SYNKINESIS OF ACCOMMODATION AND VERGENCE DURING SUSTAINED NEAR VISION

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SUMMARY

It is well established that a synkinetic relationship exists between the accommodation and vergence components of the oculomotor near response such that increased accommodation will initiate a vergence response (i.e. accommodative convergence) and conversely increased vergence will drive accommodation (i.e. convergent accommodation).

The synkinesis associated with sustained near-vision was examined in a student population consisting of emmetropes, late-onset myopes (LOMs) i.e. myopia onset at 15 years of age or later and early-onset myopes (EOMs) i.e. myopia onset prior to 15 years of age. Oculomotor synkinesis was investigated both under closed-loop conditions and with either accommodation or vergence open-loop. Objective measures of the accommodative response were made using an infra-red optometer. Differences in near-response characteristics were observed between LOMs and EOMs under both open- and closed-loop conditions. LOMs exhibit significantly higher levels of disparity-induced accommodation (accommodation driven by vergence under closed-loop conditions) and lower response accommodative convergence/ accommodation (AC/A) ratios when compared with EOMs. However no difference in convergent accommodation/convergence (CA/C) ratios were found between the three refractive groups.

Accommodative adaptation was examined by comparing the pre- to post-task shift in dark focus (DF) following near-vision tasks. Accommodative adaptation was observed following tasks as brief as 15s. Following a 45s near-vision task, subjects having pre-task DF greater than +0.75D exhibited a marked negative shift in post-task DF which was shown to be induced by beta-adrenergic innervation to the ciliary muscle. However no evidence was found to support the proposal of reduced adrenergic innervation to the ciliary muscle in LOMs.

Disparity-vergence produced a reduction in accommodative adaptation suggesting that oculomotor adaptation was not driven by the output of the near-response crosslinks. In order to verify this proposition, the effect of vergence adaptation on CA/C was investigated and it was observed that prism adaptation produced no significant change in the CA/C ratio. This would indicate that in a model of accommodation-vergence interaction, the near response cross-links occur after the input to the adaptive components of the oculomotor response rather than before the adaptive elements as reported in previous literature.

The findings of this thesis indicate differences in the relative composition of the aggregate accommodation and vergence responses in the three refractive groups examined. They may also have implications with regard to the aetiology of late-onset myopia.

Key words: accommodation, myopia, near vision,
oculomotor adaptation, vergence.

To Mum and Dad
Thank you for everything

" The eye as the dominant sense organ is a development only recently established in phylogenetic history, while the exorbitant demands of a complex and artificial civilization have put upon it highly aphysiological strains and stresses, the extent of which is difficult to appreciate adequately. Although from long custom, we accept the conditions under which we live today as normal, it by no means follows that the eye has evolved to cope with them, and the fact that it is able as a rule to meet the demands which are placed upon it, is a compliment of no mean order to the extreme adaptability of living organisms" (Duke-Elder, 1949).

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CONTENTS

Page

LIST OF TABLES

TABLE

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

The social and cultural requirements of contemporary western society frequently demand periods of sustained near-vision which may involve reading, writing, operating machinery or working with visual display units (VDUs). This thesis will investigate how the visual system reacts to sustained near-vision tasks over relatively long periods of time.

The near response is composed of three principal elements namely accommodation, convergence and pupil miosis (Davson, 1980). However other functions also occur concurrent with a change from distance to near fixation e.g. variation in head and eyelid position and cyclotorsional movements of the eyes. This thesis will be primarily concerned with the synkinetic interaction between accommodation and vergence. Specific mechanisms may exist within the near-response to allow single, clear binocular vision to be maintained over relatively prolonged periods of time. These mechanisms may relate to variations in the composition of the accommodation and vergence responses. It will be proposed that a relationship may exist between the ability to adapt to sustained near-visual tasks and the development of ametropia. Of particular interest is the development of myopia which is relatively late in onset (first becoming manifest in the mid to late teens) and has no clear hereditary basis. The aetiology of late-onset myopia (see Chapter 5) may relate to periods of sustained near-visual activity although it remains unclear whether it is induced by the actions of the accommodative system, the vergence system or an alteration in the synkinetic relationship between accommodation and vergence.

In order to examine the accommodation-vergence synkinesis it is necessary to provide a known stimulus and to monitor the output of one or both functions. The form of the stimulus may be varied to determine the composition of the various components which combine to produce the aggregate accommodation and vergence responses. Viewing through a pinhole will produce an increased depth-of-focus which in turn will render ineffective the stimulus to accommodation derived from a blurred retinal image. The accommodation system may then be described as being "open-loop" (see Chapter 4) since negative feedback loops will not influence the accommodative response. Similarly the stimulus to fusional vergence may be eliminated by totally dissociating the two eyes and this can be achieved by simply occluding one eye.

Whilst altering the nature of the near stimulus provides additional information regarding the components of the near-response, it may also alter the relative composition of the individual constituents when compared with "closed-loop" viewing i.e. with the normal negative feedback processes taking place. Thus a number of investigations will be described in this thesis which examine accommodation-vergence synkinesis under closed-loop conditions. However in the latter condition, it is difficult to identify the individual components which comprise the accommodation and vergence responses.

