Assessment of the Optical Contributions to the Age Related Deterioration in Vision. Quart. J. Exp. Physiol. **70:** 249-269.

Mountcastle, V.B. (1957) Modality and Topographic Properties of Single Neurones of Cats Somatic Sensory Cortex. J. Neurophysiol. **20:** 408-434.

Movshon, J.A. Eggers, H.M., Gizzi, M.S., Hendrickson, A.E., Kiorpes, L. and Boothe, R.G. (1987) Effects of early unilateral blur on macques's visual system III. Physiological observations. J. Neurosci. **7:** 1340-1351.

Mower, G.D. and Christen, W.G. (1985) Role of Visual Experience in Activating Critical Period in Cat Visual Cortex. J. Neurophysiol. **53** (2): 572-589.

Nealey, T.A., and Maunsell, J.H.R. (1994) Magnocelluar and Parvocellular Contributions to the Responses of Neurones in Macaque Striate Cortex. J. Neurosci. **14** (4): 2069-2079.

Nelson, R, Kolb, H. and Famiglietti, E.V. (1978) Intracellular Staining Reveals Different Levels of Stratification for On-and Off-Centre Ganglion Cells in Cat Retina. J. Neurophysiol. **41** (2): 472-483.

Newsome, W.J. and Wurtz, R.H. (1988) Probing Visual Cortical Function with Discrete Chemical Lesions. Trends Neurosci. **11:** 394-400.

Nikara, T., Bishop, P.O. and Pettigrew, J.D. (1968) Analysis of Retinal Correspondence by Studying Receptive Fields of Binocular Single Units in Cat Striate Cortex. Exp. Brain Res. **6**: 353-372.

Ogle, K.N. (1962) Spatial Localization through Binocular Vision. In Davson, H. editor. The Eye, **Vol 4**. 279 Academic Press. New York and London.

O'Leary, D.J. and Milldot, M. (1979) Eyelid Closure Causes Myopia in Humans. Experientia **35:** 1478-1479.

Osterberg, G. (1935) Topography of the Layer of Rods and Cones in the Human Retina. Acta. Ophthalmol. **6**: (Suppl): 8.

Pardhan, S. and Gilchrist, J. (1990) The Effect of Monocular Defocus on Binocular Contrast Sensitivity. Ophthalmol. Physiol. Opt. **10:** 33-36

Peichl, L. and Wassle, H. (1979) Size, Scatter and Coverage of Ganglion Cell Receptive Field Centres in the Cat Retina. J. Physiol.(Lond) **291**: 118-139.

Pettigrew, J.K. (1974) The Effect of Visual Experience on the Development of Stimulus Specificity by Kitten Cortical Neurones. J. Physiol. (Lond) **237:** 49-74.

Pirenne, M.H. (1943) Binocular and Uniocular Threshold of Vision. Nature. **152:** 698-699.

Poggio, G.F., and Fischer, B. (1977) Binocular Interactions and Depth Sensitivity in Striate and Prestriate Cortex of Behaving Rhesis Monkey. J. Physiol. (Lond) **40:** 1392-1407.

Poggio, G.F. and Poggio, T. (1984) The Analysis of Stereopsis. Ann. Rev. Neurosci. **7:** 379-412.

Pratt-Jonhson, J.A. and McDonald, A.L. (1976). Binocular Visual Field in Strabismus. Can. J. Ophthalmol. **11:** 37-39.

Pratt-Johnson, J.A. and Wee, H.S. (1969) Suppression Associated with Exotropia. Can. J. Ophthalmol. **4:** 16-19.

Ross, J.E., Clarke, D.D. and Bron, A.J. (1985) Effect of Age on Contrast Sensitivity Fuction: Uniocular and Binocular Findings. Br J. Ophthalmol. **69:** 51-56.

Romano, P.E. and Noorden, G.K. von (1969). Atypical Responses to the 4^ Prism Test. Am. J. Ophthalmol. **67:** 935-939.

Rovamo, J., Virsu, V., and Nasanen, R. (1978) Cortical Magnification Factor Predicts the Photopic Contrast Sensitivity of Peripheral Vision. Nature. **271:** 54-56.

Ryan, B.F. and Joiner, B.L. (1995) Minitab Handbook, 3rd.ed Duxberry Press.

Sawatari, A., and Callaway, E.M. (1996) Convergence of Magno and Parvocellular Pathways in Layer 4B of Macaque Primary Visual Cortex. Nature **380**: 442-446.

Schade, O.H. (1956) Optical and Photo-electric Analogue of the Eye. Opt. Soc. Amer. **46**: 721-739.

Schein, S.J. and Desimone, R. (1989) Spectral Properties of V4 Neurones in the Macaque. J. Neurosci. **10** (10): 3369-3389.

Schiller, P.H. and Lee, K. (1991) The Role of the Primate Extrastriate Area V4 in Vision. Science **251**: 1251-1253.

Schoppman, A. and Stryker, M.P. (1981) Physiological Evidence that the 2-deoxyglucose Method Reveals Orientation Columns in Cat Visual Cortex. Nature **293**: 574-576.

Sengspiel, F. and Blakemore, C., (1996) The Neural Basis of Suppression and Amblyopia in Strabismus. Eye **10**: 250-258.

Serano, M., Dale, A.M., Reppas, I.B., Kwong, K.K., Belliveau, J.W., Bradley, B.R., Rosen, B.R. and Tootell, R.B.H. (1995) Borders of Multiple Visual Areas in Humans Revealed by Functioning MRI. Science **268:** 889-893

Setrayish, S., Khodadoust, A.A. and Daryani, S.M. (1978) Microtropia. Arch. Ophthalmol. **96:** 1842-1847.

Sillito, A.M. (1977) Inhibitory Processes Underlying the Directional Specificity of Simple, Complex and Hypercomplex Cells in the Cat's Visual Cortex. J. Physiol. (Lond) **271**: 699-720.

Slataper, F.J. (1950). Age Norms of Refraction and Vision. Arch. Ophthalmol. **43:** 466-481.

Smith, E.L. (III), Levi, D.M. Manny, R.E., Harweth, R.S. and White, J. M. (1985). The Relationship between Binocular Rivalry and Strabismic Suppression. Invest. Ophthalmol. Vis. Sci. **26**: 80-87.

Sokol, S. and Nadler, D. (1979) Simulataneous electroretinograms and visually evoked potentials from adult amblyopes in response to a pattern stimulus. Invest. Ophthalmol. August: 848-855.

Sorsby, A. Benjamin, B. Davey, J.B., Sheridan M. (1961) Refraction and its Components during the Growth of the Eye from the Age of Three. Medical Research Council Special Report Series. **301**. HMSO., London.

Sperry, R.W. (1975) Lateral Specialization in the Surgically Separated Hemispheres. 5-19. In Hemispheric Specialization and Interaction. ed. Miller, B. MIT Press, Massachusetts Institute of Technology, Mass.

Stone, J. and Hoffman, K-P. (1972) Very slow conducting ganglion cells in the cat's retina: a major new functional type. Brain Res. **43**: 610-616.

Sur, M., Weller, R.E. and Sherman, S.M. (1984) Development of X and Y Cell Retinogeniculate Terminations in Kittens. Nature. **310:** 246-249.

Tanlamai, T. and Goss, D.A. (1979) Prevalence of Monocular Amblyopia Among Anisometropes. Am. J. Optom. Physiol. Optics **56:** 704-715.

Tootell, R.B., Dale, A.M., Sereno, MI. and Malach, R. (1996) New Images from Human Visual Cortex. Trends Neurosci. **19** (11): 481-489.

Tolhurst, D.J. (1973) Separate Channels for the Analysis of the Shape and the Movement of Moving Visual Stimulus. J. Physiol. (Lond) **231** (3): 385-402.

Ts'o, D. and Gilbert, C.D. (1988) The Organization of Chromatic and Spatial Interactions in the Primate Striate Cortex. J. Neurosci. **8** (5): 1712-1727.

von Noorden, G.K. (1976) The Nystagmus Compensation (Blockage) Syndrome. Am. J. Ophthalmol. **82:** 283-290.

von Noorden, G.K. (1977) Mechanisms of Amblyopia. Adv. Ophthalmol. **34:** 93-115.

von Noorden, G.K. (1976) Current Concepts of Ambyopia. In: Orthoptics Past, Present and Future. Eds; Moore, S., Mein, J., and Stockbridge, S. Symposia Specialist Medical Books. USA.

von Noorden, G.K. (1990) Binocular Vision and Ocular Motility: Theory and Management of Strabismus. 4th. ed The C.V. Mosby Company, St. Louis.

von Noorden, G.K. (1996) Binocular Vision and Ocular Motility: Theory and Management of Strabismus. 5th. ed The C.V. Mosby Company, St. Louis.

von Noorden G.K. and Crawford, M.L.J. (1978) Morphological and Physiological Changes in the Monkey Visual System after Short-Term Lid Suture. Invest. Ophthalmol. Vis. Sci. **17** (8): 762-768

von Noorden, G.K. and Crawford, M.L. (1977) Form Deprivation without Light Deprivation Produces the Visual Deprivation Syndrome in Macaca Mulatta. Brain Res. **129**: 37-44.

von Noorden, G.K. and Crawford, M.L.J. and Levacy, R.A. (1983). The LGN in human anisometropic amblyopia. Invest. Ophthalmol. Vis. Sci. **24:** 788-790.

von Noorden, G.K. and Frank, J.W. (1976) Relationship between amblyopia and the angle of strabismus. Am.Orth. J. **24**: 31-33.

Waddell, E. M. and Fells, P. (1980) Duanes Retraction Syndrome Reconsidered. Br. Orth. J. **37**: 56-65.

Wali, N., Leguire, L.E., Rogers, G.L. and Bremer, D.L. (1991) CSF Interocular Interactions in Childhood Amblyopia. Opt. and Vis. Sci. **68** (2): 81-87.

Wassle, H, Peichl, L. and Boycott, B. (1991) Functional Architecture of the Mammalian Retina. Physiol. Rev. **71**: 24-28.

Watson, A.B. and Robson, J.G. (1981) Discrimination at Threshold: Lablled Detectors in Human Vision. Vision Res. **21**: 1115-1122.

Weale, R.A. (1982) A Biography of the Eye. H.K. Lewis and Co. Ltd., London.

Wiesel, T.N., Hubel, D.H. (1965) Comparison of the effects of unilateral and bilateral eye closure on cortical unit responses in kittens. J. Neurophysiol. **28**: 1028-1040.

Wiesel, T.N., Hubel, D.H. (1966) Spatial and Chromatic Interactions in the Lateral Geniculate Body of the Rhesus Monkey. J. Neurophysiol. **29:** 1115-1156.

Wilson, H.R., McFarlane, D.K. and Philips, G.C. (1983) Spatial Frequency Tuning of Orientation Selective Units Estimated by Oblique Masking. Vision Res. **23** (9): 873-882.

Worth, C. (1903) In: Practical Orthoptics in the Treatment of Squint (1967). 5th. ed. Editors; Lyle, T.K. and Wybar, K.C. H.K. Lewis & Co. London.

Zeki, S. (1969) Representation of Central Visual Fields in Prestriate Cortex of Monkeys. Brain Res. **14:** 271-291.

Zeki, S. M. (1977) Colour Coding in the Superior Temporal Sulcus of Rhesus Monkey Visual Cortex. Proc. Roy. Soc. (Lond) **B 197:** 195-223.

Zeki, S.M. (1978) Uniformity and diversity of structure and function in rhesus monkey prestriate visual cortex. J. Physiol. (Lond) **277:** 273-290.

Zeki, S (1992) The Visual Image in Mind and Brain. Scientific American. **267** Sept. 69-76.

6.0 APPENDICES

6.1 Normal Subjects with Normal BSV

Individual Graphs and Data

6.2 Simple Anisometropic Amblyopes with Normal BSV

Individual Graphs and Data

6.3 Micro-esotropic Amblyopes with Anomalous BSV

Individual Graphs and Data

6.4 Esotropic Amblyopes with Anomalous BSV

Individual Graphs and Data

6.5 Esotropic Amblyopes without BSV

Individual Graphs and Data

6.6 Non Amblyopic Esotropes without BSV

Individual Graphs and Data

6.7 Exotropic Amblyopes without BSV

Individual Graphs

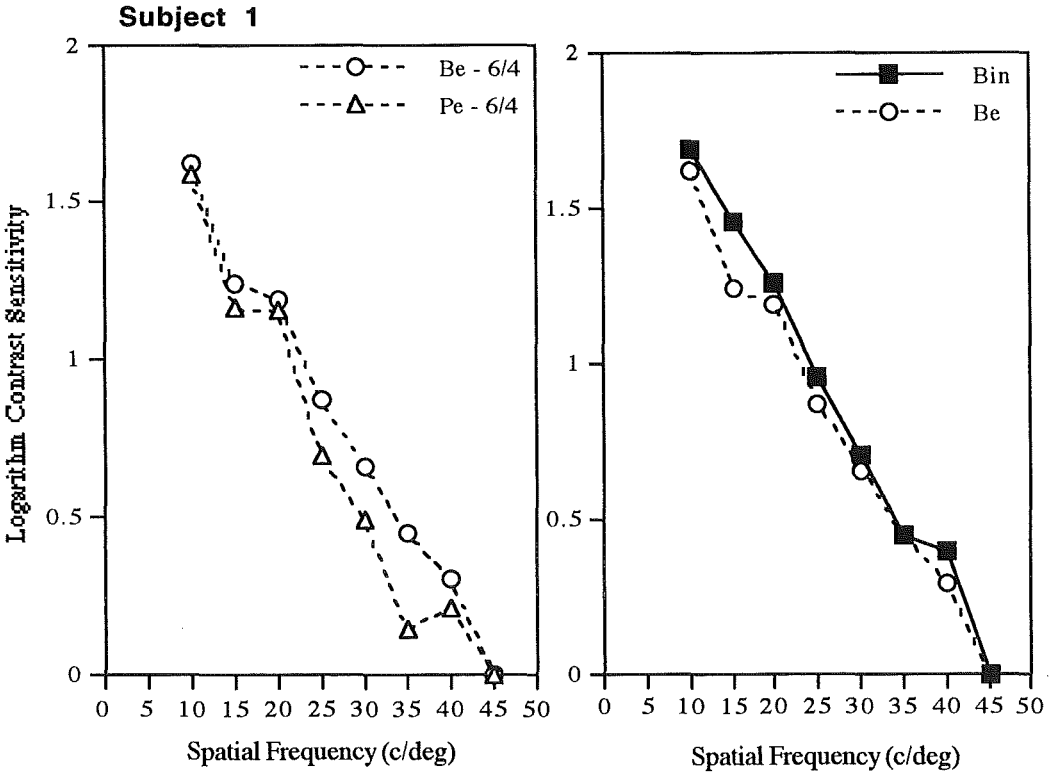
6.8 Non Amblyopic Exotropes without BSV

Individual Graphs

6.9 Dichoptic Viewing

6.9.1 The Normal Group
6.9.2 Simple Anisometropic Amblyopes
6.9.3 Micro-esotropia Amblyopes with Anomalous BSV
6.9.4 Esotropia Amblyopia without BSV

6.1 Normal Group

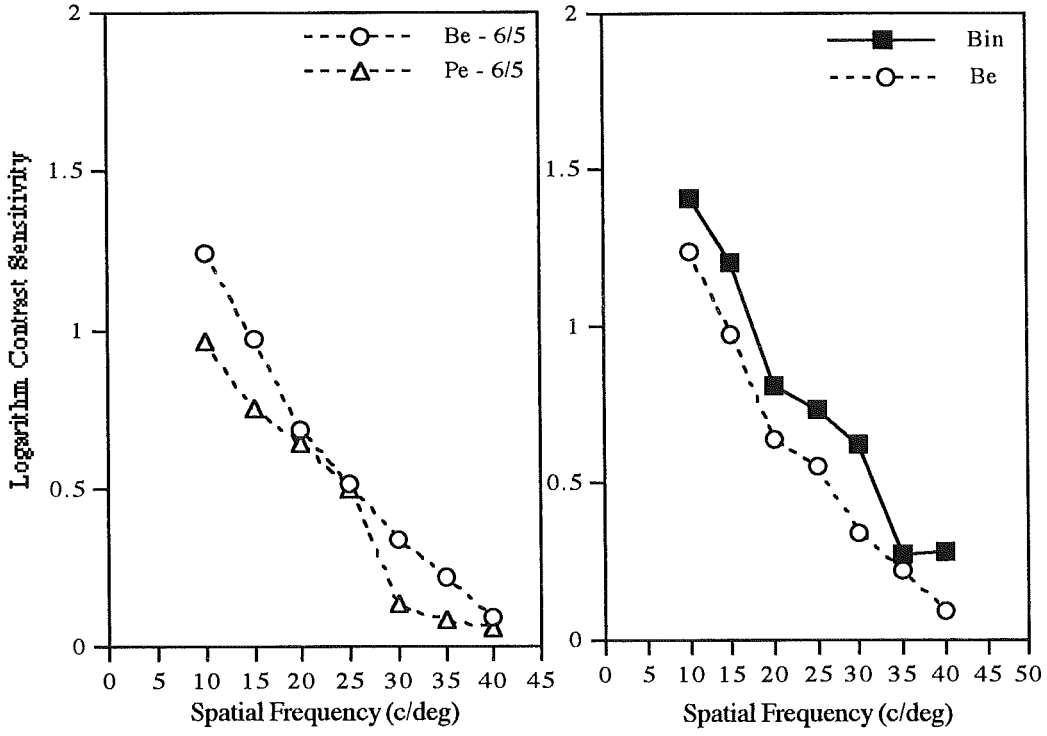


The contrast sensitivity in the better eye was significantly greater than that in the poorer eye. The mean percentage enhancement was 40%±14%SE (P.<0.05). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 16% ± 3%SE (P. <0.01).

Clinical Data

Refractive Error:	RE: -3.25ds LE: -3.25ds
Visual Acuity:	RE: 6/4 LE: 6/4
Angle of Deviation:	N: BI 4^ D: BI 4^
Amplitude of Accommodation:	RE: 9.5D LE: 8.5D
Pupils:	RE: 4mm LE: 4mm

Subject 2

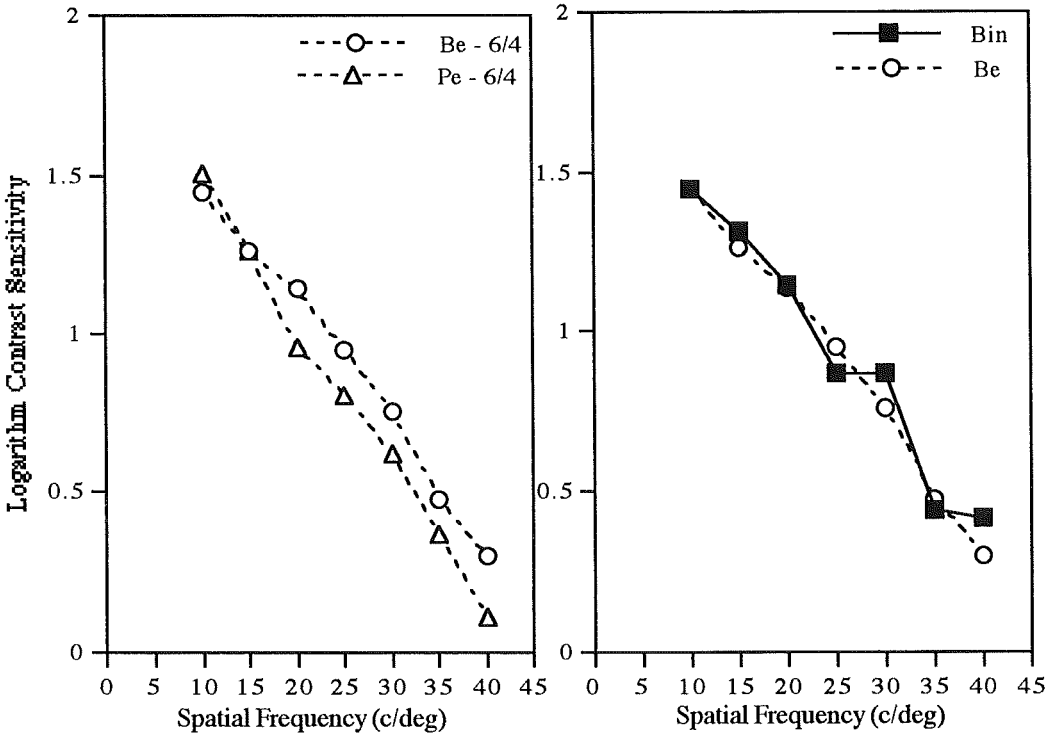


The contrast sensitivity in the better eye was significantly greater than that in the poorer eye. The mean percentage enhancement was 36%±13%SE (P.<0.05). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 49% ± 10%SE (P. <0.01).

Clinical Data

Refractive Error:	Nil
Visual Acuity:	RE: 6/5 LE: 6/5
Angle of Deviation:	N: BI 4^ D: BI 4^
Amplitude of Accommodation:	RE: 6.75D LE: 6.75D
Pupils:	RE: 4mm LE: 4mm.

Subject 3

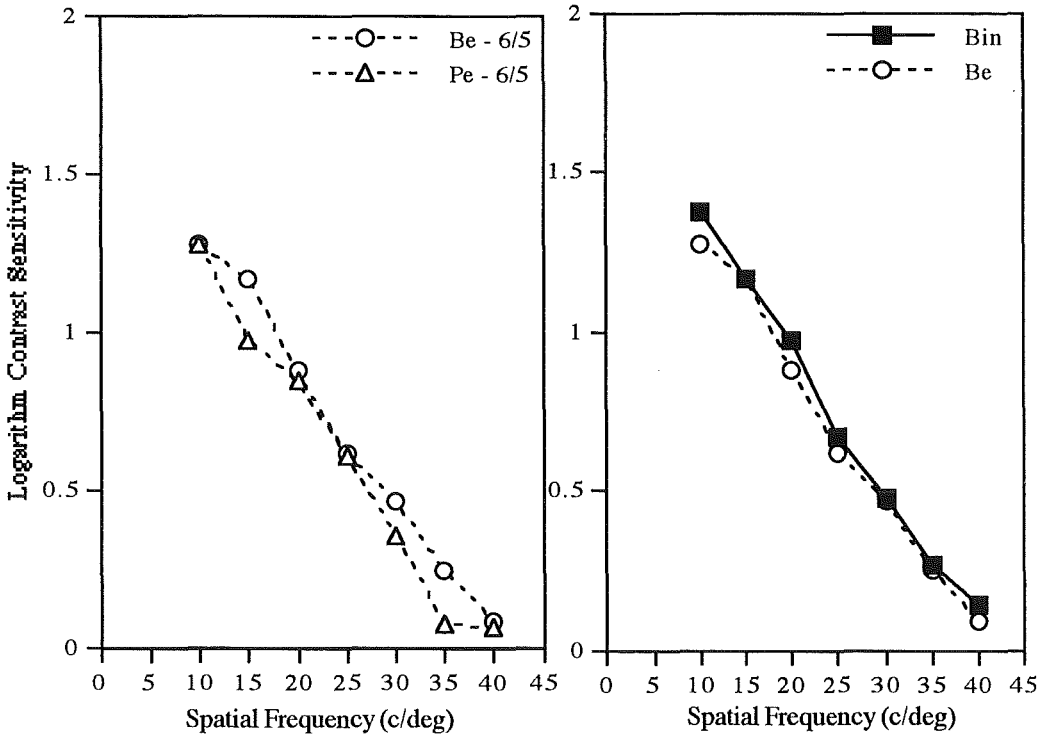


The contrast sensitivity in the better eye was significantly greater than that in the poorer eye. The mean percentage enhancement was 28%±9%SE (P.<0.05). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 7% ± 7%SE (P. ns).

Clinical Data

Refractive Error:	RE: -0.75ds LE: -1.50ds
Visual Acuity:	RE: 6/4 LE: 6/4
Angle of Deviation:	N: BO 4^ D: BO 2^
Amplitude of Accommodation:	RE: 6.25D LE: 7.25D
Pupils:	RE: 3mm LE: 3mm

Subject 4

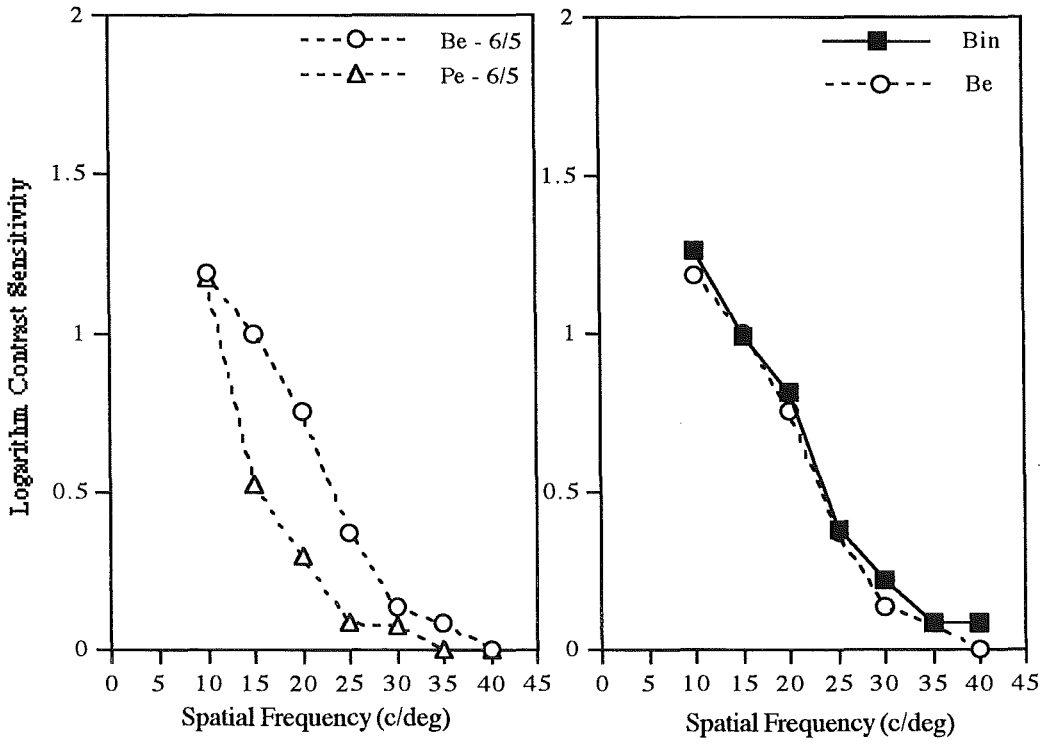


The contrast sensitivity in the better eye was significantly greater than that in the poorer eye. The mean percentage enhancement was 21%±9%SE (P.<0.05). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 11% ± 4%SE (P.<0.05).

Clinical Data

Refractive Error:	RE: -0.75ds LE: -0.50ds
Visual Acuity:	RE: 6/5 LE: 6/5
Angle of Deviation:	N: BO 2^ D: BO 1^
Amplitude of Accommodation:	RE: 6.50D LE: 5.75D
Pupils:	RE: 4mm LE: 4mm

Subject 5

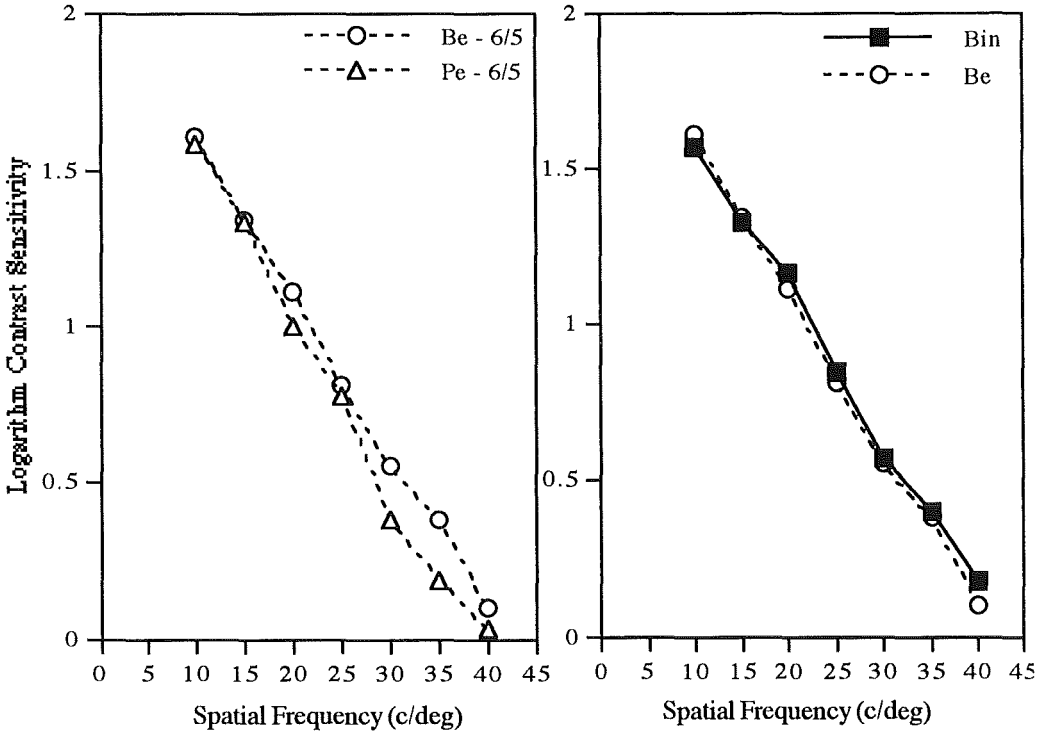


The contrast sensitivity in the better eye was greater than that in the poorer eye. The mean percentage enhancement was 75%±33%SE (P.ns). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 11% ± 4%SE (P.<0.05).

Clinical Data

Refractive Error:	Nil
Visual Acuity:	RE: 6/5 LE: 6/5
Angle of Deviation:	N: BI 4^ D: BI 4^
Amplitude of Accommodation:	RE: 4.25D LE: 5.25D
Pupils:	RE: 4mm LE: 4mm

Subject 6

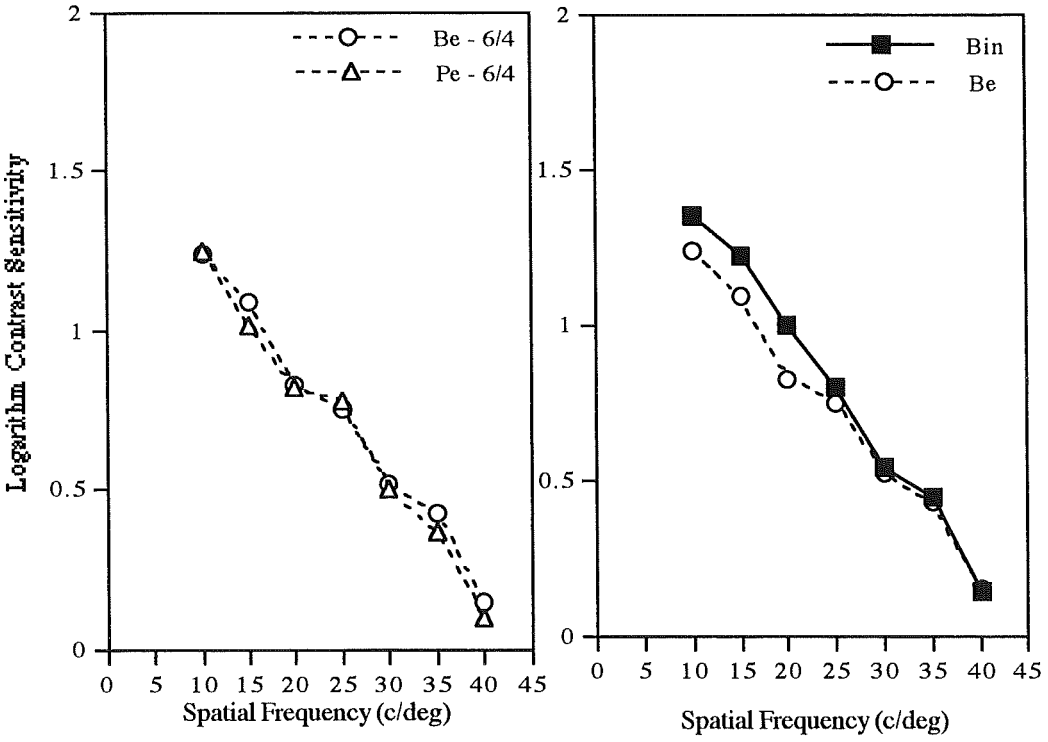


In subject number 6, the contrast sensitivity in the better eye was significantly greater than that in the poorer eye. The mean percentage enhancement was 23%±8%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 6% ± 3%SE but this was not significant (P.ns).

Clinical Data

Refractive Error:	Nil
Visual Acuity:	RE: 6/5 LE: 6/5
Angle of Deviation:	N: BO 4^ D: BO 4^
Amplitude of Accommodation:	RE: 10.25D LE: 10.25D
Pupils:	RE: 3mm LE: 3mm

Subject 7

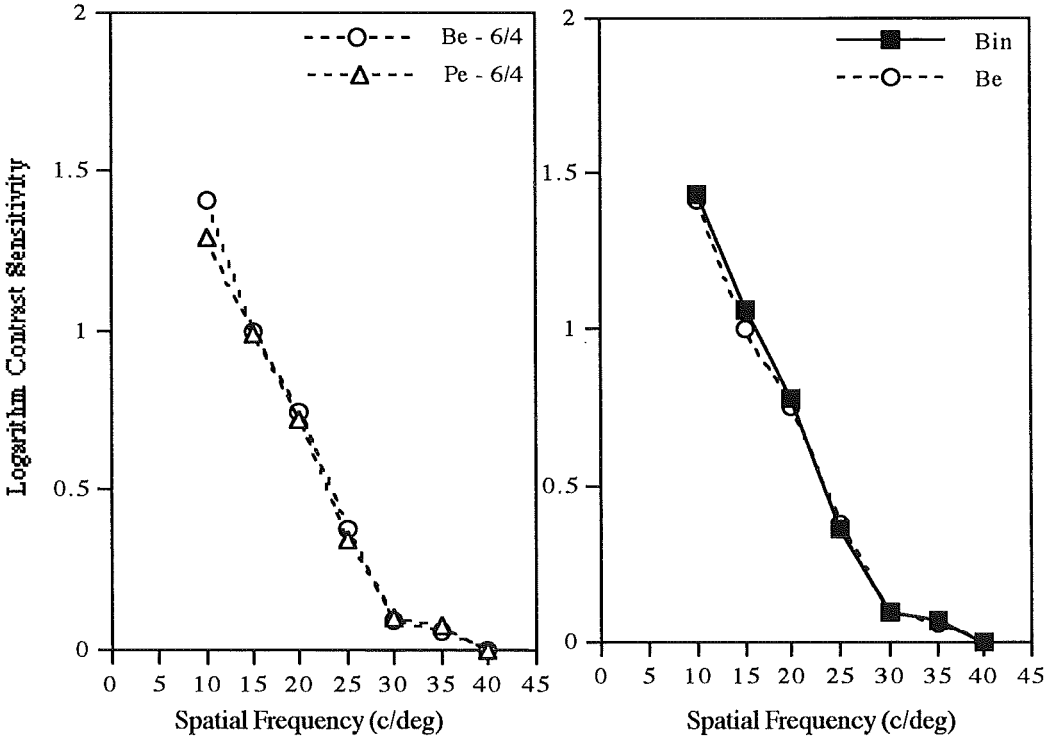


In subject number 7, the contrast sensitivity in the better eye was greater than that in the poorer eye. The mean percentage enhancement was 6%±4%SE (P.ns). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 19% ± 7%SE (P.<0.05).

Clinical Data

Refractive Error:	Nil
Visual Acuity:	RE: 6/4 LE: 6/4
Angle of Deviation:	N: BI 4^ D: BI 4^
Amplitude of Accommodation:	RE: 4.75D LE: 4.75D
Pupils:	RE: 4mm LE: 4mm

Subject 8

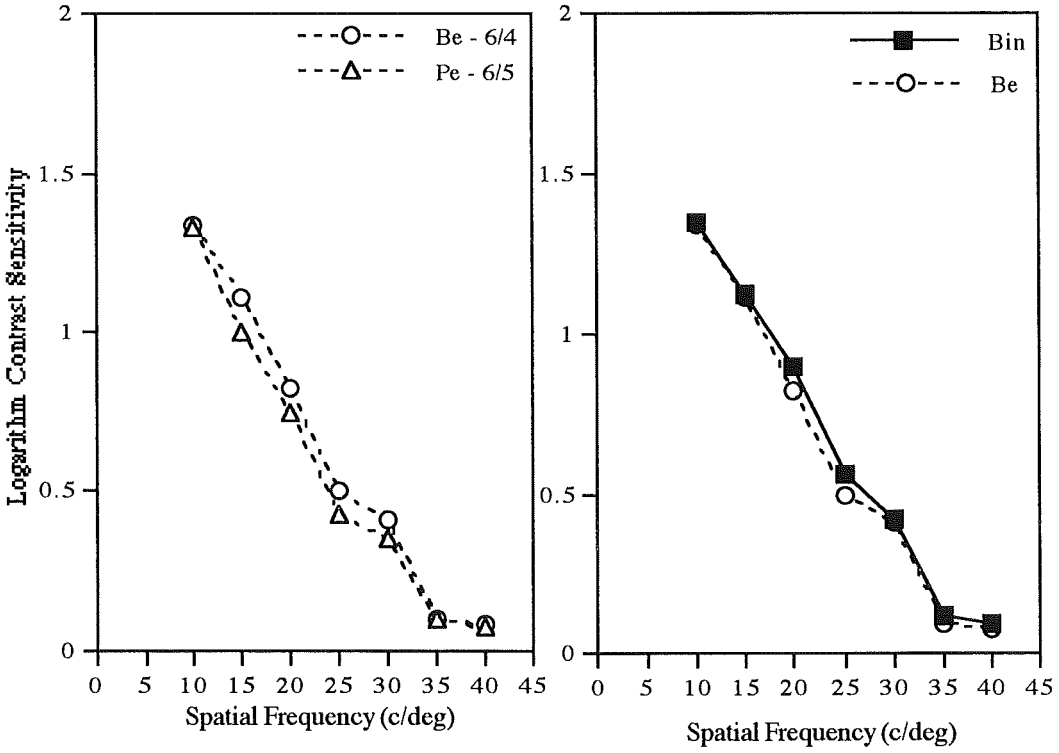


The contrast sensitivity in the better eye was greater than that in the poorer eye. The mean percentage enhancement was 7%±4%SE (P.ns). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 3% ± 2%SE (P.ns).

Clinical Data

Refractive Error:	RE: +0.50ds LE: +1.00ds
Visual Acuity:	RE: 6/4 LE: 6/4
Angle of Deviation:	N: BO 14^ D: BO 6^
Amplitude of Accommodation:	RE: 5.25D LE: 5.00D
Pupils:	RE: 5mm LE: 5mm

Subject 9

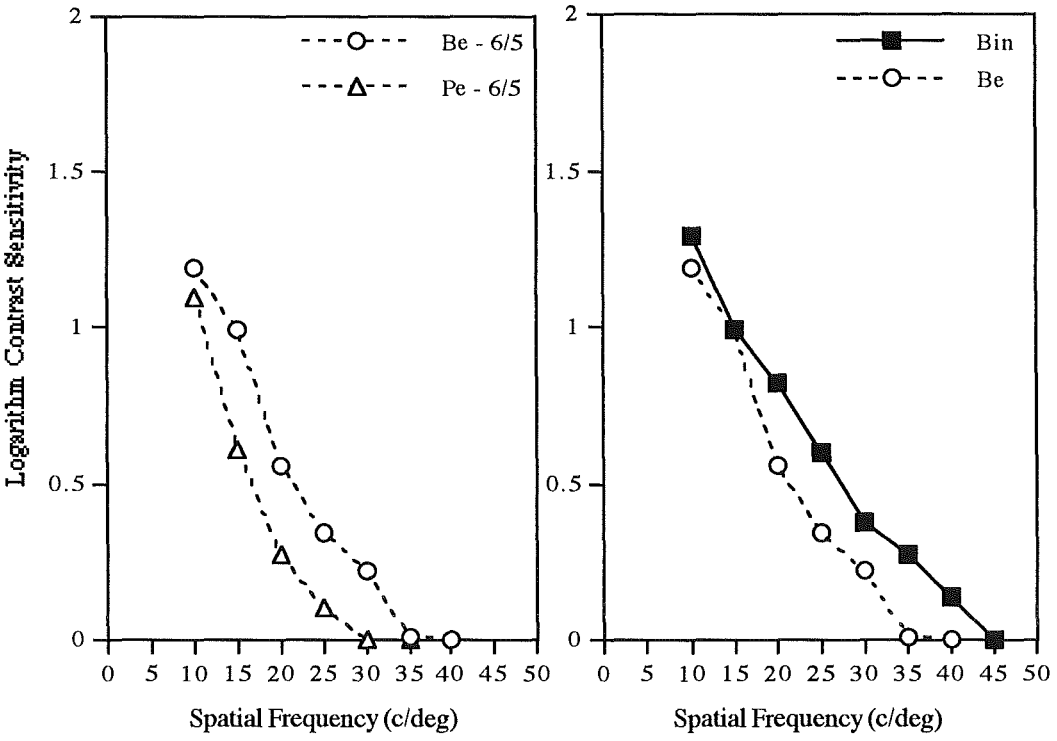


The contrast sensitivity in the better eye was significantly greater than that in the poorer eye. The mean percentage enhancement was 12%±4%SE (P.<0.05). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 7% ± 3%SE (P.<0.05).