Schor (1979) described the fusional response as consisting of two elements; fast fusional vergence which acts within one second in order to reduce retinal disparity and slow fusional vergence which maintains the vergence response. The terms reflex or phasic vergence and adaptive or tonic vergence may also be used to describe the outputs of the fast and slow neural integrators respectively. According to the model of accommodation-vergence interaction proposed by Schor (1983a), the stimulus initiating tonic (adaptive) vergence is the output of phasic (reflex) vergence. The onset of adaptive vergence is accompanied by a simultaneous reduction in reflex vergence in order to maintain the aggregate vergence response. Schor (1986) suggested that an analogous system may also exist for accommodation such that reflex accommodation provides a stimulus to adaptive accommodation. It has been suggested that the role of the adaptive components of the oculomotor response serve to maintain sustained single, clear binocular vision without excessive fatigue (Rosenfield and Gilmartin, 1988a). Thus the reflex elements of accommodation and vergence are poised to respond to any subsequent rapid change in accommodation-vergence stimulus.

The requirement for near-vision will vary widely between individuals. It is well established that infants are mainly concerned with their immediate surroundings and more distant objects are often ignored (Rosner, 1982). This observation almost certainly relates to the fact that newborn infants exhibit a sustained accommodative response of around 5D (Haynes et al.,1965). Recent studies using photorefraction (Braddick et al., 1979) and retinoscopy (Banks, 1980) have suggested that neonates are capable of varying their accommodative response, although only within a limited range. Atkinson (1984) noted that if a target is placed at a viewing distance of greater than 75cms (1.33D) then the infant tends to over-accommodate and furthermore the accommodative response shows large fluctuations. However accurate accommodation is achieved over a wide range of target distances by 3-4 months of age (Atkinson, 1984).

As children progress through the modern educational process, there are increasing demands on the near-visual system and an important point to be considered is that school work requires other activities besides mere visual observation. Van Alphen (1961) noted that "learning, as opposed to mere close work, has a more complicated psycho-visual mechanism." He stated that learning may induce stress and anxiety which are not commonly found in routine reading and psychological variations may also play a role in the development of late-onset myopia. Birnbaum (1984) described reading as;

> *"a relatively recent culturally-imposed task which imposed unique demands not typically found in nature. These include demands for containment or immobilization; for vigilant attention on flat, two dimensional material; and for information-processing through symbols."*

The near-vision requirements in adults show extreme variation depending on a large number of factors including occupation, hobbies, degree of education and cultural factors and the prescribing of a refractive correction for near-viewing must take these factors into consideration (Borish, 1970; Michaels,1980).

Birnbaum (1984) noted that reading and related tasks imposed demands," inconsistent with our biological heritage and physiology." The human visual system is primarily designed to detect rapid changes in the visual environment. The reason for this may relate back to the evolution of the human species. The early hominids who lived between 5 and 10 million years ago had to scavenge, hunt and gather food in order to survive (Tullar, 1977). In addition these hominids were themselves preyed upon by other carnivores. Clearly therefore there was a need to perceive rapid changes in the environment. However with evolutionary progression, the hominids developed the ability to make tools and thereby create missiles both for use in hunting and as defensive weapons. It would seem likely that the creation of these tools and weapons represented one of the earliest sustained near-vision tasks performed by man's ancestors.

Modern man no longer has to hunt in order to survive although Morris (1967) suggested that some contemporary activities (e.g. sports) may represent hunting substitutes. Nevertheless the visual system still responds to changes in the environment (Lindsay and Norman, 1977; Haber and Hershenson, 1980) with a tendency to suppress steady-state information (Gilmartin, 1982). Ditchburn and Ginsborg (1952) and Riggs et al. (1953) demonstrated that a stabilised retinal image i.e. one where the image remained on the same part of the retina, irrespective of eye movements, would cause the image of the object of regard to disappear within a few seconds. Cornsweet (1969) noted that eye movements eliminate luminance and temporal continuity in order to obtain a constantly changing pattern of retinal illumination over a period of time.

Clearly the visual system has evolved to detect changes in the environment rather than steady-state information. However it would appear that the visual system is able to cope extremely well with sustained near-vision in view of the relatively low incidence of asthenopia associated with near-vision amongst the general population. The ability to maintain clear, single vision at near may relate to adaptational processes which may serve to reduce either the vergence requirement (e.g. suppression or fixation disparity), the accommodation demand (e.g. the onset of myopia) or to alter the synkinetic relationship between accommodation and vergence (possibly via the accommodative convergence/accommodation (AC/A) or convergent accommodation/convergence (CA/C) ratios). These adaptational processes will be discussed in later chapters but initially the accommodation and vergence components of the near-response will be considered separately.

CHAPTER 2

THE ACCOMMODATIVE MECHANISM

2.1 INTRODUCTION

Borish(1970) defined accommodation as " the function whereby the converging power of the optical system of an eye is increased so that light diverging from a near source may be brought to a focus upon the retina". The term *accommodation* was first introduced by C.A.Burow in 1841. Prior to this time the term *adaptation* had been adopted to describe dioptric changes in the eye.

In a historical review of work on accommodation, Duke-Elder and Abrams (1970) observed that the existence of an accommodative mechanism was indicated in the classical experiment of Scheiner (1619). If two pinholes are made in a card, separated by a distance of less than the diameter of the pupil, and the observer views a needle held at right angles to the axis joining the two pinholes, then the needle appears single. However if the observer focuses upon an object placed at a different viewing distance, then the needle will appear double. These observations indicate that there is a mechanism in the eye which is capable of adjusting the dioptric power. Prior to a discussion of the accommodative mechanism the anatomy of the ocular structures involved will be summarised in section 2.2.