Clinical Data

Refractive Error:	RE: -4.75ds LE: -5.50ds
Visual Acuity:	RE: 6/4 LE: 6/5
Angle of Deviation:	N: BI 4^ D: BI 2^
Amplitude of Accommodation:	RE: 1.75D LE: 3.00D
Pupils:	RE: 4mm LE: 4mm

Subject 10

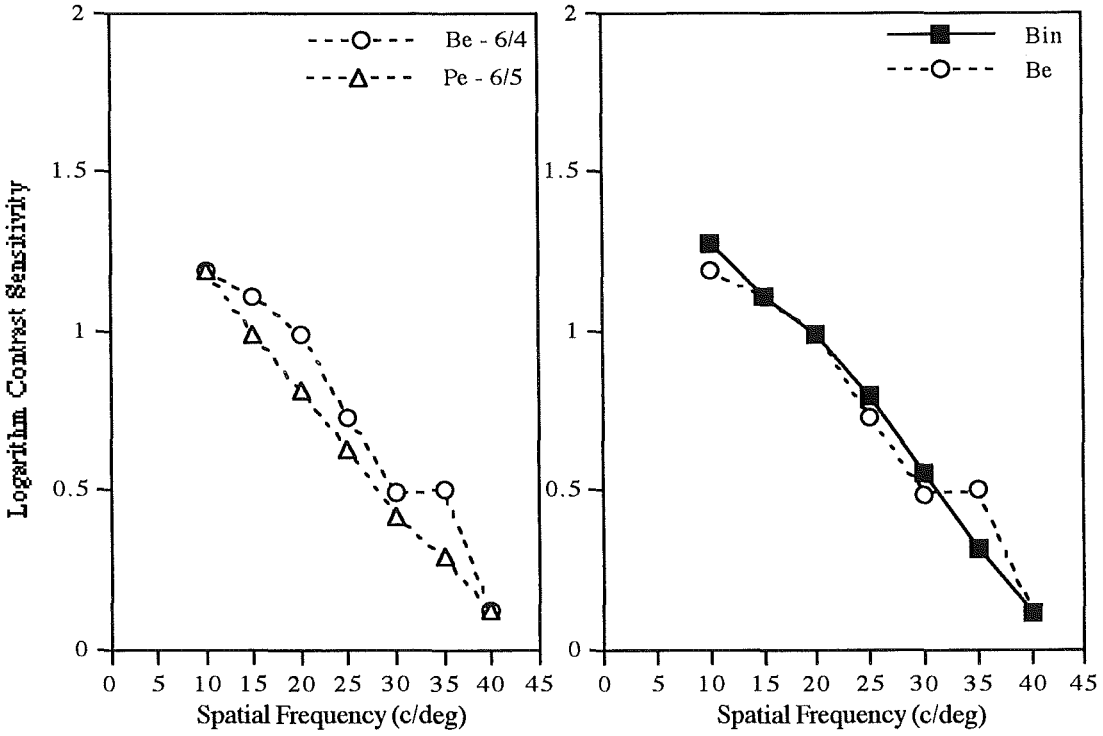


In subject number 10, the contrast sensitivity in the better eye was significantly greater than that in the poorer eye. The mean percentage enhancement was 66% 20%SE (P <0.05, paired t-test). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 32% ± 17%SE (P. ns).

Clinical Data

Refractive Error:	RE: -7.50ds LE: -8.25ds
Visual Acuity:	RE: 6/5 LE: 6/5
Angle of Deviation:	N: BO 6^ D: BI 4^
Amplitude of Accommodation:	RE: 0.75D LE: 0.75D
Pupils:	RE: 3mm LE: 3mm

Subject 11



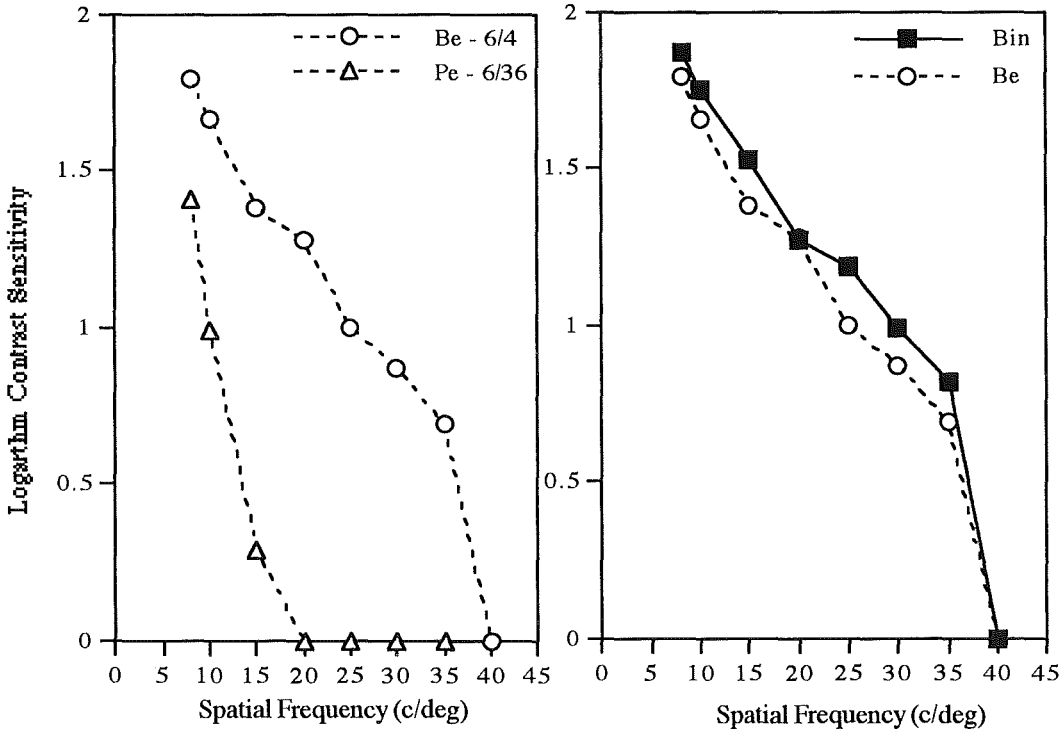
The contrast sensitivity in the better eye was significantly greater than that in the poorer eye. The mean percentage enhancement was 30%±9%SE (P.<0.05). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 3% ± 7%SE (P.ns).

Clinical Data

Refractive Error:	RE: +1.75ds LE: +2.00ds
Visual Acuity:	RE: 6/4 LE: 6/5
Angle of Deviation:	N: BI 2^ D: BI 1^
Amplitude of Accommodation:	RE: 1.50D LE: 1.00D
Pupils:	RE: 4mm LE: 4mm

6.2 Simple Anisometropic Amblyope Group

Subject 1

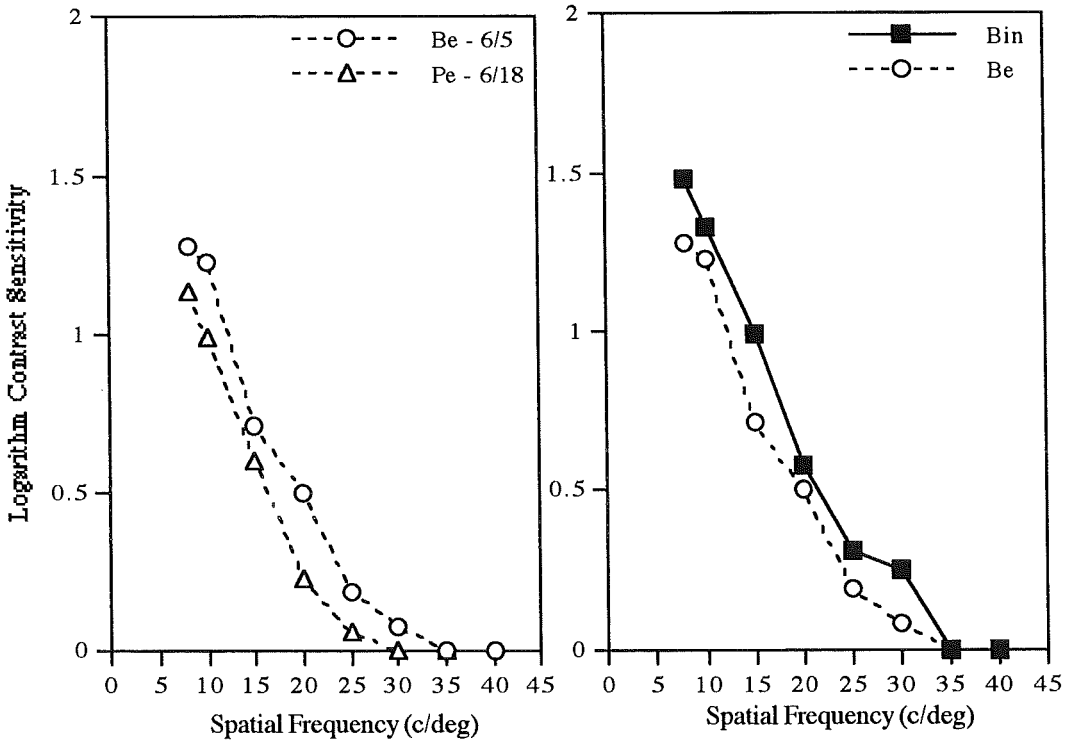


The contrast sensitivity in the poorer eye was significantly less than that in the better eye. The mean percentage reduction was 83%±5%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 29% ± 7%SE (P.<0.05).

Clinical Data

Refractive Error:	RE: -0.25ds LE: +2.50ds
Visual Acuity:	RE: 6/4 LE: 6/36
Angle of Deviation:	N: BO 6^ D: BO 6^
Amplitude of Accommodation:	RE: 5.50D LE: 5.00D
Pupils:	RE: 4mm LE: 4mm

Subject 2

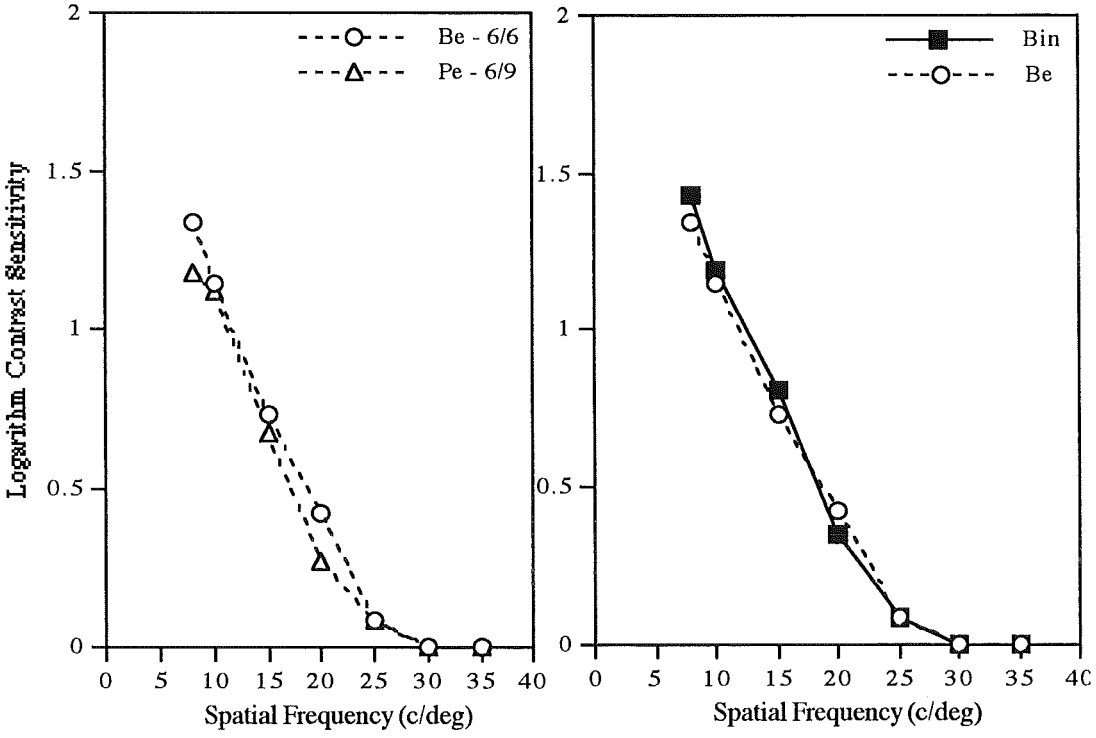


The contrast sensitivity in the poorer eye was significantly reduced compared to that in the better eye. The mean percentage reduction was 30%±5%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 47% ± 11%SE (P.<0.01).

Clinical Data

Refractive Error:	RE: +3.00ds LE: +0.50ds
Visual Acuity:	RE: 6/18 LE: 6/5
Angle of Deviation:	N: BO 2^ D: BO 2^
Amplitude of Accommodation:	RE: 2.00D LE: 2.00D
Pupils:	RE: 4mm LE: 4mm

Subject 3

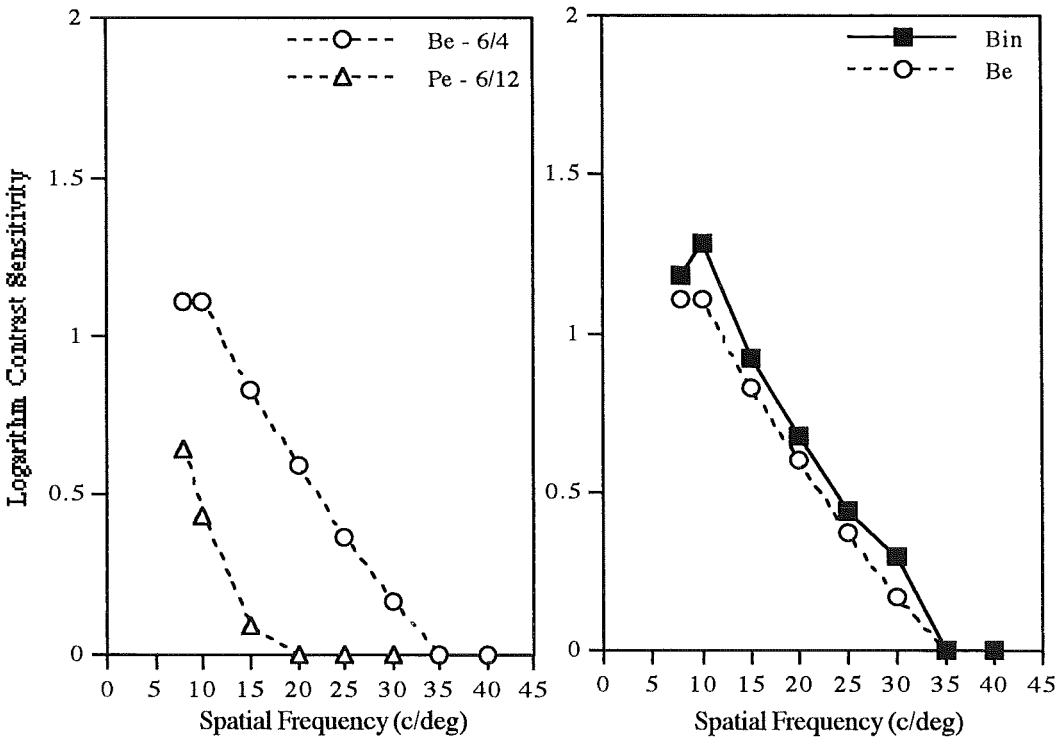


In subject number 3, the contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 13%±5%SE (P.ns). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 6% ± 6%SE (P. ns).

Clinical Data

Refractive Error:	RE: -4.00ds LE: -1.25ds
Visual Acuity:	RE: 6/9 LE: 6/6
Angle of Deviation:	N: BI 8^ D: BI 2^
Amplitude of Accommodation:	RE: 1.00D LE: 1.50D
Pupils:	RE: 3mm LE: 3mm

Subject 4

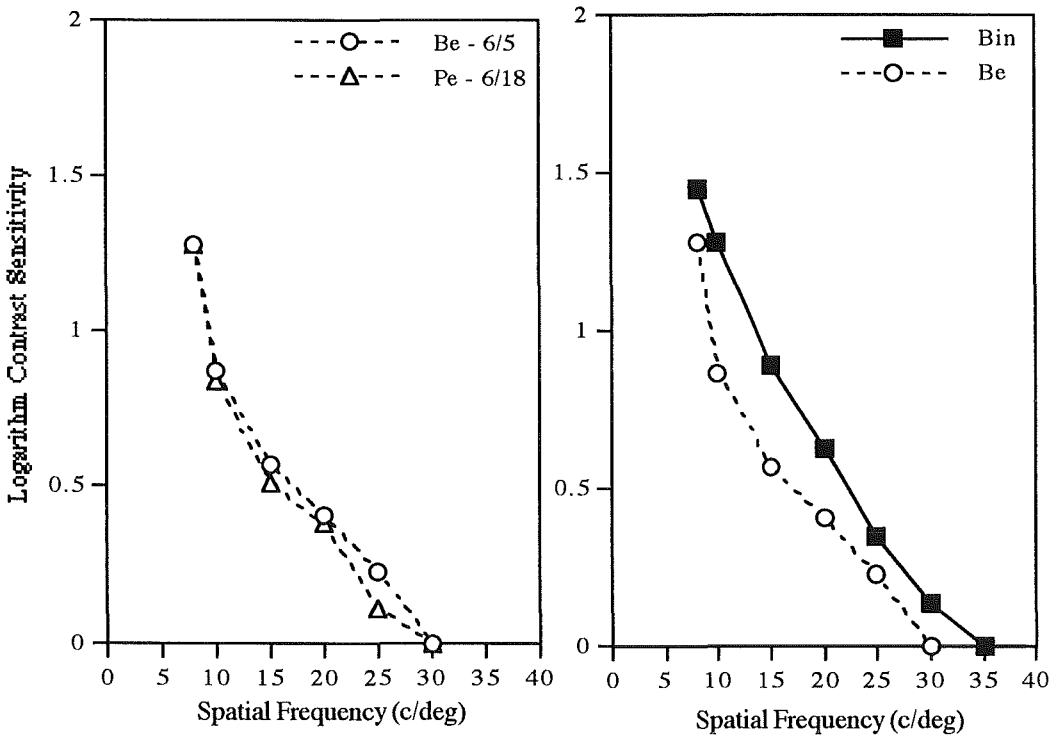


In subject number 4, the contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 65%±7%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 28% ± 5%SE (P. <0.01).

Clinical Data

Refractive Error:	RE: +2.00ds LE: +0.50ds
Visual Acuity:	RE: 6/12 LE: 6/4
Angle of Deviation:	N: BI 4^ D: BI 4^
Amplitude of Accommodation:	RE: 7.25D LE: 7.75D
Pupils:	RE: 3mm LE: 3mm

Subject 5

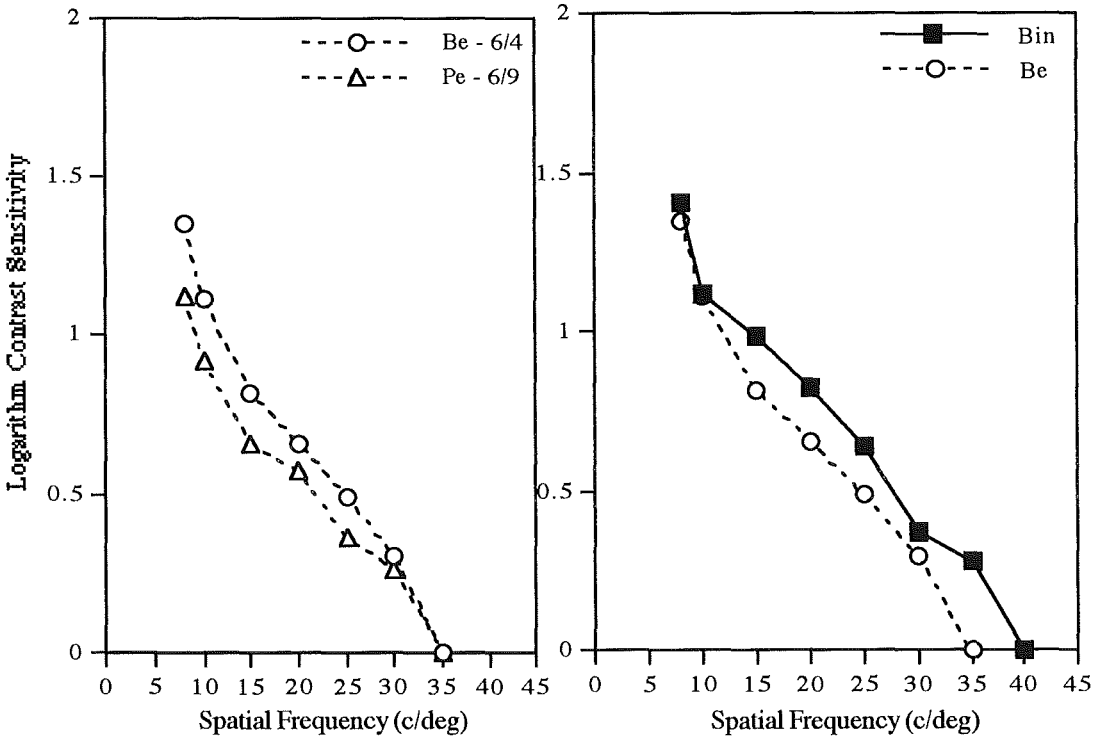


In subject number 5, the contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 8%±3%SE (P.ns). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 77% ± 20%SE (P. <0.01).