2.2. THE ANATOMY OF THE ACCOMMODATIVE MECHANISM

2.2A THE LENS

The lens is a transparent bi-convex body of crystalline appearance placed between the iris and the vitreous (Wolff, 1976). The equatorial diameter of the adult lens is usually 9-10mm . However the axial diameter varies markedly with accommodation (see section 2.3). Wolff (1976) stated that the relaxed anterior lens surface is less convex than the posterior surface, is approximately spherical and has an average radius of curvature of 10mm (normally ranging between 8 and 14mm). In an earlier paper, Fisher (1969) examined the lens curvature by photographing the lens profile. He assumed that the excised lens was fully accommodated and observed that the anterior lens surface of the excised lens adopted an elliptical form. Fisher (1969) presented the values of conic constants for the observed lens profile. He concluded that there was no evidence for the conoidal shape described by Tscherning (1904) and Fincham (1937). The posterior surface is not spherical although centrally it has an approximately spherical shape with a radius of curvature of 4.6-7.5mm (Alpern, 1969). However towards the lens periphery the posterior surface becomes considerably flattened.

The crystalline lens is not homogenous having a refractive index of 1.41 in the central nucleus whereas in the outer cortical layers the refractive index drops to 1.38 (Nakoa et al.,1969a and 1969b). Thus the lens forms a gradient-index optical element (Marchand, 1978). This index gradient gives the lens the power equivalent of a homogeneous lens possessing the same surface curvatures but having a refractive index of 1.42 (Charman, 1983). The refractive index of the lens is higher than that of the aqueous and vitreous humours (1.33) and the refractive power of the lens is considerably less than that of the cornea (≈43D; Emsley, 1953). The lens contributes a varying supplement ranging from 14D in the 10 year old to less than 1D in the 52 year old eye (Hamasaki et al., 1956). The structure of the lens is composed of three elements namely;

i) the lens capsule
ii) the lens epithelium
iii) the lens fibres

2.2Ai THE LENS CAPSULE

The lens substance is enclosed in a thin, transparent envelope known as the lens capsule. It is very resistant to pathological and chemical influences (Duke-Elder and Wybar, 1961) and is highly elastic, having the same Poisson ratio* as common rubber. However the capsule contains no true elastic tissue and Wolff (1976) suggested that its elasticity must reside in the disposition of the fibrils which form the capsule. The fibrils are probably composed of a form of collagen as they are known to contain the amino acids found in collagen (Hogan et al., 1971).

Fincham (1937) noted that the thickness of the capsule varied in different positions. It was thinnest at the posterior pole (2.8µm), and increased to 6.3µm, 2mm away from the posterior pole and 14.8µm, 3mm away from the posterior pole. However the anterior surface was much thicker with an average thickness of 15.5µm at the anterior pole, 22.5µm 2mm from the anterior pole but reducing to 18.5µm, 3mm from the pole on the anterior surface.

2.2Aii THE LENS EPITHELIUM

The lens epithelium consists of a single layer of cubical cells spread over the anterior surface of the lens posterior to the capsule (see Fig. 2.1). There is no corresponding posterior epithelium since the posterior cells were used in filling the central cavity of the lens vesicle. As the anterior epithelial cells progress towards the equator they gradually become columnar and are eventually converted into lens fibres. Three regions of epithelium have been described, central cells with few mitoses; intermediate cells which divide more frequently and equatorial cells which show the most frequent mitoses and undergo the transition from tall columnar to pyramidal shape, and then elongate to form lens fibres. The base of the cell i.e. that part in contact with the capsule, becomes the posterior part of the lens fibre while the opposite end forms the anterior portion of the lens fibre (Duke- Elder and Wybar, 1961).

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*Poisson's ratio : The ratio of lateral strain to longitudinal strain. Given by the equation $\frac{d}{D} : \frac{l}{L}$ where D = original diameter, L = original length
d = decrease in diameter, l = increase in length .

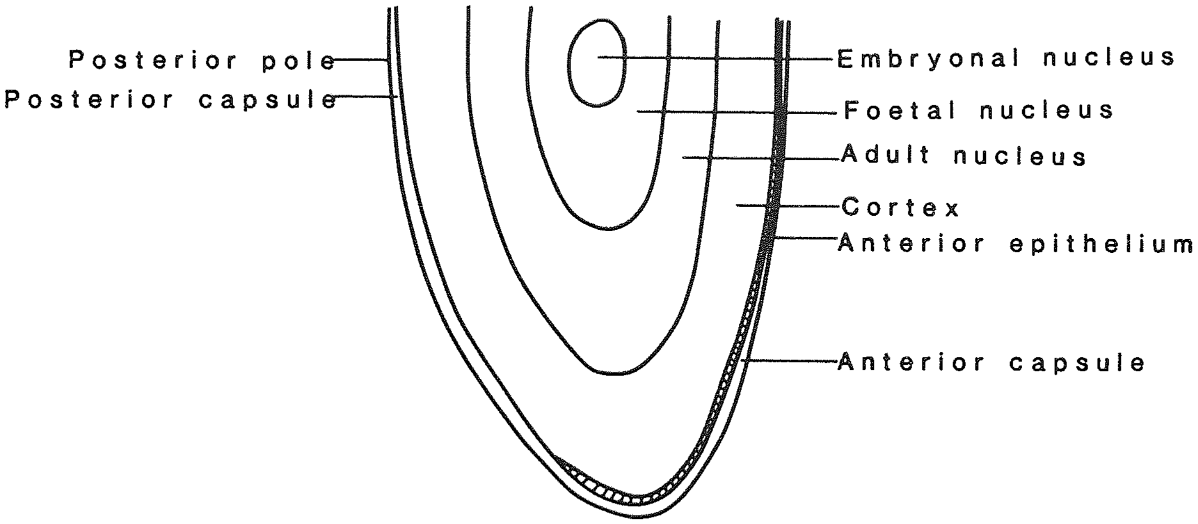

Fig. 2.1 Transverse section of the inferior portion of the adult crystalline lens

2.2Aiii THE LENS FIBRES

All but the oldest lens fibres are actually elongated, nucleated cells. Each fibre is an elongated hexagonal prism. The earliest formed fibres are situated in the central nucleus of the lens, these gradually lose their nuclei and become true fibres. The newest fibres are laid on the external aspects of the lens giving it a laminated structure. Wolff (1976) stated that the cortical fibres are approximately 7µm wide and about 8-12µm in length.

As the inner fibres are older, they become more sclerosed and less translucent than the newer peripheral fibres. This change in light transmission allows the nucleus and cortex to be differentiated by biomicroscopy. Examination of the lens under the slit-lamp reveals distinct layers within the lens nucleus (see Fig. 2.1).

1) The *embryonal nucleus*. An optically clear central zone formed in the first three months of embryonic life.

2) The *foetal nucleus*. Formed from the third to eighth month of foetal life.

3) The *adult nucleus*. Formed after puberty in adult life.

These bands of discontinuity are variable and may be affected by a number of factors including pathological or endocrine disorders.

2.2B THE CILIARY ZONULE (also known as the Zonule of Zinn or Suspensory Ligament of the Lens)

The ciliary zonule consists of a series of homogenous, transparent fibrils which run from the inner limiting membrane of the ciliary body to the zonular lamella of the lens capsule in the region of the lens equator. The zonule holds the lens in position and enables the ciliary body to act upon the lens. The fibres from the posterior ciliary body pass to both the anterior and posterior lens capsule near the equator as do the fibres from the anterior ciliary body. Hogan et al. (1971) stated that the gel-like structure of the zonules is similar to that of the vitreous except for the more definite organization of the fibrils in the region of the suspensory ligament. The gel is formed into strands connected by a matrix arranged in two sheets, the space between the two layers being filled with a fine meshwork of similarly connected strands. For a fuller description of the anatomical structure of the zonule see Duke-Elder and Wybar (1961); Hogan et al. (1971), Wolff (1976), Rohen (1979) and Marshall et al. (1982).

2.2C THE CILIARY MUSCLE

The ciliary muscle is composed of flat bundles of smooth muscle which form a ring with the external surface lying against the inner surface of the anterior portion of the sclera. In cross-section the muscle takes the form of a right-angled triangle, the right angle being internal and facing the ciliary processes. The muscle fibres have been divided into three types (Salzmann, 1912); the most external muscle fibres being described as *longitudinal* or meridional, the intermediate fibres are denoted as oblique or *radial* and the most internal fibres are termed *circular* fibres (see Fig. 2.2).

The longitudinal fibres, also called Brücke's muscle, have their origin at the scleral spur and adjacent trabeculae. The origin from the scleral spur is a narrow tendinous ring which passes between the circularly running fibres of the spur.

The radial fibres form a less compact muscular mass compared with the longitudinal fibres. These two groups are separated by a fibrous connective tissue which also permeates within the radial fibres so that the fibre bundles are loosely arranged and widely separated from each other. This is in contrast with the compact nature of the longitudinal fibres.

The circular fibres (also known as Müller's muscle) occupy the most anterior portion of the ciliary body. They lie nearest to the lens and run parallel to the margin of the cornea. They pass circularly around the globe in a direction so oblique as to be almost parallel to

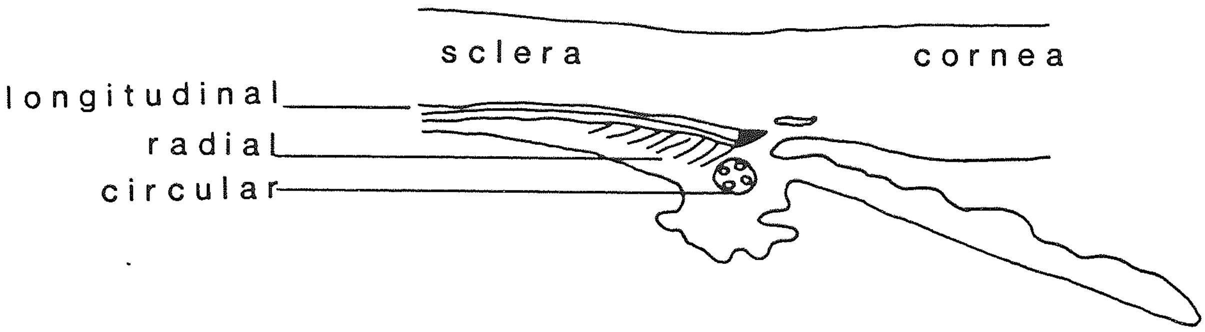

Fig. 2.2 Diagramatic representation of the ciliary muscle (redrawn from Duke-Elder and Wybar, 1961)

the equator.

Alpern (1969) stated that it may be functionally more realistic to regard the meshwork of intermingling muscle fibres as different portions of the same muscle. Indeed, Fincham (1937) considered that this discrete division of muscle fibres within the ciliary muscle was too rigid. The innervation to the ciliary muscle will be considered in section 2.4.