Clinical Data

Refractive Error:	RE: -4.50ds LE: -2.00ds
Visual Acuity:	RE: 6/18 LE: 6/5
Angle of Deviation:	N: BI 4^ D: BI 4^
Amplitude of Accommodation:	RE: 6.50D LE: 7.50D
Pupils:	RE: 4mm LE: 4mm

Subject 6

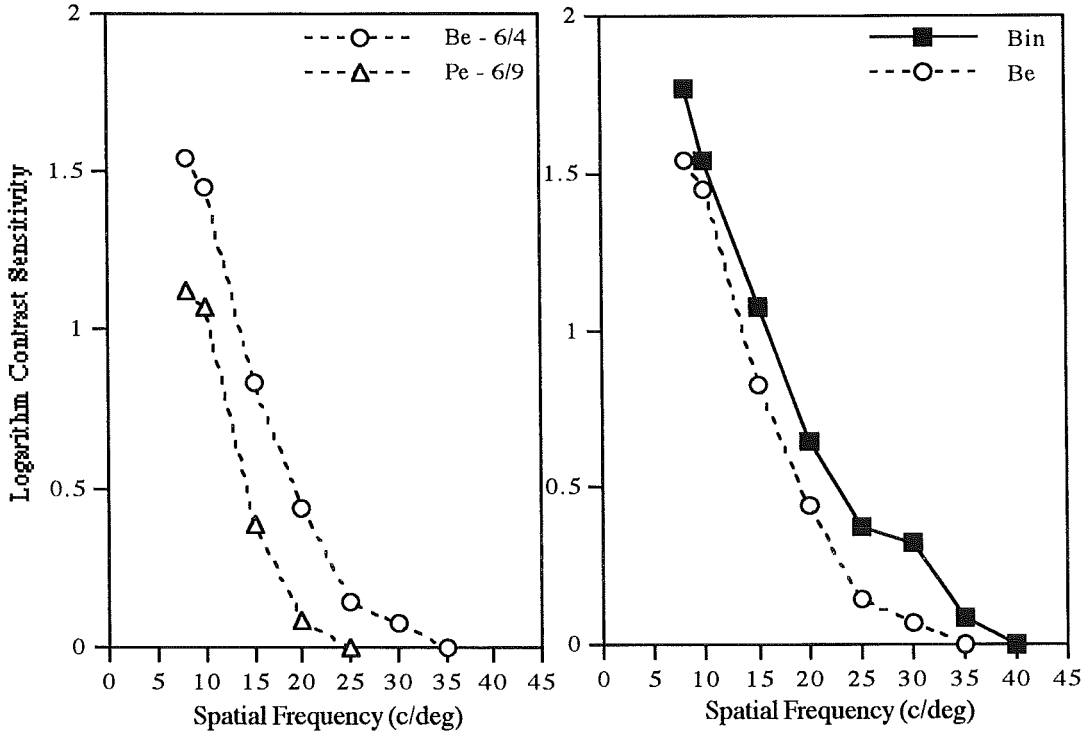


In subject number 6, the contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 27%±4%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 37% ± 11%SE (P. <0.01).

Clinical Data

Refractive Error:	RE: -1.25ds LE: -2.50ds
Visual Acuity:	RE: 6/4 LE: 6/9
Angle of Deviation:	N: BI 6^ D: BI 6^
Amplitude of Accommodation:	RE: 6.50D LE: 6.00D
Pupils:	RE: 4mm LE: 4mm

Subject 7

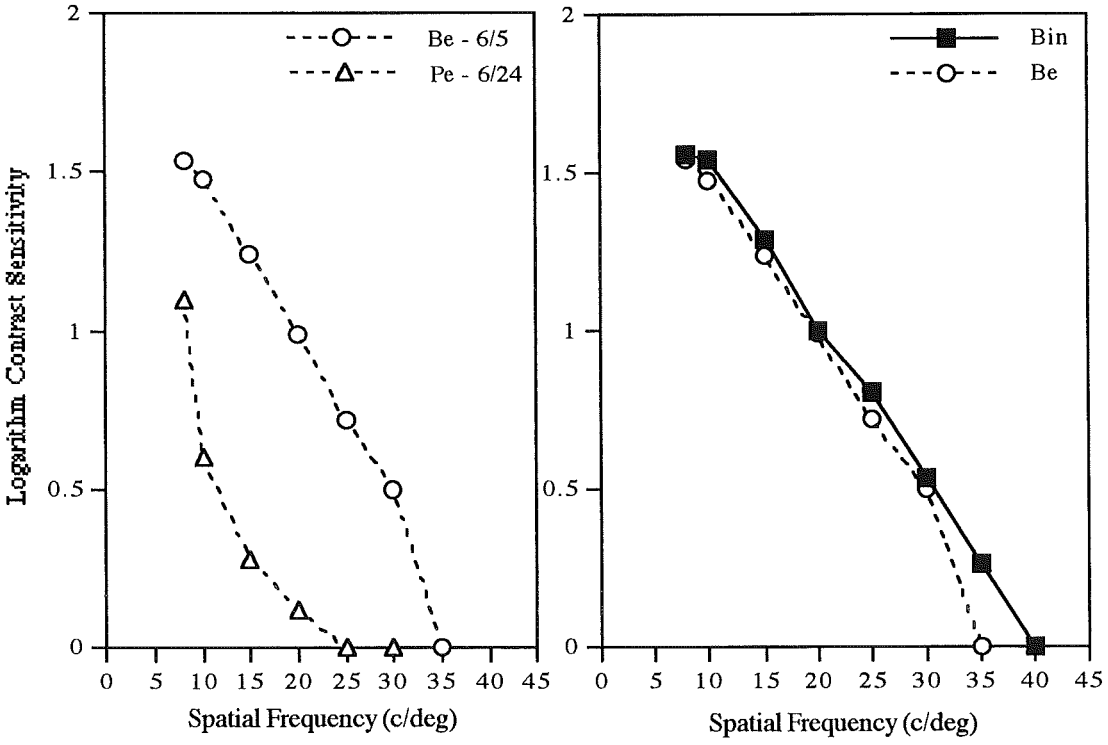


In subject number 7, the contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 50%±8%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 55% ± 9%SE (P. <0.01).

Clinical Data

Refractive Error:	RE: -0.25ds LE: --2.50ds
Visual Acuity:	RE: 6/9 LE: 6/4
Angle of Deviation:	N: BI 4^ D: BI 4^
Amplitude of Accommodation:	RE: 6.00D LE: 8.00D
Pupils:	RE: 4mm LE: 4mm

Subject 8

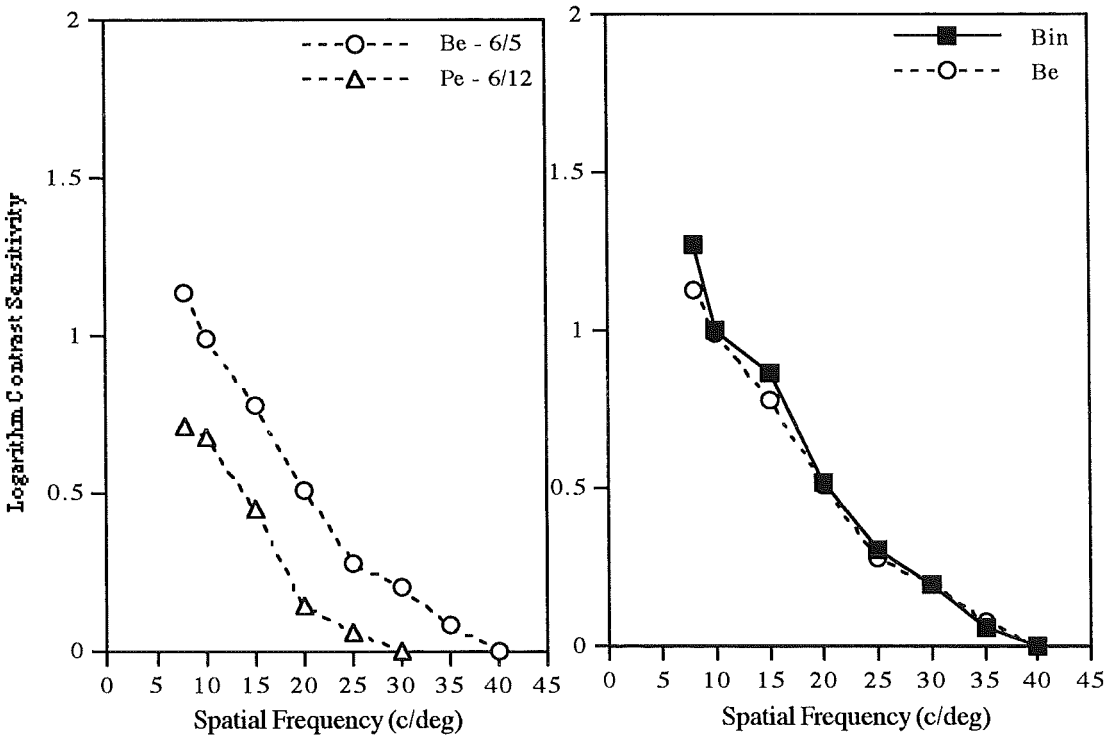


In subject number 8, the contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 79%±4%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 22% ± 11%SE (P. ns).

Clinical Data

Refractive Error:	RE: +0.50ds LE: +3.75ds
Visual Acuity:	RE: 6/5 LE: 6/24
Angle of Deviation:	N: BO 6^ D: B0 6^
Amplitude of Accommodation:	RE: 6.00D LE: 3.00D
Pupils:	RE: 4mm LE: 4mm

Subject 9



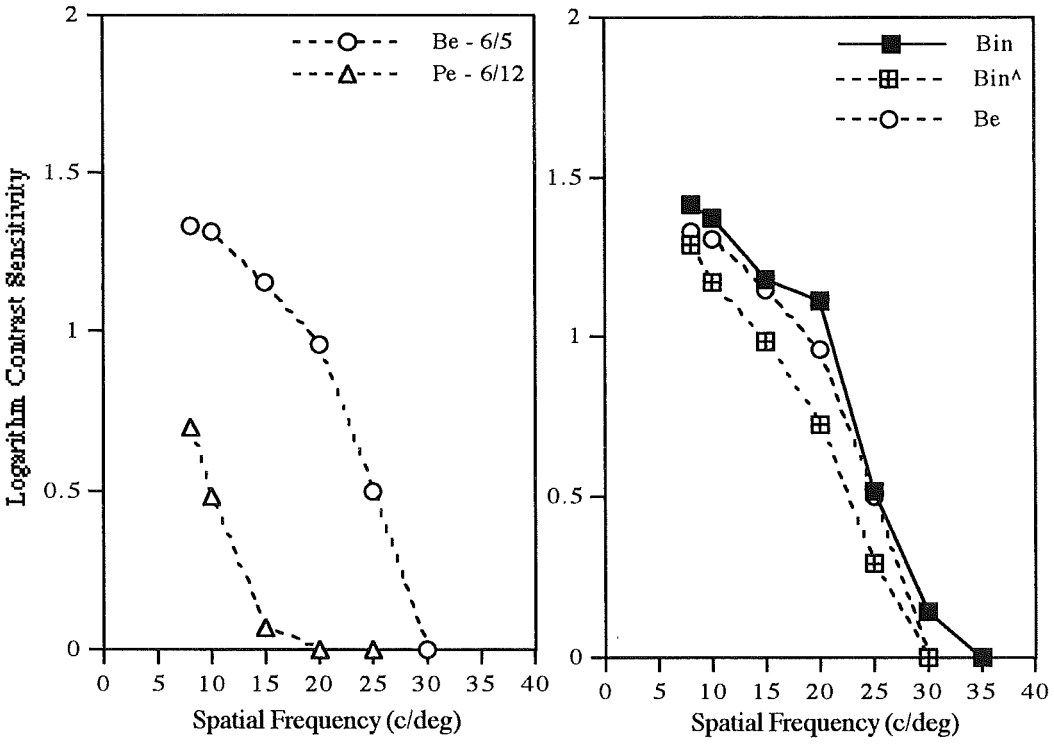
In subject number 9, the contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 50%±4%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 11% ± 6%SE (P. ns).

Clinical Data

Refractive Error:	RE: -5.00ds LE: Plano
Visual Acuity:	RE: 6/12 LE: 6/5
Angle of Deviation:	N: BI 6^ D: BI 1^
Amplitude of Accommodation:	RE: 4.50D LE: 6.00D
Pupils:	RE: 3mm LE: 3mm

6.3 Micro-esotropic Amblyope Group

Subject 1

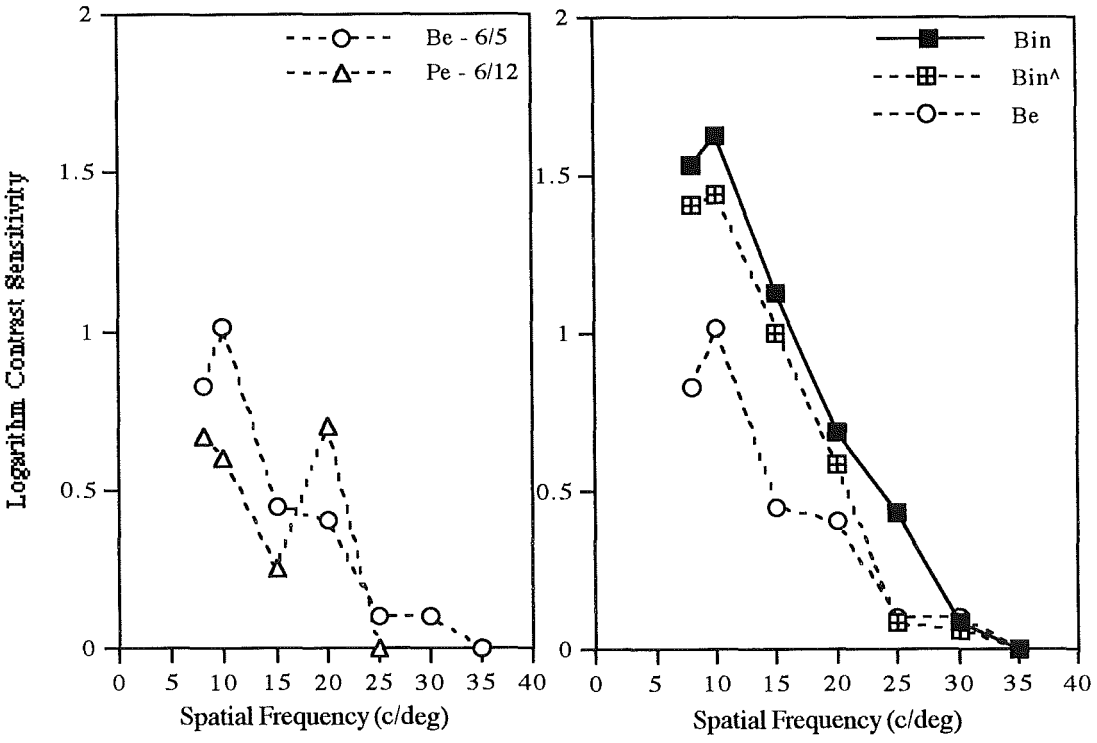


The contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 87%±3%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 15% ± 6%SE (P. <0.05). Under conditions of bifoveal stimulation (Bin^) the binocular contrast sensitivity was reduced by 37% ± 5%SE (P<0.01) compared to that achieved binocularly (Bin).

Clinical Data

Refractive Error:	RE: +2.50ds LE: Plano
Visual Acuity:	RE: 6/12 LE: 6/5
Total Angle of Deviation:	N: BO 12^ D: BO 6^
Angle of Manifest Deviation:	N: BO 6^
Amplitude of Accommodation:	RE: 4.00D LE: 7.50D
Pupils:	RE: 4mm LE: 4mm

Subject 2

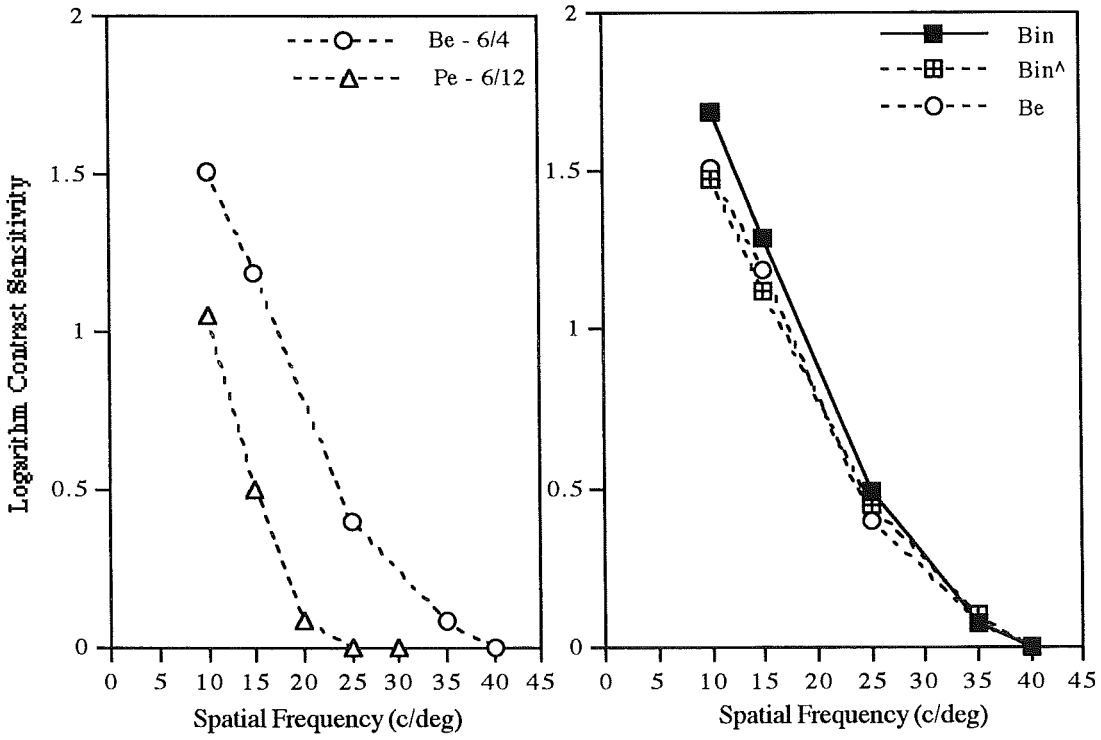


The contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 43%±7%SE (P.<0.01).The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 67% ± 30%SE (P. <0.05). Under conditions of bifoveal stimulation (Bin^) the binocular contrast sensitivity was reduced by 23% ± 7%SE (P<0.01) compared to that achieved binocularly (Bin).