2.3 THE MECHANISM OF ACCOMMODATION

A number of possible mechanisms have been suggested in order to account for the change in refractive power including elongation of the globe (Sturm, 1697; Hosack, 1794; Listing, 1853), changes in corneal curvature (Lobé, 1742) or changes in pupil size (von Haller, 1763). However Decartes (1677) was the first to propose that accommodation was accomplished by a change in the shape of the lens. This was subsequently proved by Porterfield (1759). Interestingly the ciliary muscle had not yet been discovered at this time and Hunter (1794) in a lecture which he was to have given to the Royal Society had he not died prior to their meeting, considered the crystalline lens itself to be muscular, a view based upon his studies of the lenses of cuttlefish.

Further evidence for accommodation being produced by changes in the crystalline lens came from the study of Young (1801)who observed that accommodation was absent in aphakic patients. Later Langenbeck (1849) noted that the Purkinje images formed at the surfaces of the lens altered upon accommodation. Cramer (1851) showed by electrical stimulation that changes in the crystalline lens were produced by muscular activity. However he suggested that the ciliary muscle pulled the choroid forward so that the vitreous pressed on the posterior surface of the lens; the lens periphery being held in place by the contracted pupil while the central lens portion bulged forward. Hensen and Völckers (1873) confirmed the forward pull of the contracted ciliary muscle, demonstrating that if two needles were inserted through the sclera into the ciliary body, stimulation of the ciliary muscle resulted in a backward movement of the free ends of the needles, thus indicating a forward movement of the buried ends. However von Graefe (1860) disproved the suggestion that the pupil restrains movement of the lens as he demonstrated the presence of a full amplitude of accommodation in a patient with aniridia.

Helmholtz (1909) observed that on accommodation, the size of the IIIrd and IVth Purkinje images formed by reflection at the crystalline lens surfaces approximated and became smaller while those Purkinje images reflected from the corneal surfaces (Ist and IInd) remained practically stationary. The slight change in corneal shape has subsequently been shown to be caused by the convergence response associated with accommodation (Löpping and Weale, 1965). Helmholtz considered that the lens was elastic and under tension from the zonules. Contraction of the ciliary muscle caused the elastic lens to become more convex due to the relaxation of the zonular fibres.

This view was opposed by Tscherning (1909) who considered that ciliary muscle contraction would increase the tension in the zonule. Tscherning concluded that during accommodation the lens became flattened in the periphery and bulged forward conoidally along its axis. However it may be observed that the more recent work of Fisher (1969) has contradicted the suggestion that the anterior lens surface adopts a conoidal shape. Fisher indicated that the anterior surface of the excised human lens had an ellipsoid profile.

Helmholtz's theory was verified by Fincham (1937) who demonstrated that the anterior surface of the lens increased in curvature upon accommodation, thereby producing an increase in the centre thickness of the lens. Fincham noted that although accommodation is brought about by the reduction in tension of the suspensory ligaments produced by contraction of the ciliary muscle; the ultimate force which changes the lens shape is not the elasticity of the lens substance but rather the elasticity of the lens capsule. Fincham observed an eye in which the capsule had been perforated and the lens substance absorbed so that the empty capsule was filled with aqueous humour. This case was originally described by Graves (1925). Examination of the empty capsule with a slit-lamp indicated that when the patient was viewing a distant object, the anterior and posterior layers of the capsule were nearly flat and lay close to each other (see Fig. 2.3). However when the patient viewed a near object, the anterior layer bulged forward in the centre becoming convex while the thin posterior layer became slack and sagged backwards without any definite form.

In addition Fincham examined the extracted lens from a young monkey, firstly with the capsule *in situ* and then again after the capsule had been removed. On removal of the capsule the lens surfaces became less convex whilst the equatorial diameter of the lens increased. Thus Fincham concluded that the change in shape of the lens during accommodation is brought about by the moulding action of the capsule. As the capsule is thickest at the equator (see section 2.2Ai) the maximum force occurs here during accommodation (Fisher, 1969). However there is little change in the posterior surface of the lens where the capsule is considerably thinner. This suggestion that the change in lens shape is brought about by the action of the lens capsule upon the lens substance became known as the *capsular theory* (Fincham, 1958).

Weale (1962), in a discussion of the capsular theory, noted that Fincham (1937) had described the lens substance as plastic. Weale stated that by definition a plastic substance is "one whose shape can be moulded by an external force" and therefore this implies that the shape will be maintained when the external moulding force is withdrawn. Weale also recorded Fincham's observation that " the lens-substance could be distorted by light pressure, but always returned to the same form which was assumed to be its natural form when not under compression by the capsule". Furthermore Fincham had indicated that when the lens capsule was removed, the monkey lens became thinner and increased its equatorial diameter. Weale considered that these observations implied a degree of elasticity within the lens substance whereas a truly plastic structure

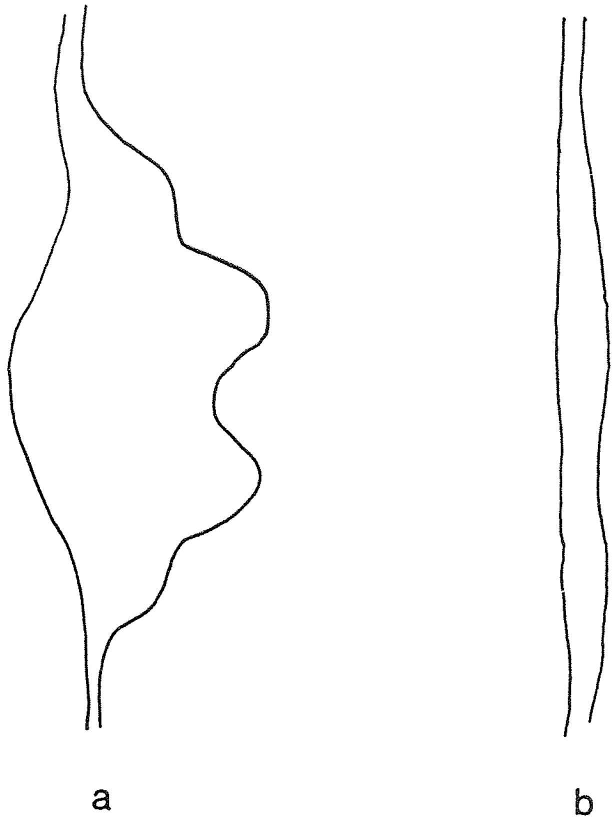

Fig. 2.3 The lens capsule in accommodation (Redrawn from Fincham, 1958).

a) The accommodated state, the anterior layer bulged forward centrally while the thin posterior layer became slack and sagged backward with no definite form.

b) The appearance of the capsule when viewing a distant object: the layers are nearly flat and lie close to one another.

would remain in the form to which it had been moulded.

Kikkawa and Sato (1963) examined the visco-elastic properties of the rabbit crystalline lens. Application of an external force produced rapid deformation of the lens. They examined this deformation in a normal lens and in a lens where the capsule had been carefully removed in order to determine its elastic properties. Kikkawa and Sato reported that the lens capsule was highly elastic but additionally observed a degree of elasticity within the lens substance. They cited the studies of Wanko and Gavin (1958, 1960) who observed by electron microscopy, a complex series of interdigitations at the boundaries of individual cells in the lens epithelium and in the equatorial portions of the lens fibres. These interdigitations may play a role in the "elastic after-effect" because of their high frictional resistance during the process of deformation.

Fisher(1969) described a method for determining the energy released by the anterior lens capsule during accommodation. This was based upon three factors namely;

(i) The determination of pressure required to distend the capsule by a standard volume.

(ii) Calculation from the photographed lens profiles of the degree of capsular contraction which occurs when the lens changes from the unaccommodated to the accommodated form.

(iii) Capsular volume changes *in vitro* are related to the surface area changes calculated for the lens *in vivo.*

Using this technique, Fisher was able to compute the effective energy of the capsule and plot this against amplitude of accommodation for eyes of different ages. This is illustrated in Fig. 2.4. Fisher noted that accommodation was proportional to the effective energy change in the lens at least up to 45 years of age. Furthermore he observed that the ability of the capsule to mould the lens depended not only on surface tension but