Clinical Data

Refractive Error:	RE: +7.50ds LE: +5.50ds
Visual Acuity:	RE: 6/12 LE: 6/5
Total Angle of Deviation:	N: BO 6^ D: BO 4^
Angle of Manifest Deviation:	N: BO 6^
Amplitude of Accommodation:	RE: 4.75D LE: 5.25D
Pupils:	RE: 3mm LE: 3mm

Subject 3

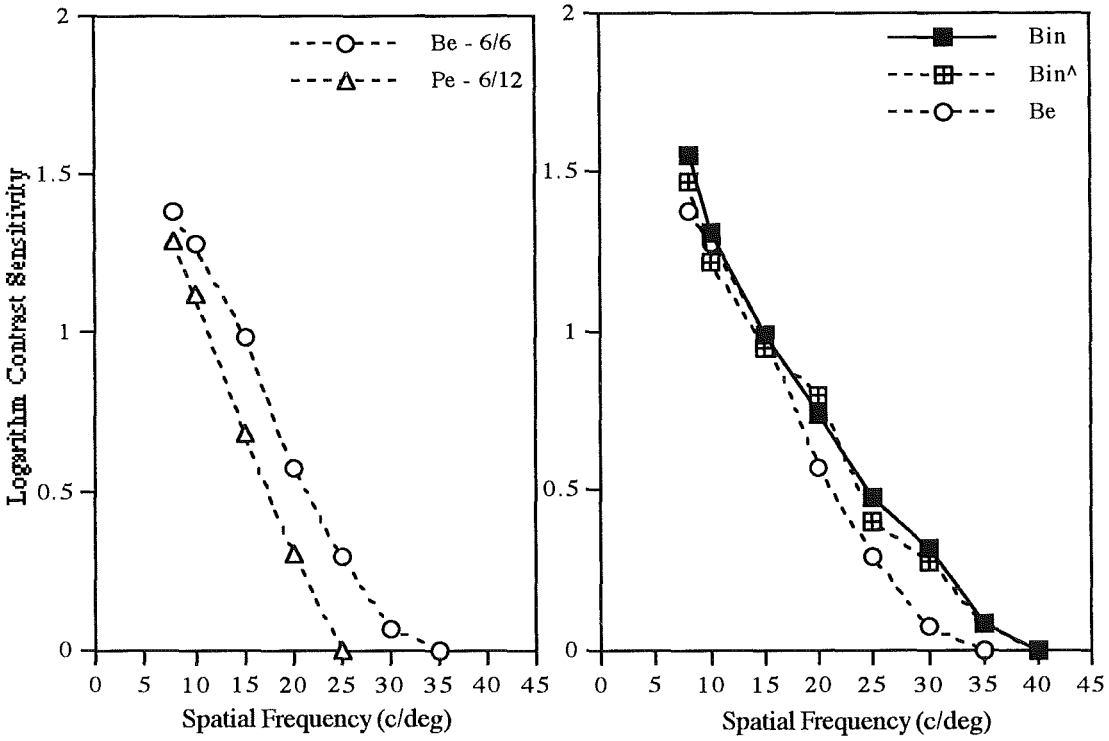


The contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 70%±6%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 25% ± 10%SE (P.ns). Under conditions of bifoveal stimulation (Bin^) the binocular contrast sensitivity was reduced by 21% ± 8%SE (P.ns) compared to that achieved binocularly (Bin).

Clinical Data

Refractive Error:	RE: +1.75ds LE: +3.50ds
Visual Acuity:	RE: 6/4 LE: 6/12
Total Angle of Deviation:	N: BO 4^ D: BO 2^
Angle of Manifest Deviation:	N: BO 4^
Amplitude of Accommodation:	RE: 8.50D LE: 8.50D
Pupils:	RE: 3mm LE: 4mm

Subject 4

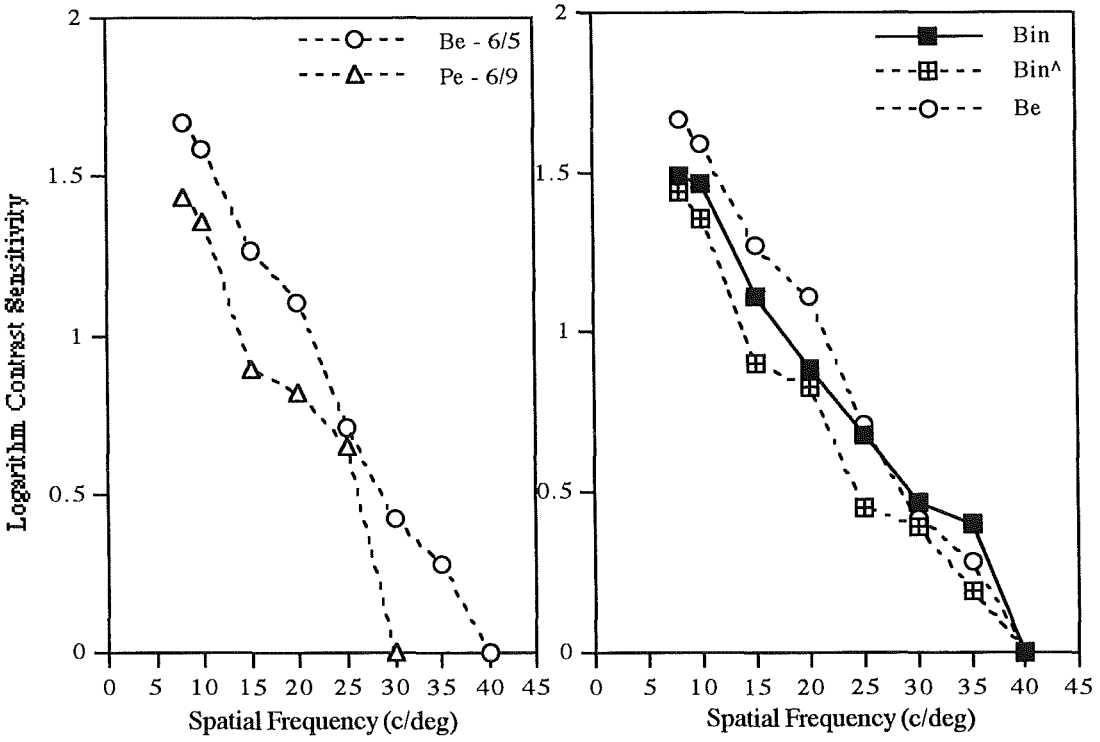


The contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 40%±6%SE (P.<0.01).The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 37% ± 10%SE (P.<0.01). Under conditions of bifoveal stimulation (Bin^) the binocular contrast sensitivity was reduced by 8% ± 4%SE (P.ns) compared to that achieved binocularly (Bin).

Clinical Data

Refractive Error:	RE: -0.50ds LE: +1.25ds	
Visual Acuity:	RE: 6/6	LE: 6/12
Total Angle of Deviation:	N: BO 10^	D: BO10^
Angle of Manifest Deviation:	N: BO 4^	
Amplitude of Accommodation:	RE: 6.50D	LE: 5.50D
Pupils:	RE: 4mm	LE: 4mm

Subject 5

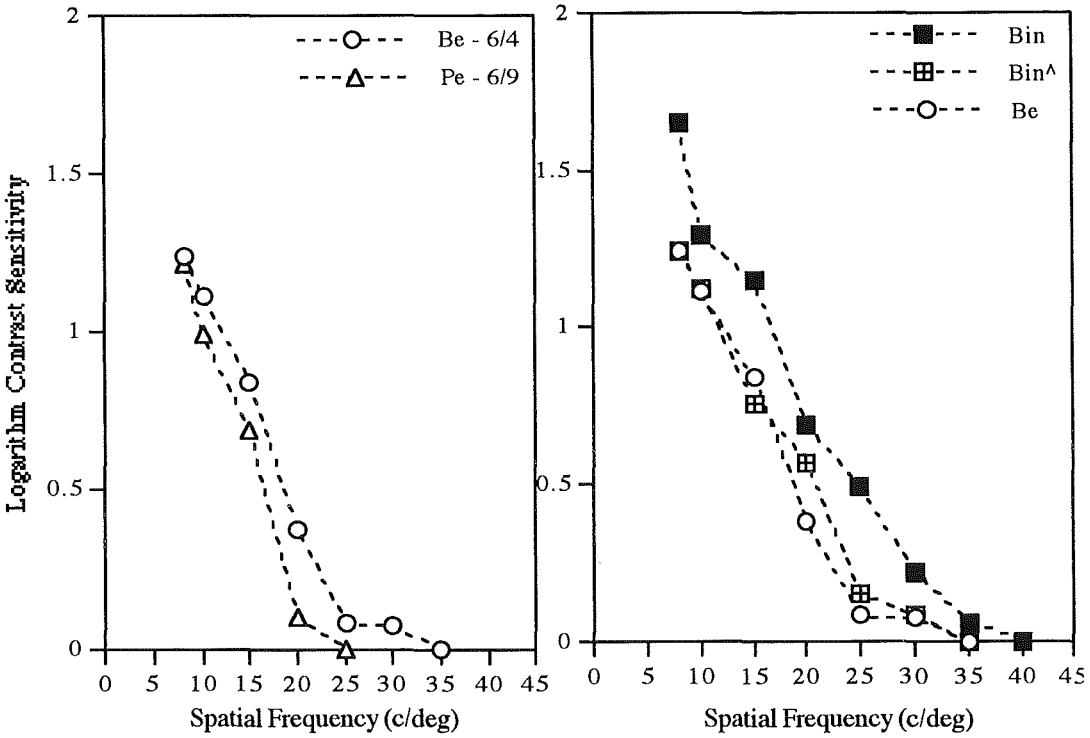


The contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 42%±8%SE (P.<0.01).The binocular logarithm contrast sensitivity (Bin) was less than that of the better eye (Be) by 26% ± 10%SE (P.ns). Under conditions of bifoveal stimulation (Bin^) the binocular contrast sensitivity was reduced by 26% ± 5%SE (P.<0.01) compared to that achieved binocularly (Bin).

Clinical Data

Refractive Error:	RE: +1.00ds LE: +0.75ds
Visual Acuity:	RE: 6/9 LE: 6/5
Total Angle of Deviation:	N: BO 6^ D: BO 6^
Angle of Manifest Deviation:	N: BO 6^
Amplitude of Accommodation:	RE: 7.75D LE: 8.00D
Pupils:	RE: 4mm LE: 4mm

Subject 6



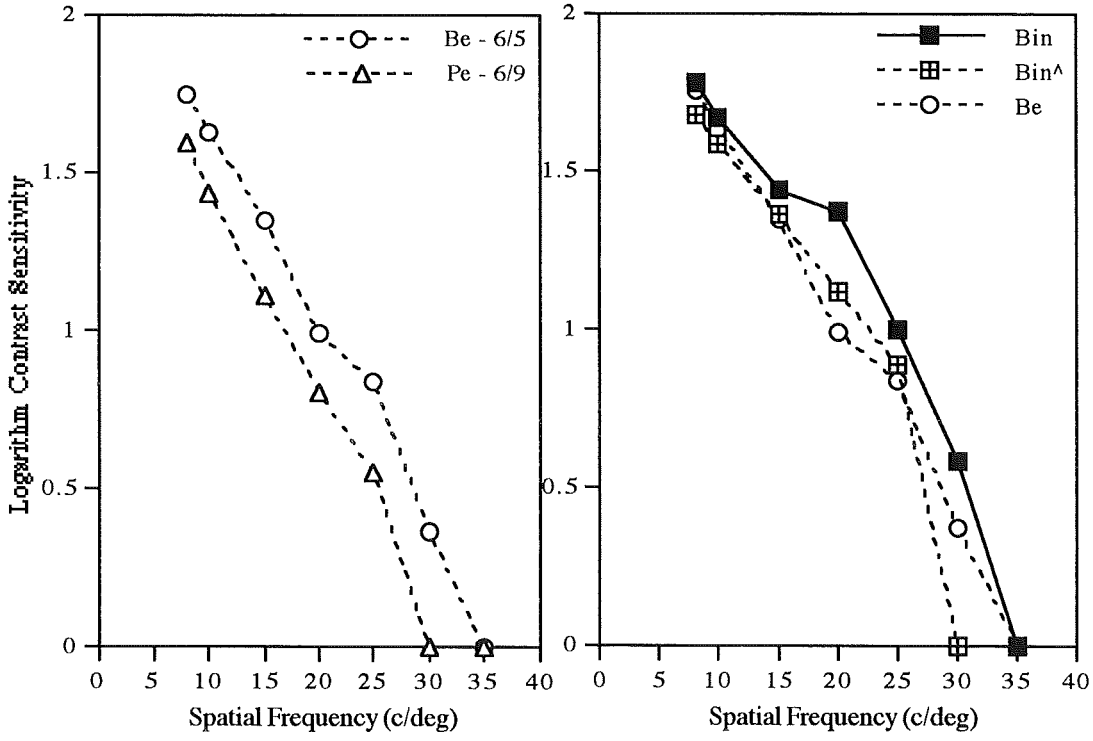
The contrast sensitivity in the poorer eye was reduced compared to that in the better eye. The mean percentage reduction was 26%±7%SE (P.<0.05).The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 90% ± 21%SE (P.<0.05). Under conditions of bifoveal stimulation (Bin^) the binocular contrast sensitivity was reduced by 39% ± 7%SE (P.<0.01) compared to that achieved binocularly (Bin).

Clinical Data

Refractive Error:	RE: +1.25ds LE: ++3.00ds
Visual Acuity:	RE: 6/6 LE: 6/12
Total Angle of Deviation:	N: BO 10^ D: BO10^
Angle of Manifest Deviation:	N: BO 4^
Amplitude of Accommodation:	RE: 6.50D LE: 5.50D
Pupils:	RE: 4mm LE: 4mm

6.4 Esotropic Amblyopes with BSV

Subject 1

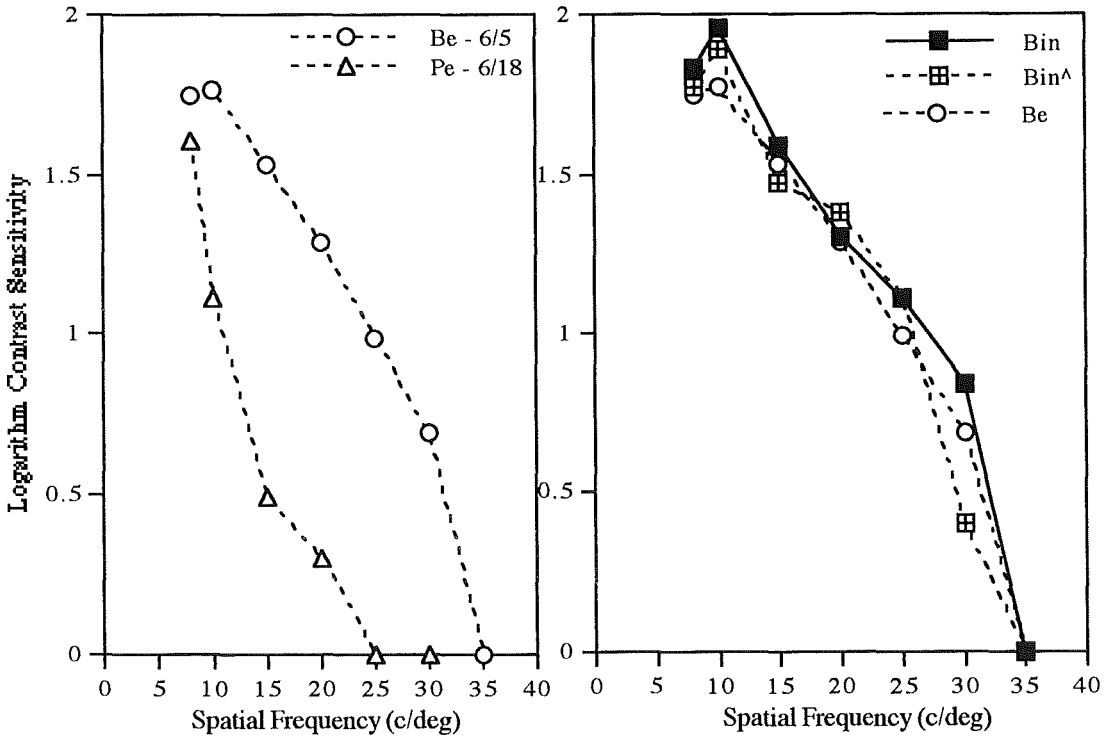


The poorer eye (Pe) was less than the better eye by 44%± 4%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 48% ± 20%SE (P.ns). Under conditions of bifoveal stimulation, (Bin^) the binocular logarithm contrast sensitivity was reduced by 37% ± 9%SE (P.<0.05) compared to that with both eyes open (Bin).

Clinical Data

Refractive Error:	RE: +4.75ds LE: +3.50ds
Visual Acuity:	RE: 6/9 LE: 6/5
Angle of Deviation:	N: BO 14^ D: BO6^
Amplitude of Accommodation:	RE: 8.25D LE: 8.50D
Pupils:	RE: 3mm LE: 3mm

Subject 2

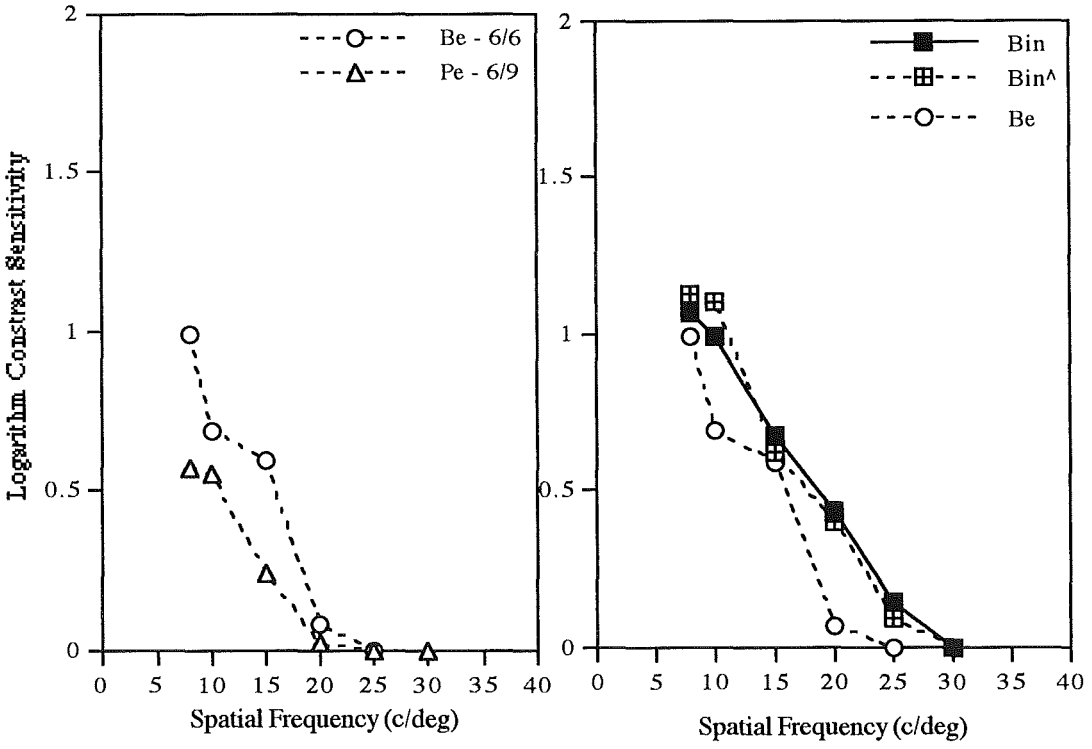


The poorer eye (Pe) was less than the better eye by 85%± 12%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 26% ± 8%SE (P. <0.05). Under conditions of bifoveal stimulation, (Bin^) the binocular logarithm contrast sensitivity was reduced by 29% ± 12%SE (P.ns) compared to that with both eyes open (Bin).

Clinical Data

Refractive Error:	RE: +1.00ds LE: +0.50ds
Visual Acuity:	RE: 6/18 LE: 6/5
Angle of Deviation:	N: BO 4^ D: BO 4^
Amplitude of Accommodation:	RE: 8.00D LE: 8.25D
Pupils:	RE: 4mm LE: 4mm

Subject 3



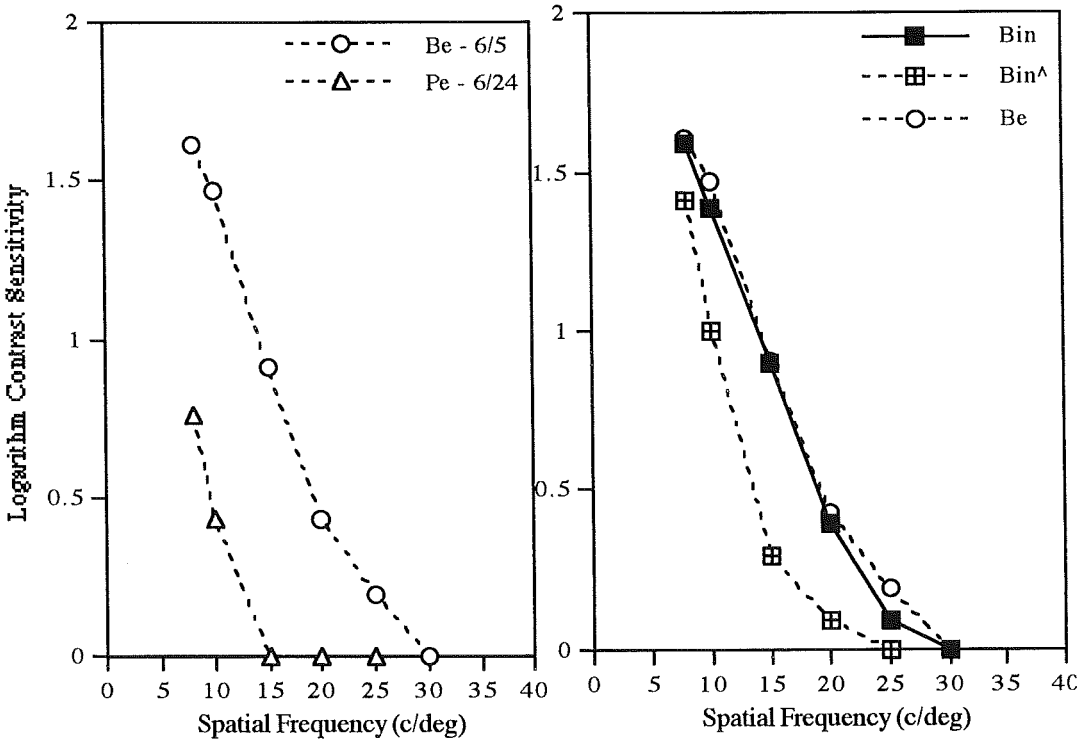
The poorer eye (Pe) was less than the better eye by 44%± 12%SE (P.ns). The binocular logarithm contrast sensitivity (Bin) exceeded that of the better eye (Be) by 59% ± 21%SE (P.< 0.05). Under conditions of bifoveal stimulation, (Bin^) the binocular logarithm contrast sensitivity was reduced by 7% ± 11%SE (P. ns) compared to that with both eyes open (Bin).

Clinical Data

Refractive Error:	RE: -0.25ds LE: -0.25ds
Visual Acuity:	RE: 6/9 LE: 6/6
Angle of Deviation:	N: BO 6^ D: BO 6^
Amplitude of Accommodation:	RE: 5.00D LE: 5.50D
Pupils:	RE: 5mm LE: 5mm

6.5 Esotropic Amblyopes without BSV

Subject 1

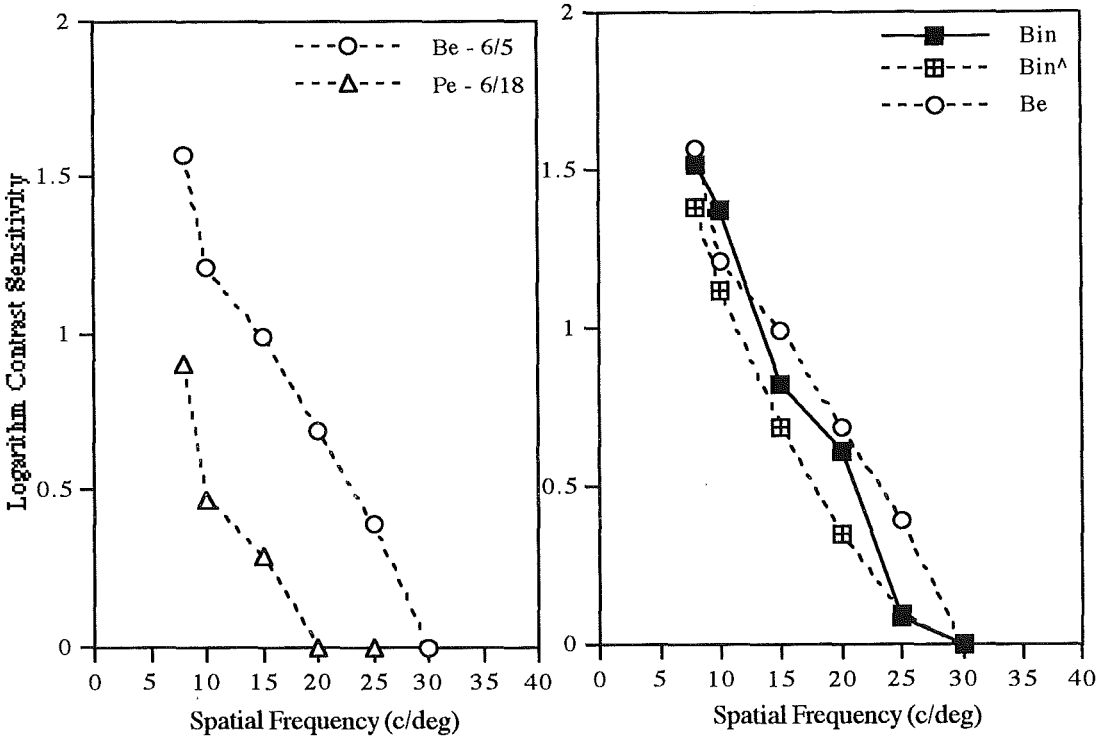


The poorer eye was less than the better eye by 73%±9% (P<0.01). The binocular logarithm contrast sensitivity (Bin) was reduced by 11% ± 3%SE (P.<0.05) compared with that of the better eye (Be). Under conditions of bifoveal stimulation, (Bin^) the binocular logarithm contrast sensitivity was reduced further by 44% ± 10% (P.<0.05) compared with the logarithm contrast sensitivity with both eyes open (Bin).

Clinical Data

Refractive Error:	RE: +5.00ds LE: +4.00ds
Visual Acuity:	RE: 6/24 LE: 6/5
Angle of Deviation:	N: BO12 l/r10^ D: BO11 l/r11^
Amplitude of Accommodation:	RE: 3.00D LE: 4.25D
Pupils:	RE: 4mm LE: 4mm

Subject 2

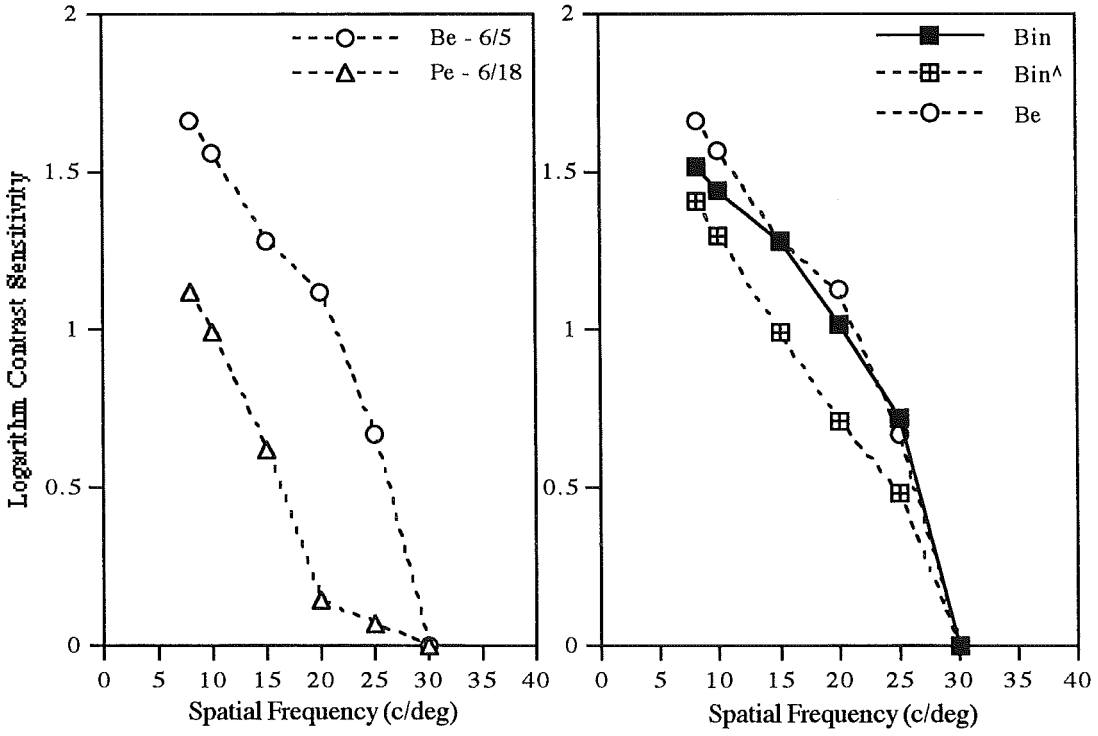


The poorer eye (Pe) was less than the better eye by 79%± 4%SE (P.< 0.01). The binocular logarithm contrast sensitivity (Bin) was less than that of the better eye (Be) by 18% ± 16%SE (P.ns). When the logarithm contrast sensitivity under conditions of bifoveal stimulation (Bin^), was compared to that with both eyes open, the binocular logarithm contrast sensitivity was reduced by 29% ± 9%SE (P<0.05).

Clinical Data

Refractive Error:	RE: -1.00ds LE: -2.75ds	
Visual Acuity:	RE: 6/18	LE: 6/5
Angle of Deviation:	N: BO 30^	D: BO 30^
Amplitude of Accommodation:	RE: 3.00D	LE: 7.50D
Pupils:	RE: 4mm	LE: 4mm

Subject 3

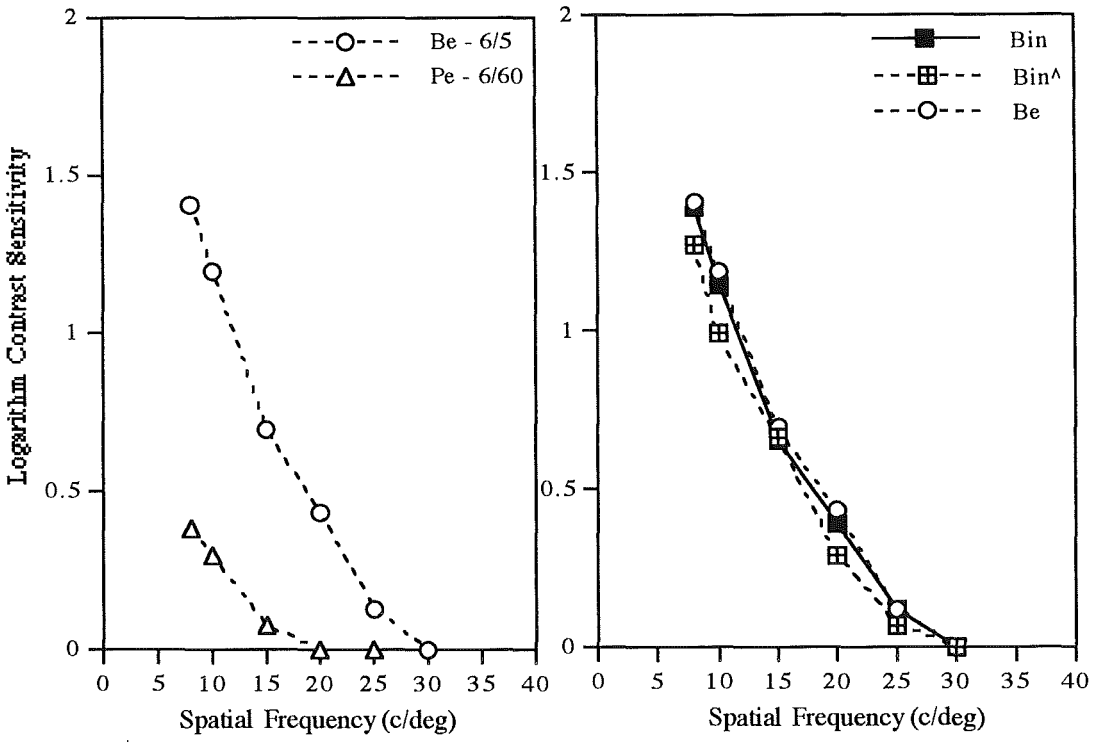


The poorer eye (Pe) was less than the better eye by 75%± 3%SE (P.<0.01). The binocular logarithm contrast sensitivity (Bin) was less than that of the better eye (Be) by 14% ± 8%SE (P. ns). Under conditions of bifoveal stimulation, (Bin^) the binocular logarithm contrast sensitivity was reduced by 34% ± 5%SE (P.<0.05) when compared to that with both eyes open.

Clinical Data

Refractive Error:	RE: +5.00ds LE: +6.50ds	
Visual Acuity:	RE: 6/5	LE: 6/18
Angle of Deviation:	N: BO10 l/r4^	D: BO 10 l/r4^
Amplitude of Accommodation:	RE: 7.50D	LE: 8.00D
Pupils:	RE: 5mm	LE: 5mm

Subject 4

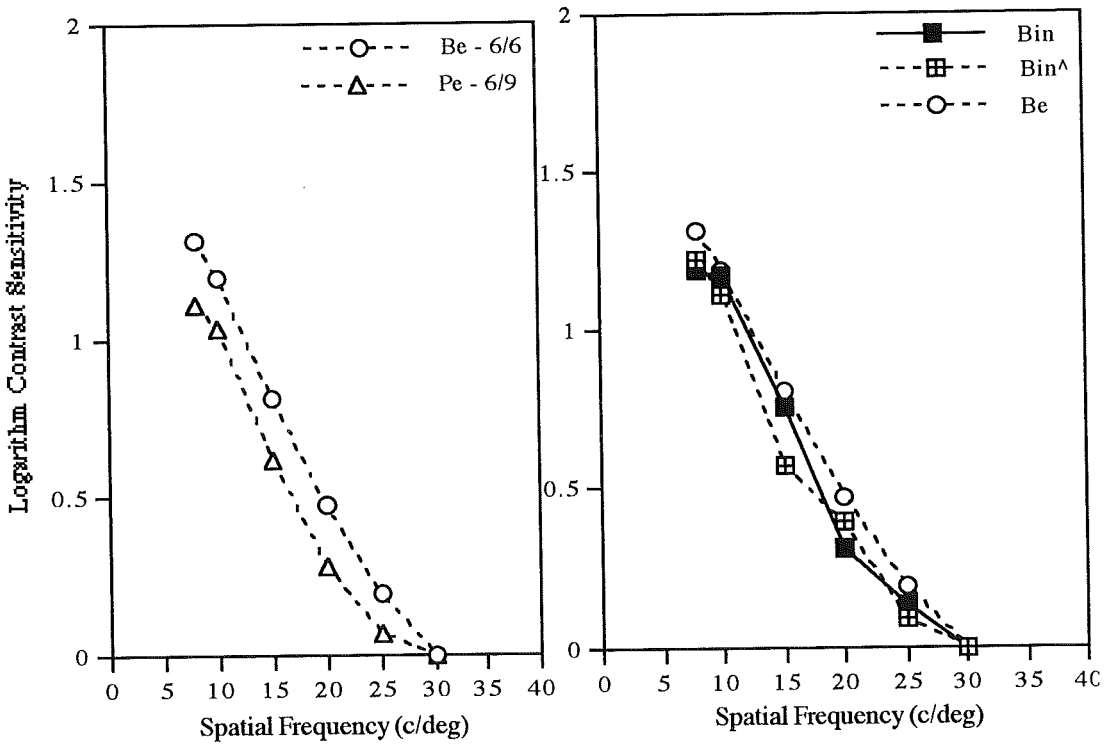


The poorer eye (Pe) was less than the better eye by 68%± 10%SE (P.< 0.01). The binocular logarithm contrast sensitivity (Bin) was less than that of the better eye (Be) by 7%±2%SE (P.< 0.05). Under conditions of bifoveal stimulation, (Bin^) the binocular logarithm contrast sensitivity was reduced by 13% ± 6%SE (P. <0.05) when compared to that with both eyes open (Bin).

Clinical Data

Refractive Error:	RE: +1.50DS LE: -0.75DS
Visual Acuity:	RE: 6/60 LE: 6/5
Visuoscopy;	RE: 2 degrees from fovea
Angle of Deviation:	N: BO 6^ D: BO 6^
Amplitude of Accommodation:	RE: 2.75D LE: 7.00D
Pupils:	RE: 5mm LE: 5mm

Subject 5



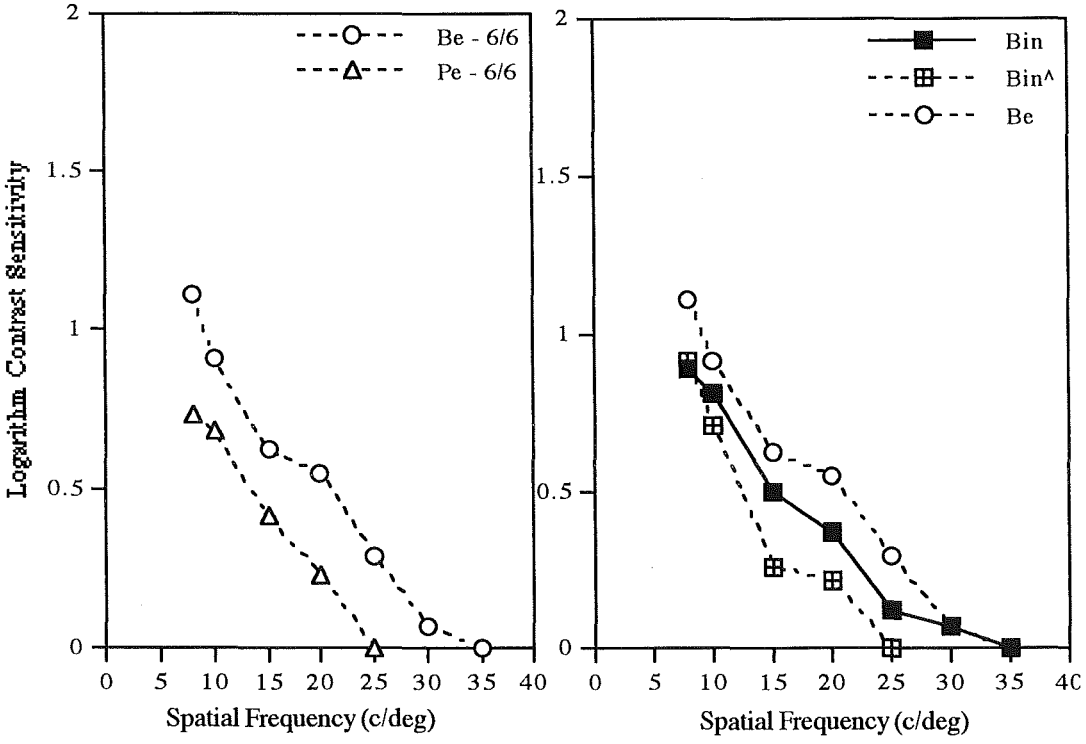
The poorer eye (Pe) was less than the better eye by 31%± 2%SE (P.< 0.01). The binocular logarithm contrast sensitivity (Bin) was less than that of the better eye (Be) by 17% ± 5%SE (P.<0.05). Under conditions of bifoveal stimulation, (Bin^) there was no significant difference in the bifoveal logarithm contrast sensitivity (Bin^) when compared to that with both eyes open (Bin) 4% ± 9%SE (P.ns).

Clinical Data

Refractive Error:	RE: -1.00ds LE: -1.50ds	
Visual Acuity:	RE: 6/6	LE: 6/9
Angle of Deviation:	N: BO 6^	D: BO 6^
Amplitude of Accommodation:	RE: 1.50D	LE: 1.25D
Pupils:	RE: 4mm	LE: 4mm

6.6 Non-Amblyopic Esotropes without Binocular Single Vision

Subject 1

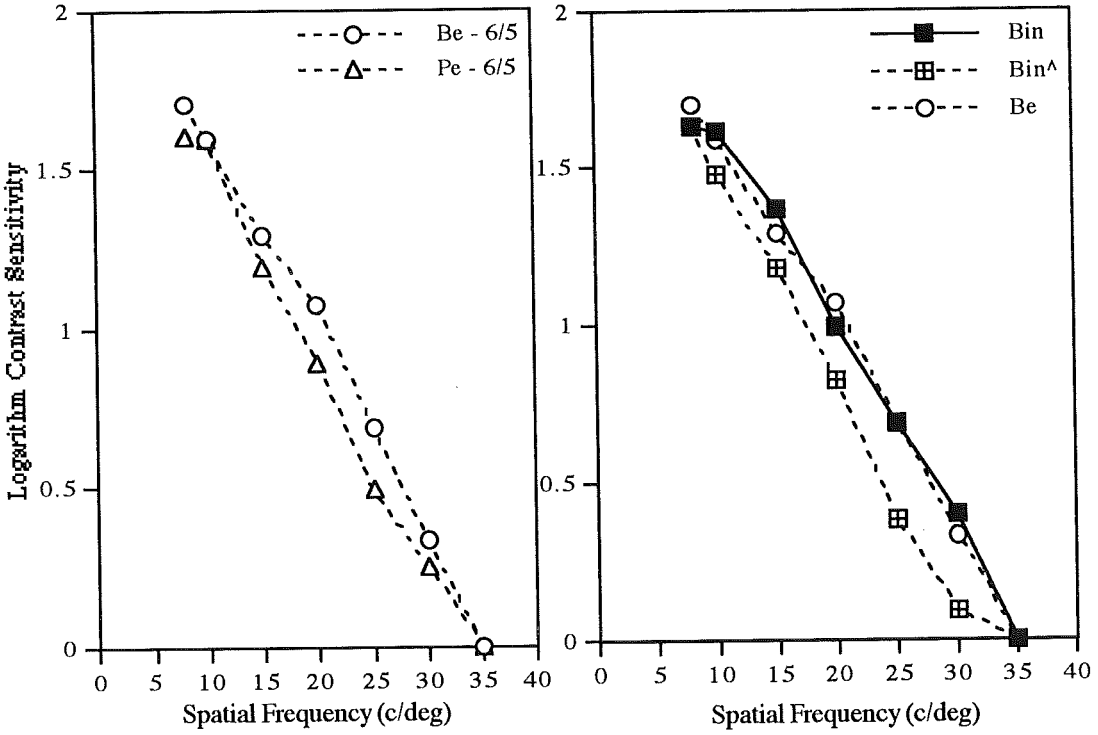


The logarithm contrast sensitivity in the poorer eye (Pe) was less than that of the better eye by 44%± 5%SE (P.< 0.01). The binocular contrast sensitivity (Bin) was less than that of the better eye (Be) by 26% ± 6%SE (P. < 0.05). Under conditions of bifoveal stimulation (Bin^) when compared to that with both eyes open (Bin) the bifoveal contrast sensitivity was less than the binocular contrast sensitivity by 24%±8% (P<0.01).