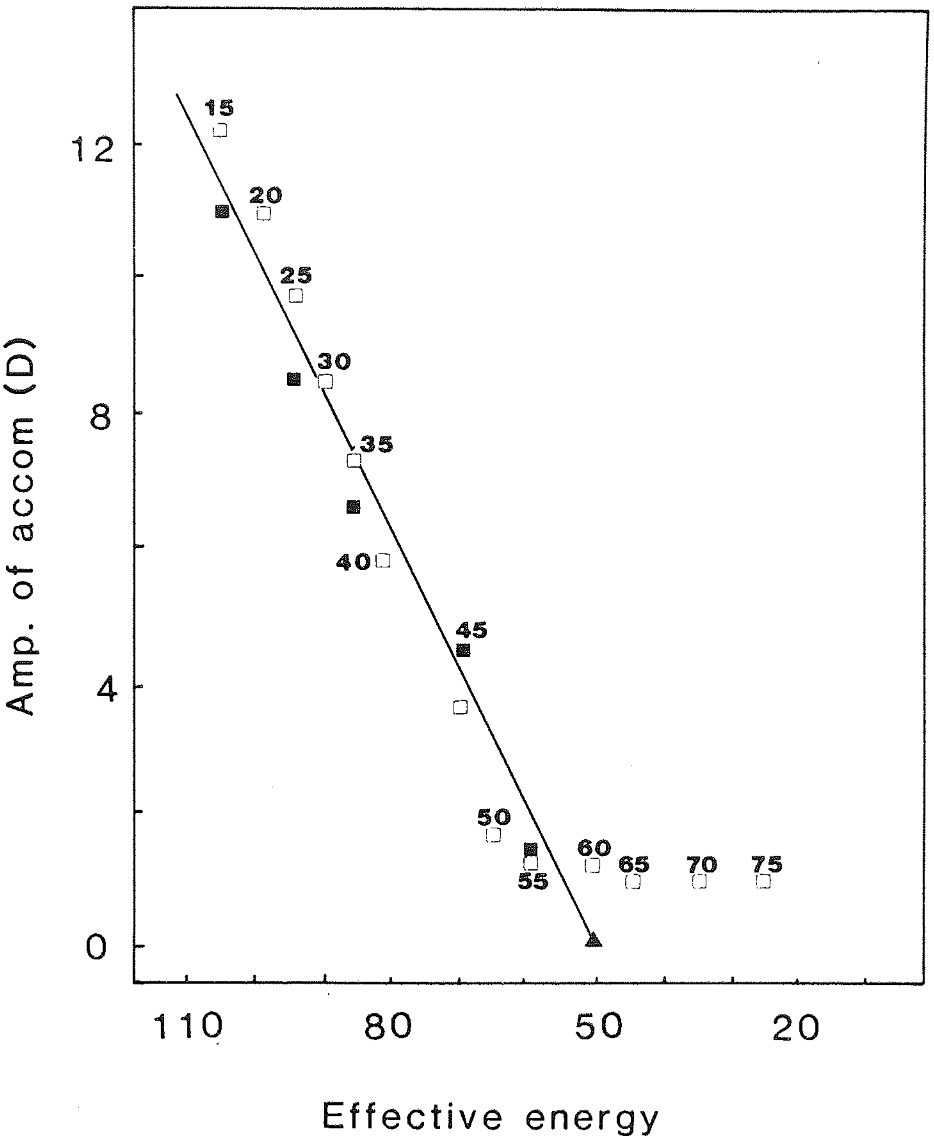

Fig.2.4 Presbyopic changes in amplitude of accommodation and effective energy of the lens capsule. Effective energy shown in units of ergs per mm change in lens diameter. Open squares: data from Duane (1922). Closed squares: data from Brückner (1959). Triangle: data from Hamasaki et al. (1956). Ages shown in years (15 to 75). Redrawn from Fisher (1969).

also upon the pressure which it exerts perpendicular to its surface.

2.3A THE ROLE OF THE VITREOUS IN ACCOMMODATION

Coleman (1970) proposed that during accommodation the vitreous moves anteriorly thereby altering the shape of the lens. Fincham (1937) noted that the anterior portion of the lens protrudes forward during accommodation but little change is seen in the posterior portion of the lens. This is despite the fact that the lens capsule is thicker anteriorly than posteriorly. Coleman stated that if the vitreous had no function in the process of accommodation then the posterior surface should protrude more than the anterior surface. Alpern (1969) offered a geometric explanation of this situation stating;

> *"Assume that all lens changes are restricted to the central regions because of the thick capsule in the periphery. Under these conditions it can be shown that the rate of change of the angle of slope of the tangents to the surface at the centre with change in the equatorial diameter varies inversely with the cube of the cosine of the angle of slope. Since the anterior curve is flattest, its angle of slope is largest and it therefore must undergo the greatest curvature change when the accommodation changes."* (p.234)

Coleman however suggested that this phenomenon results from vitreous pressure exerted upon the posterior surface of the lens. He noted that the anterior third of the vitreous is the most solidified portion and that the vitreous is attached to the ora serrata. As the ora serrata moves forward during accommodation (Moses, 1987) then Coleman reasoned that the anterior portion of the vitreous must be drawn forward against the posterior aspect of the lens. Coleman hypothesised that the vitreous and zonules formed a diaphragm between the posterior and vitreous chambers. Coleman used ultrasonography to measure the movement of the lens during accommodation. He observed that the posterior lens surface moved backwards by 0.20mm when a subject accommodated while in a normal seated position. However when the subject looked upwards, there was no displacement of the posterior surface. Coleman concluded that the vitreous supported the posterior lens surface during accommodation.

Later Fisher (1982) examined anterior and posterior lenticular movements *in vitro*. The stress relationship between the lens capsule and lens substance was altered in order to simulate accommodation. Fisher observed greater movement of the anterior lenticular pole compared with the posterior pole. He concluded that differences between anterior and posterior polar movements are solely due to inherent differences in the lenticular structure and that the vitreous plays a negligible role in modifying the position or shape of the lens during accommodation.

2.4 INNERVATION OF THE ACCOMMODATIVE RESPONSE

In a historical review of the innervation of the accommodative response, Duke-Elder and Wybar (1961) cited Agababow (1893-97) as being the first to provide a minute description of the nerve supply to the ciliary muscle. Agababow described four types of nerve endings namely; motor endings in the nerve fibres, vasomotor endings in the vessel walls, "reticular plates" which he associated with ordinary sensation and arborizations which he credited with a proprioceptive function. It is the motor fibres to the ciliary muscle which will be considered in more detail in this section.

The ciliary muscle is innervated by the autonomic nervous system and it is now generally accepted that it receives supply from both parasympathetic and sympathetic divisions. These two divisions will be considered in sections 2.4A and 2.4B respectively.

2.4A PARASYMPATHETIC INNERVATION OF THE CILIARY MUSCLE

The efferent pathway starts from the peristriate region of the visual cortex and thereafter travels down the internal corticotectal tract to the hypothalamus and continues onto the Edinger-Westphal nucleus. Parasympathetic fibres have their origin in the Edinger-Westphal nucleus which lies near the IIIrd nerve nucleus in the floor of the aqueduct of Sylvius. The fibres pass out of the mid-brain in the main trunk of the IIIrd nerve which, just before entering the orbit, divides into superior and inferior divisions. The parasympathetic fibres continue in the inferior branch and pass into the inferior oblique branch of the oculomotor nerve. They subsequently leave this branch to form the motor root of the ciliary ganglion. In the ganglion the parasympathetic fibres are thought to synapse (Behr, 1924; Kuntz, 1929; Warwick, 1954; Ruskell and Griffiths, 1979) although Westheimer and Blair (1973) proposed that the fibres pass through the ganglion without synapsing. The post-ganglionic fibres, the majority of which are myelinated (Gaskell, 1889) enter the globe via the short ciliary nerves, which pierce the sclera around the optic nerve. The parasympathetic fibres then pass forward in the perichoroidal space to supply the ciliary and sphincter pupillae muscles (O'Connor Davies, 1981).