Clinical Data

Refractive Error:	RE: Nil LE: Nil	
Visual Acuity:	RE: 6/6	LE: 6/6
Angle of Deviation:	N: BO 18^	D: BO 12^
Amplitude of Accommodation:	RE: 8.00D	LE: 8.00D
Pupils:	RE: 4mm	LE: 4mm

Subject 2

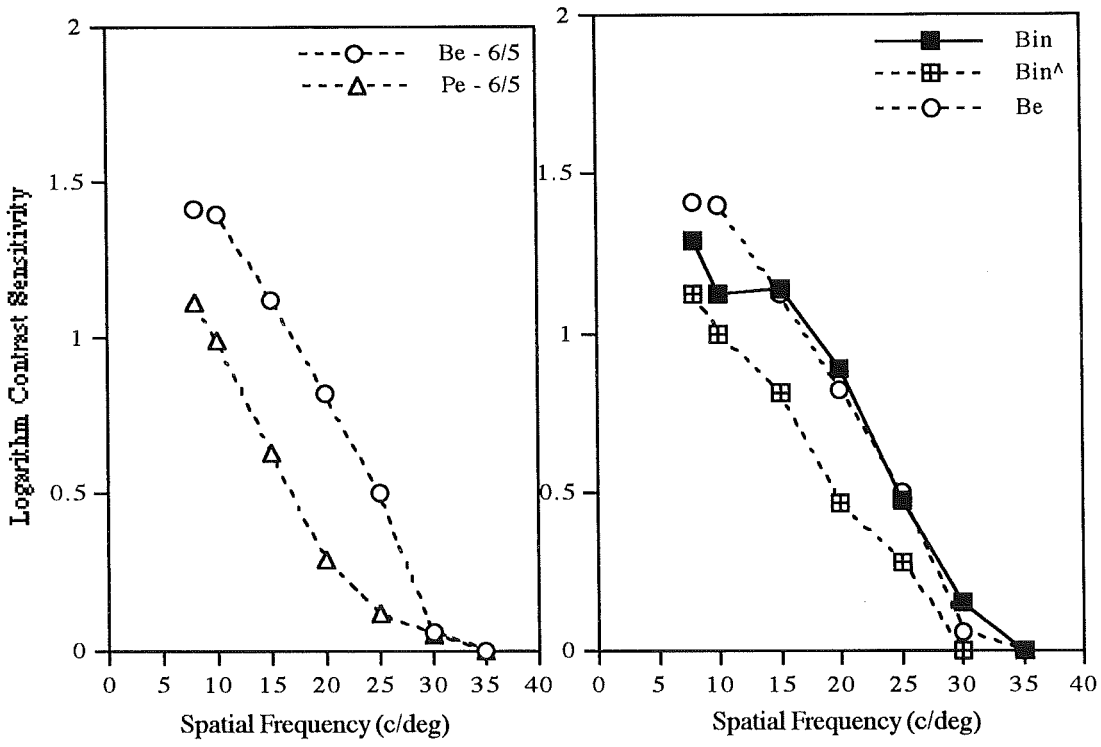


The contrast sensitivity in the poorer eye (Pe) was less than that of the better eye by 22%± 4%SE (P.< 0.01). There was no significant increase in binocular contrast sensitivity (Bin) +2% ± 6% (P.ns) when compared to that of the better eye (Be). However, the bifoveal contrast sensitivity (Bin^) was less than that achieved under binocular condions (Bin) by 33%±8% (P<0.05).

Clinical Data

Refractive Error:	RE: Nil LE: Nil	
Visual Acuity:	RE: 6/5	LE: 6/5
Angle of Deviation:	N: BO 25^ L/R 16^	D: BO 25^ L/R 16^
Amplitude of Accommodation:	RE: 6.00D	LE: 6.50D
Pupils:	RE: 4mm	LE: 4mm

Subject 3

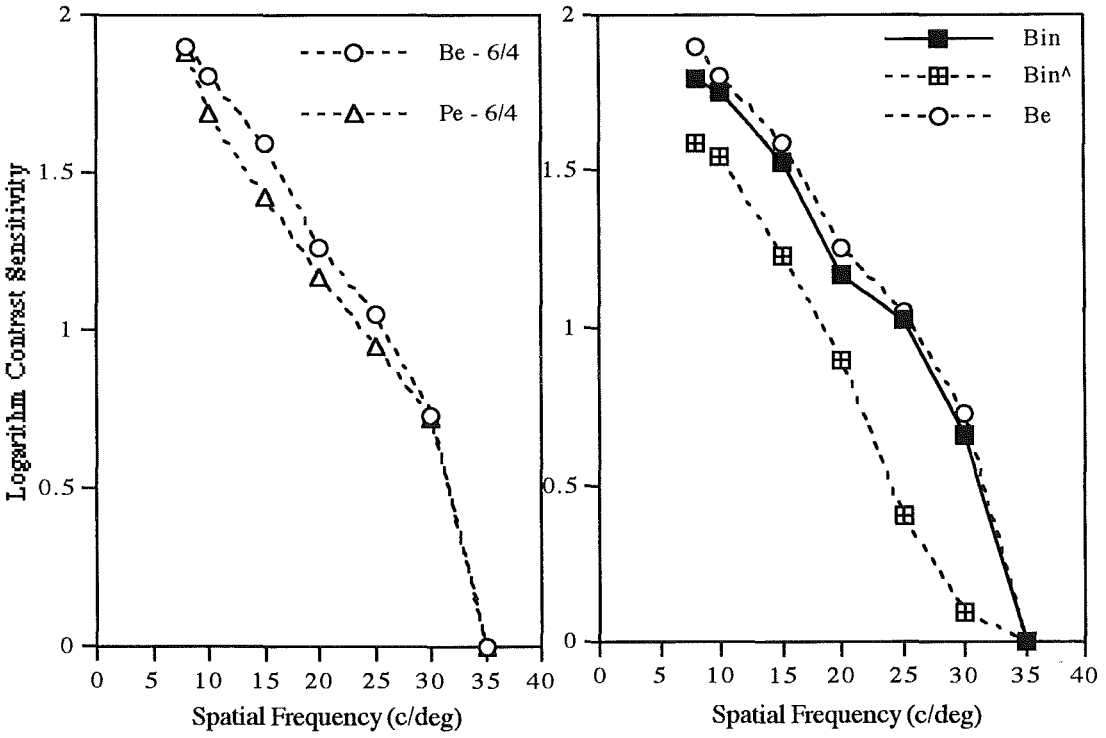


The contrast sensitivity in the poorer eye (Pe) was less than that of the better eye by 51%± 9%SE (P.< 0.01).The binocular logarithm contrast sensitivity (Bin) was reduced marginally and not significantly by 5% ± 11% (P.ns) when compared to that of the better eye (Be). Under conditions of bifoveal stimulation (Bin^) the contrast sensitivity was less than that achieved binocularly (Bin) by 39%±5% (P<0.01).

Clinical Data

Refractive Error:	RE: -1.50DS LE: -1.75ds	
Visual Acuity:	RE: 6/5	LE: 6/5
Angle of Deviation:	N: BO 16^	D: BO 12^
Amplitude of Accommodation:	RE: 9.00D	LE: 9.25D
Pupils:	RE: 5mm	LE: 5mm

Subject 4



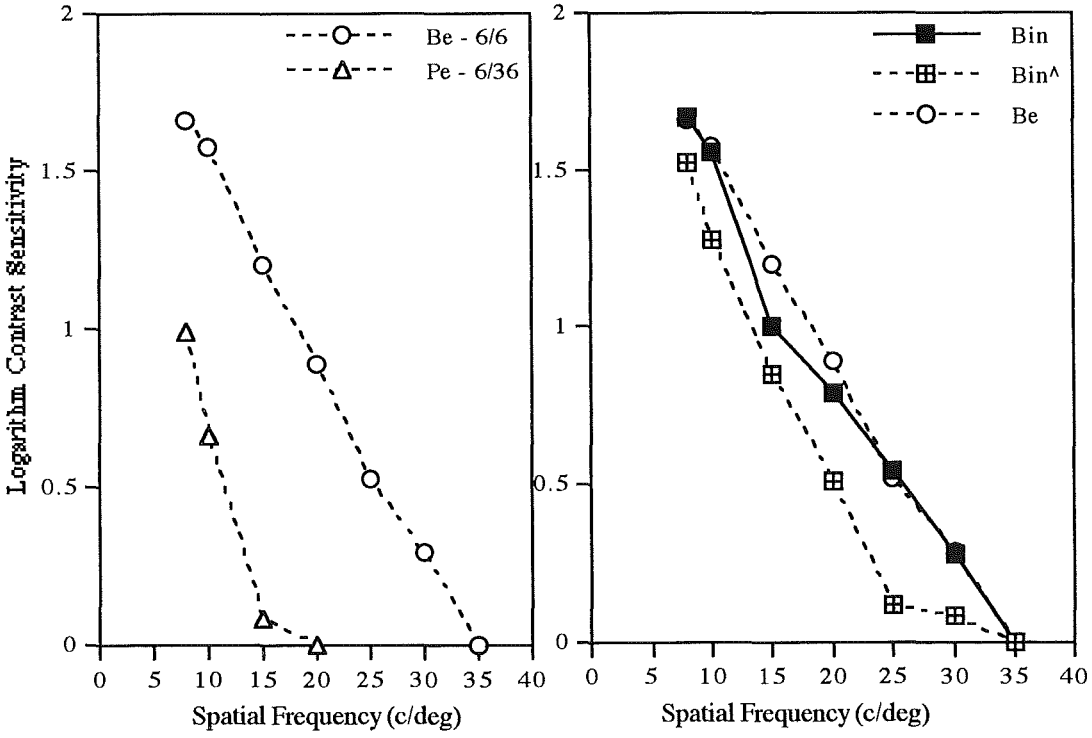
The contrast sensitivity in the poorer eye (Pe) was less than that of the better eye by 18%± 3%SE (P.< 0.05. The binocular logarithm contrast sensitivity (Bin) was reduced significantly reduced by 14% ± 2% (P <0.01) when compared to that of the better eye (Be). Under conditions of bifoveal stimulation, the contrast sensitivity was also reduced. The magnitude of reduction was 53%±6% (P<0.01).

Clinical Data

Refractive Error:	RE: +5.25ds LE: +4.75ds	
Visual Acuity:	RE: 6/4	LE: 6/4
Angle of Deviation:	N: BO 18^	D: BO 18^
Amplitude of Accommodation:	RE: 6.50D	LE: 6.75D
Pupils:	RE: 4mm	LE: 4mm

6.7 Exotropic Amblyopes without BSV

Subject 1

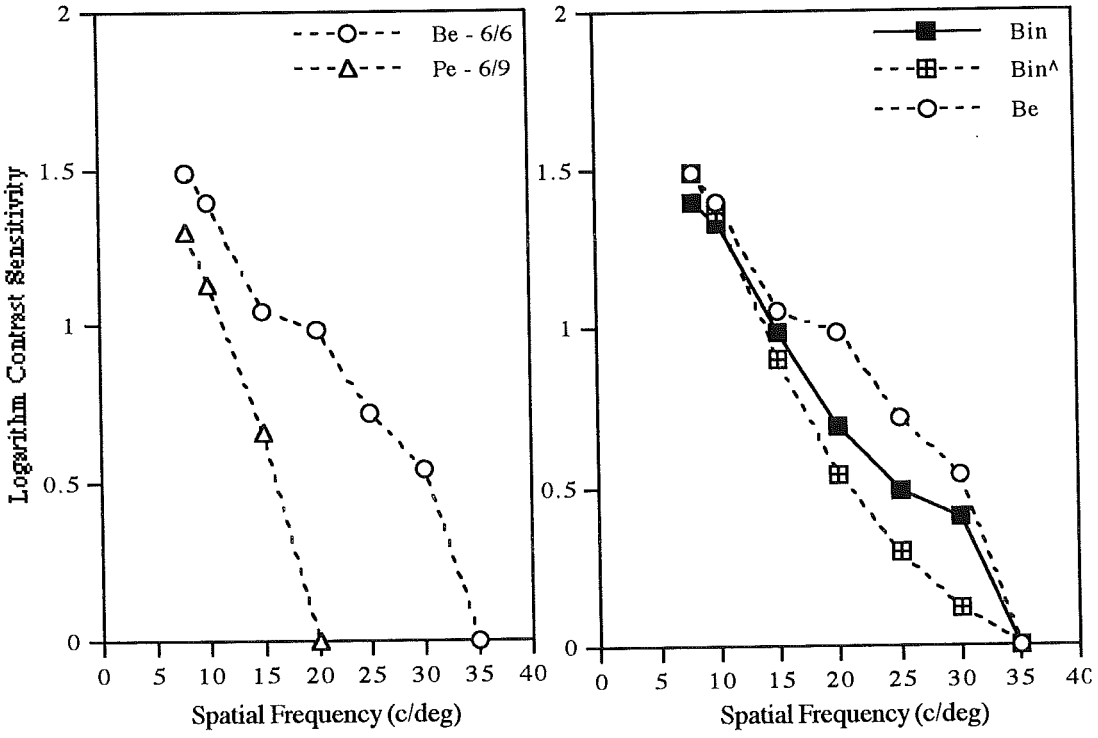


The contrast sensitivity in the poorer eye (Pe) was less than that of the better eye by 87%± 3%SE (P.< 0.01). The binocular logarithm contrast sensitivity (Bin) was reduced significantly reduced by 11% ± 7% (P. ns) when compared to that of the better eye (Be). Under conditions of bifoveal stimulation, the contrast sensitivity was also reduced. The magnitude of reduction was 44%±5% (P< 0.01).

Clinical Data

Refractive Error:	RE: +1.50DC LE: +1.75DS/+1.25DC	
Visual Acuity:	RE: 6/6	LE: 6/36
Angle of Deviation:	N: BI 16^ R/L 6^	D: BI 16^ R/L 8^
Amplitude of Accommodation:	RE: 2.0D	LE: 2.0D
Pupils:	RE: 4mm	LE: 4mm

Subject 2



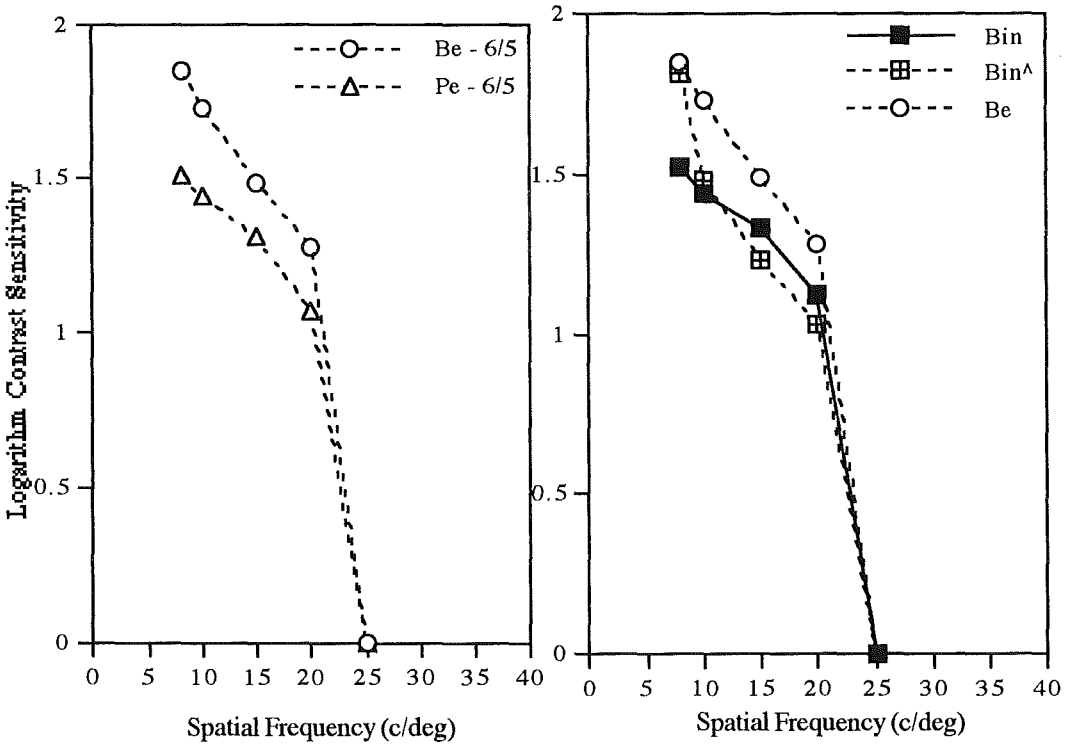
The contrast sensitivity in the poorer eye (Pe) was less than that of the better eye by 56%± 12%SE (P.< 0.05). The binocular logarithm contrast sensitivity (Bin) was reduced significantly reduced by 29% ± 6% (P <0.01) when compared to that of the better eye (Be). Under conditions of bifoveal stimulation, the bifoveal contrast sensitivity was also reduced. The magnitude of reduction was 19%±11% (P. ns)

Clinical Data

Refractive Error:	RE: +1.00DS/+3.50DC LE: +2.25DC	
Visual Acuity:	RE: 6/9	LE: 6/6
Angle of Deviation:	N: BI 18^	D: BI 18^
Amplitude of Accommodation:	RE: 7.0D	LE: 7.0D
Pupils:	RE: 4mm	LE: 4mm

6.8 Non-Amblyopic Exotropes without BSV

Subject 1

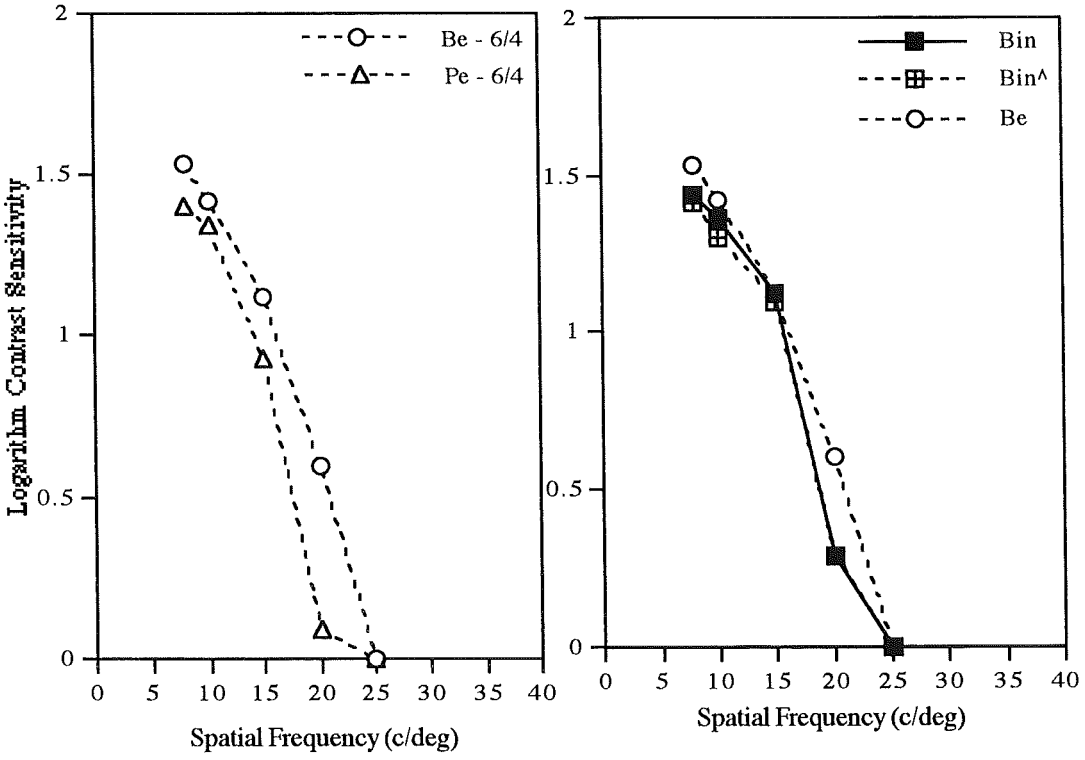


The contrast sensitivity in the poorer eye (Pe) was less than that of the better eye by 44%± 5%SE (P.< 0.01). The binocular logarithm contrast sensitivity (Bin) was reduced significantly reduced by 41% ± 6% (P <0.01) when compared to that of the better eye (Be). Under conditions of bifoveal stimulation (Bin^), the bifoveal contrast sensitivity was marginally greater than that achieved binocularly (Bin) by 8%±4% (P = 0.1).

Clinical Data

Refractive Error:	Nil	
Visual Acuity:	RE: 6/5	LE: 6/5
Angle of Deviation:	N: BI 16^	D: BI 16^
Amplitude of Accommodation:	RE: 6.0D	LE: 6.0D
Pupils:	RE: 4mm	LE: 4mm

Subject 2



The contrast sensitivity in the poorer eye (Pe) was less than that of the better eye by 41%± 6%SE (P.< 0.01). The binocular logarithm contrast sensitivity (Bin) was reduced by 22% ± 11% (P. ns) when compared to that of the better eye (Be). Under conditions of bifoveal stimulation, contrast sensitivity was slightly greater than that achieved binocularly (8%; P.ns)

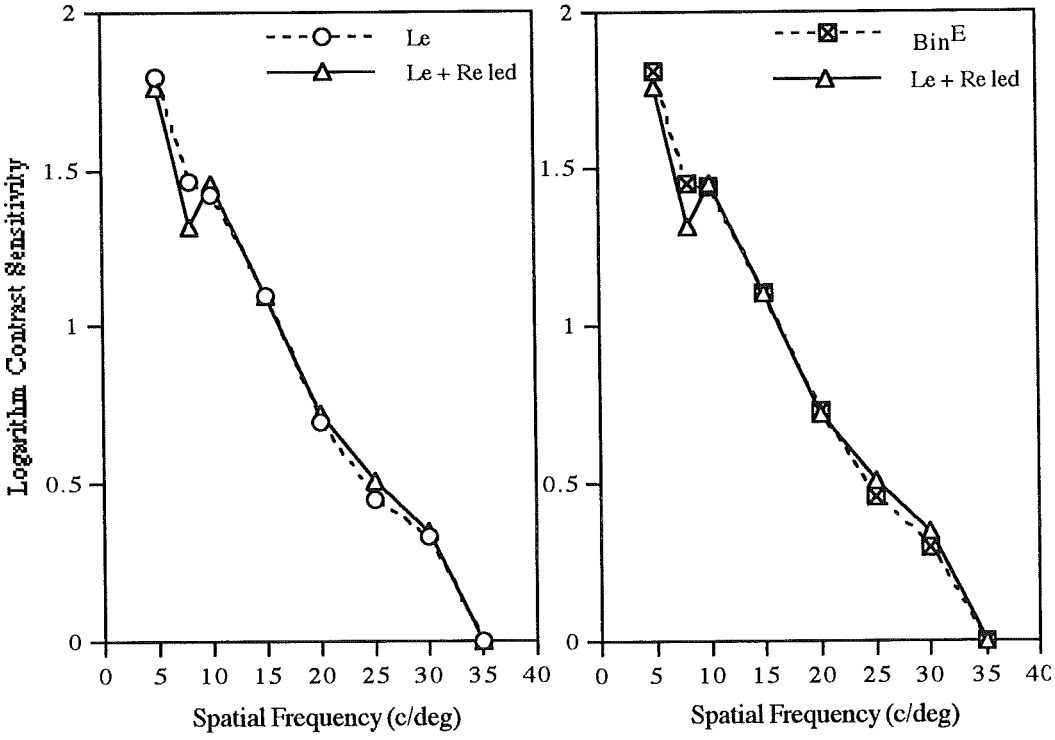
Clinical Data

Refractive Error:	RE: -3.00DS/+0.75DC LE: -0.50DC	
Visual Acuity:	RE: 6/4	LE: 6/4
Angle of Deviation:	N: BI 12^	D: BI 12^
Amplitude of Accommodation:	RE: 8.0D	LE: 8.0D
Pupils:	RE: 4mm	LE: 4mm

6.9 DICHOPTIC VIEWING

6.9.1 The Normal Group

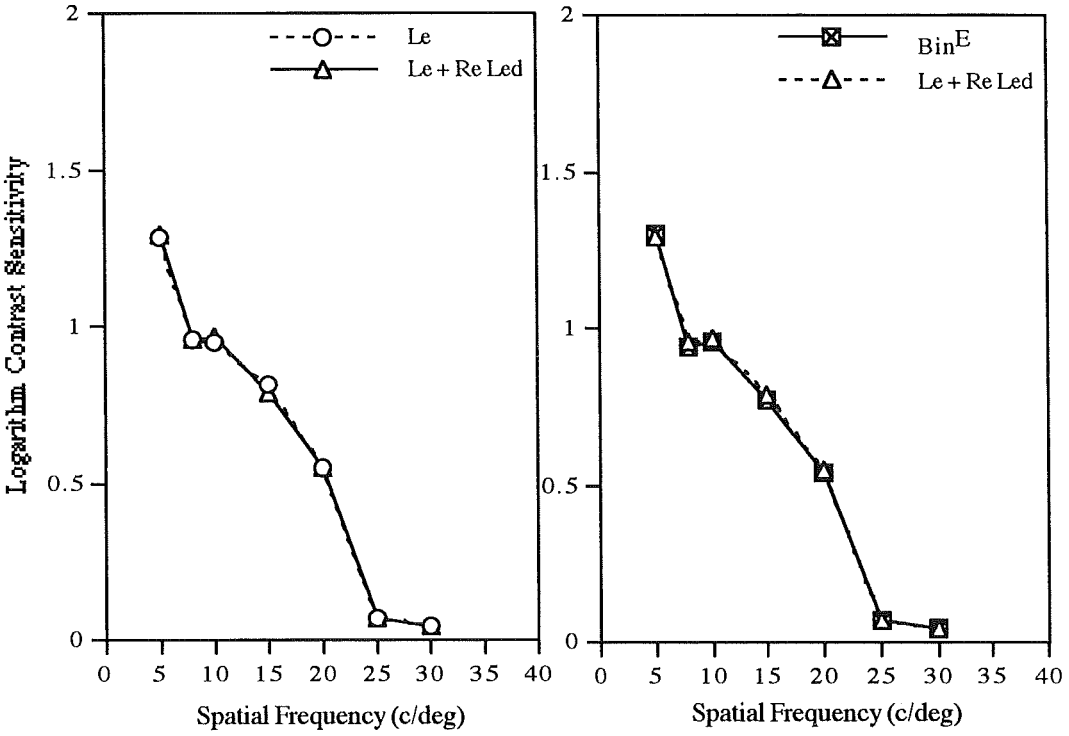
Subject 1



The mean difference between the contrast sensitivities while viewing the grating pattern with the left eye (Le) and the Led with the right eye (Re) compared to that with the grating pattern alone viwed with the left eye was +0.05%±5%; P ns. The mean percentage difference between contrast sensitivities with the addition of the eccentrically placed grating pattern (Bin^E) was 2%±5%; P. ns.

The clinical data for this subject is contained in appendix 5.1, subject 1.

Subject 2

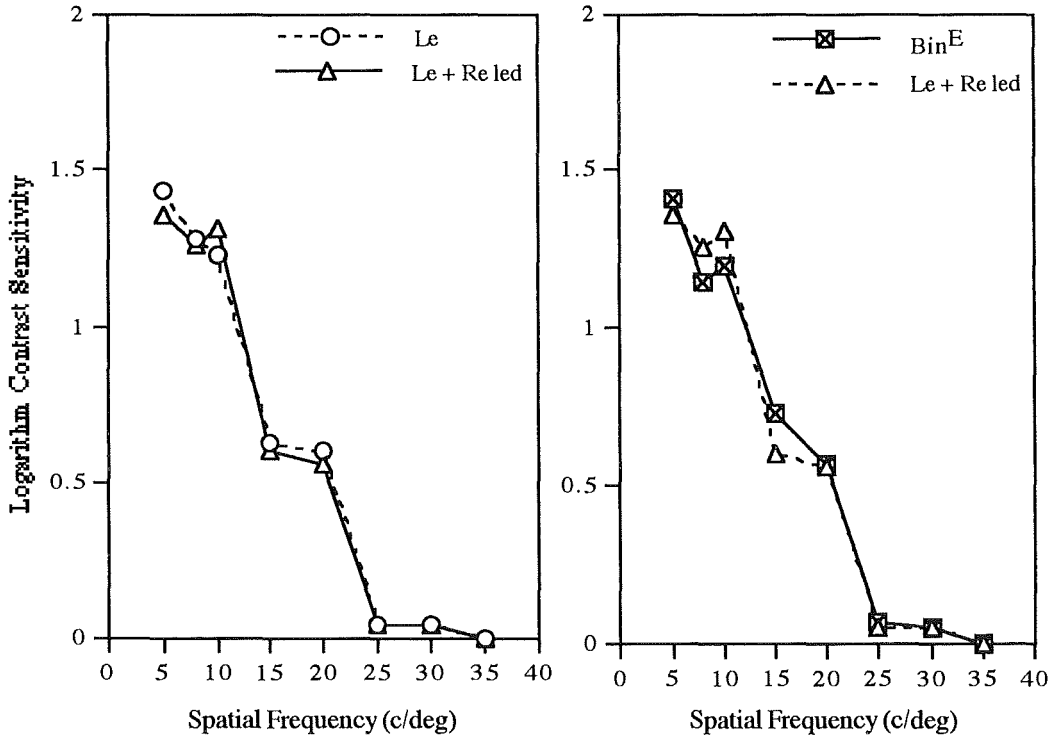


The mean difference between the contrast sensitivities while viewing the grating pattern with the left eye (Le) and the Led with the right eye (Re) compared to that with the grating pattern alone viwed with the left eye was +0%; P ns. The mean percentage difference between contrast sensitivities with the addition of the eccentrically placed grating pattern (Bin^E) was -2%±1%; P. ns.

Clinical Data

Refractive Error:	RE: -1.75DS LE: -1.25DS	
Visual Acuity:	RE: 6/5	LE: 6/5
Angle of Deviation:	N: BI 4^	D: BI 4^
Amplitude of Accommodation:	RE: 8.0D	LE: 8.0D
Pupils:	RE: 4mm	LE: 4mm

Subject 3

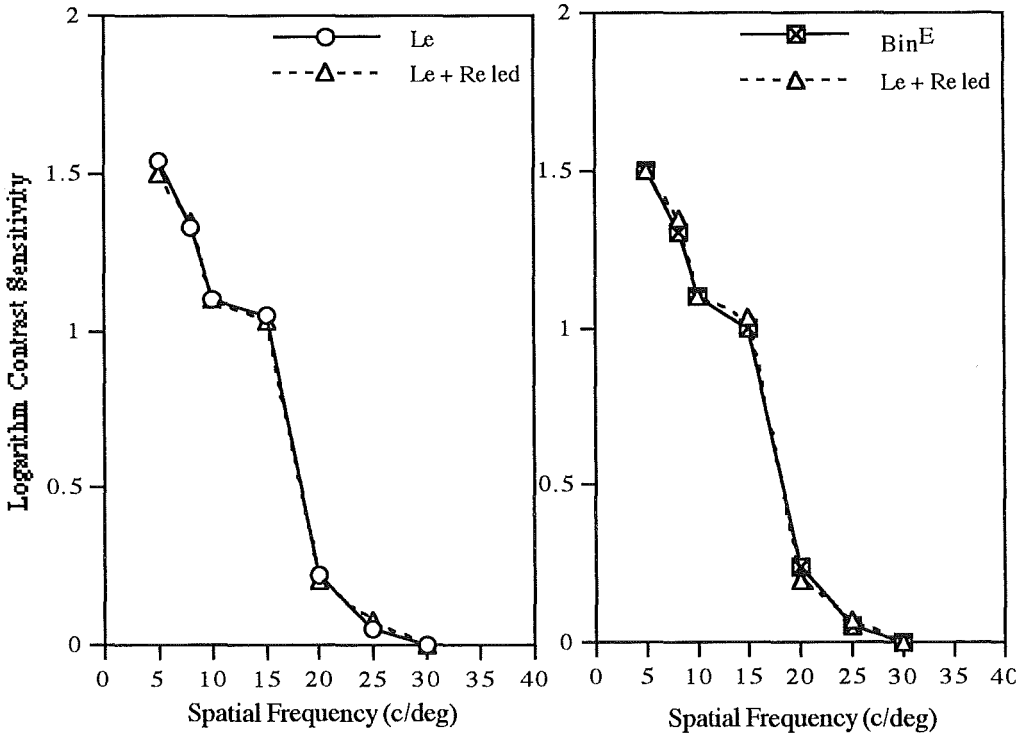


The mean difference between the contrast sensitivities while viewing the grating pattern with the left eye (Le) and the Led with the right eye (Re) compared to that with the grating pattern alone viwed with the left eye was -2%±4%; P ns. The mean percentage difference between contrast sensitivities with the addition of the eccentrically placed grating pattern (Bin^{E}) was -2%±7%; P. ns.

Clinical Data

Refractive Error:	RE: -3.25ds LE: -3.25ds	
Visual Acuity:	RE: 6/4	LE: 6/4
Angle of Deviation:	N: BI 4^	D: BI 4^
Amplitude of Accommodation:	RE: 9.5D	LE: 8.5D
Pupils:	RE: 5mm	LE: 5mm

Subject 4

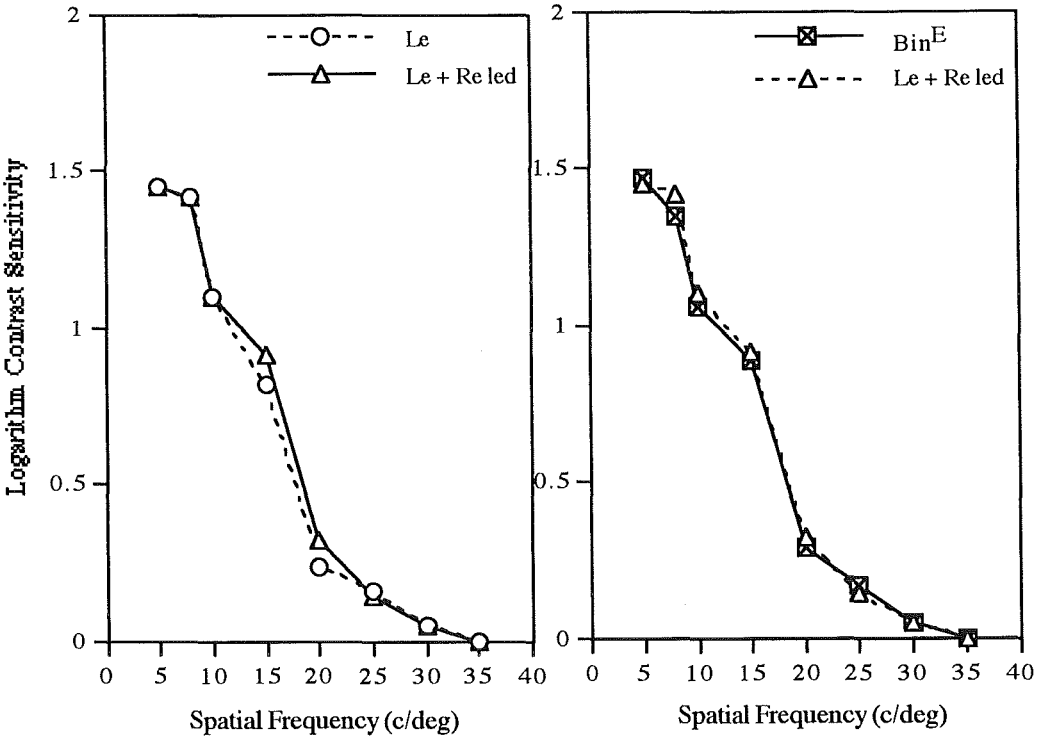


The mean difference between the contrast sensitivities while viewing the grating pattern with the left eye (Le) and the Led with the right eye (Re) compared to that with the grating pattern alone viwed with the left eye was -1%±2%; P ns. The mean percentage difference between contrast sensitivities with the addition of the eccentrically placed grating pattern (Bin^{E}) was -2%±3%; P. ns.

Clinical Data

Refractive Error:	RE: -5.00DS LE: -5.00DS	
Visual Acuity:	RE: 6/5	LE: 6/5
Angle of Deviation:	N: BO 4^	D: BO 2^
Amplitude of Accommodation:	RE: 6.0D	LE: 5.50D
Pupils:	RE: 4mm	LE: 4mm

Subject 5

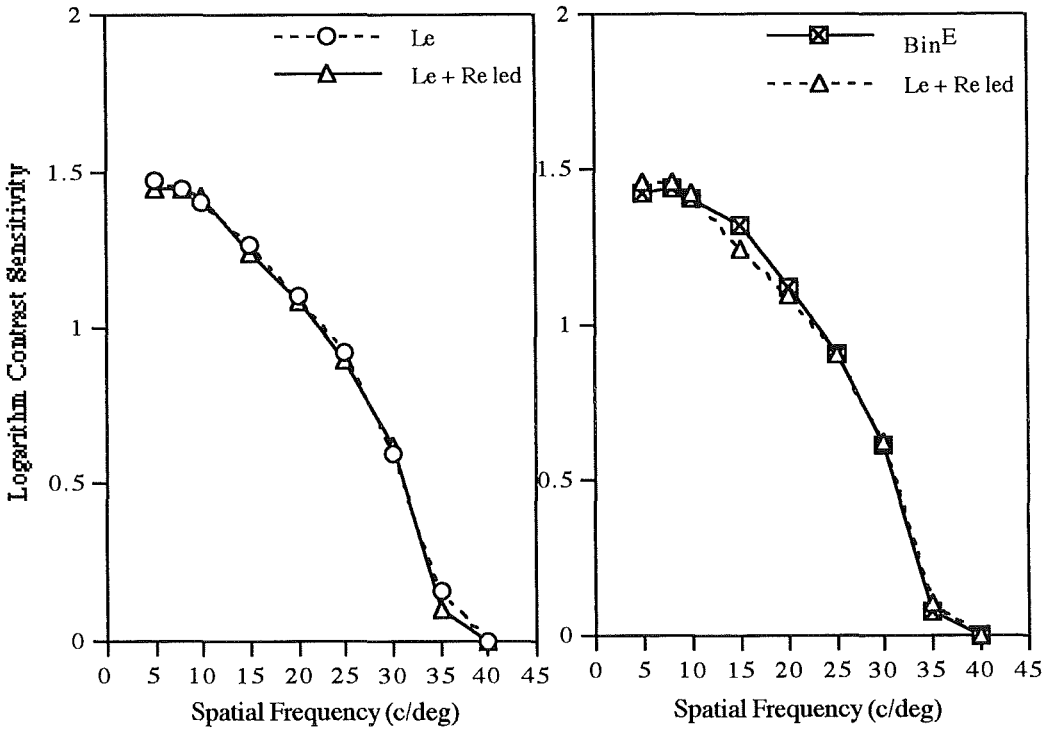


The mean difference between the contrast sensitivities while viewing the grating pattern with the left eye (Le) and the Led with the right eye (Re) compared to that with the grating pattern alone viwed with the left eye was +5%±4%; P ns. The mean percentage difference between contrast sensitivities with the addition of the eccentrically placed grating pattern (Bin^E) was -4%±3%; P. ns.

Clinical Data

Refractive Error:	RE: -5.25ds LE: -2.00ds	
Visual Acuity:	RE: 6/4	LE: 6/4
Angle of Deviation:	N: BO 4^	D: BO 4^
Amplitude of Accommodation:	RE: 4.0D	LE: 4.25D
Pupils:	RE: 4mm	LE: 4mm

Subject 6



The mean difference between the contrast sensitivities while viewing the grating pattern with the left eye (Le) and the Led with the right eye (Re) compared to that with the grating pattern alone viwed with the left eye was +3%±2%; P ns. The mean percentage difference between contrast sensitivities with the addition of the eccentrically placed grating pattern (Bin^E) was 0%; P. ns.

Clinical Data

Refractive Error:	RE: Nil LE: Nil	
Visual Acuity:	RE: 6/5	LE: 6/5
Angle of Deviation:	N: BI 4^	D: BI 2^
Amplitude of Accommodation:	RE: 5.0D	LE: 6.0D
Pupils:	RE: 4mm	LE: 4mm

6.9.2 The Simple Anisometropic Amblyopes

The dichoptic viewing graphs for the two subjects examined, subject 1 and subject 7 are contained within the results chapter, section 3.4.2.

6.9.3 Micro-esotropic Amblyopes

The dichoptic viewing graphs for the two subjects examined, subject 1 and subject 5 are contained within the results chapter, section 3.4.3.1

6.9.4 Esotropic Amblyopes without BSV

The dichoptic viewing graphs for the three subjects examined, subject, 3 subject 4 and subject 5 are contained within the results chapter, section 3.4.3.2