Variations in the ciliary ganglion are common and a number of workers have described accessory ciliary ganglia which may vary in nature, e.g some of which are thought to contain sensory fibres (Nicholson, 1924) while others may carry sympathetic fibres to the ciliary muscle(Mawas, 1936; Ernyei, 1936). However the majority of the accessory ciliary ganglia are described as being parasympathetic in nature (Duke-Elder and Wybar, 1961). Axenfeld (1907) first established that ganglia were frequently associated with the ciliary nerves immediately behind the globe or in the scleral canals which cross the outer coats of the eye. Givner (1939) found such a ganglion, described as the *accessory ganglion of Axenfeld*, to be present in 10 consecutive eyes examined.

A number of studies have directly induced accommodation by electrical stimulation at various sites on the efferent pathway e.g. at the Edinger-Westphal nucleus (Pitts, 1964); oculomotor nerve (Morgan 1944a); ciliary ganglion (Marg, 1954; Ripps et al., 1962) and short ciliary nerves (Olmstead, 1944).

2.4B SYMPATHETIC INNERVATION OF THE CILIARY MUSCLE

The role of sympathetic innervation of the ciliary muscle during accommodation was reviewed by Gilmartin (1986) who cited anatomical, physiological, pharmacological, clinical and psychological evidence for the sympathetic supply playing a role in the control of accommodation.

The sympathetic fibres travel from the cervical sympathetic trunk and synapse at the superior cervical ganglion. From there they pass along the trunk of the internal carotid to the cavernous plexus. They then pass forward to the eye as two long ciliary nerves (Morgan, 1944a) and the short ciliary nerves via the sympathetic root of the ciliary ganglion (Wolff,1976).

The first pharmacological evidence for an inhibitory action of the sympathetic innervation to accommodation was provided by Jessop (1886), who observed that the topical instillation of cocaine (a sympathomimetic drug) produced relaxation of the human ciliary muscle. In a later study, Jessop (1888) stimulated the long ciliary nerves of dogs and cats following pre-treatment with pilocarpine in order to induce pseudo-myopia. Jessop observed that sympathetic stimulation produced a hypermetropic shift in accommodation. This finding was confirmed by Morat and Doyon (1891) who directly stimulated the cervical portion of the sympathetic chain in dogs. However both the studies of Jessop and Morat and Doyon assessed changes in accommodation by observing the position of the Purkinje images and Gilmartin (1986) pointed out that the accuracy of this method in the absence of accurate photographic techniques may be questioned.

Cogan (1937) in a review of sympathetic innervation of the ciliary muscle presented evidence based upon sympathectomies (producing partial Horner's syndrome) and subconjunctival injections of epinephrine (adrenaline). Cogan found that the presence of partial Horner's syndrome produced a mean increased capacity for near accommodation in 5 subjects of 1.4D. However Gilmartin (1986) indicated that Cogan could not differentiate between the effect produced by removal of the sympathetic motor supply to the ciliary muscle and the increased ciliary body volume (which would produce a relative myopic shift) associated with vascular engorgement following denervation of the ciliary body blood vessels.

In a series of nerve stimulation experiments on rats, guinea-pigs, rabbits, cats, dogs and monkeys, Olmstead and co-workers demonstrated that cervical sympathetic stimulation produced inhibition of accommodation, even when the oculomotor nerve was severed intercranially (Morgan et al. 1940; Olmsted and Morgan, 1941; Mohney et al. 1942: Olmsted, 1944). However the question of whether the hypermetropic shifts were a consequence of changes in ciliary body vasculature remained unresolved. Indeed Fleming (1957) unequivocally stated that the myopia which resulted from superior cervical ganglionectomy was produced by engorgement of the ciliary body with blood.

Törnqvist (1966) concluded from his observations of sympathetic nerve stimulation in 13 young adult monkeys that changes in the vascular structure played no part in the regulation of accommodation. Törnqvist observed that all monkeys exhibited a hypermetropic shift in refraction following stimulation of the cervical sympathetic nerve. It was found that these shifts were not inhibited by alpha-adrenergic antagonists, even though these drugs significantly diminished the reduction in ciliary body volume that would follow the vasoconstrictive effects of sympathetic stimulation. Thus it would appear that the hypermetropic shifts were independent of vascular changes. Törnqvist also observed that the magnitude and time course of accommodation changes induced by sympathetic stimulation were related to the level of background parasympathetic tone. The sympathetically-mediated hypermetropic shifts associated with the endogenous parasympathetic tone were around 0.50-1.00D and took approximately 10s to develop. However following the topical instillation of a parasympathomimetic (pilocarpine) or an anticholinesterase (physostigmine) in order to produce an increase in background parasympathetic activity; sympathetic responses were 2-4 times greater than that previously observed for the same degree of stimulation. Furthermore these increased adrenergic responses took around 20-40s to develop.

In a later paper Törnqvist (1967) produced background parasympathetic activity by direct electrical stimulation of the oculomotor nerve Again he found that the decrease in accommodative response which was induced by cervical sympathetic nerve stimulation developed slowly with a maximum effect after 10-40s. Previous studies have reported that parasympathetically mediated accommodative responses normally occur within 1-2s of stimulation (Campbell and Westheimer, 1960). These findings clearly indicate that sympathetically mediated changes in accommodation occur too slowly to provide an effective temporal response to the rapidly changing stimulus conditions of the normal visual environment.

2.4Bi ADRENERGIC RECEPTORS IN THE CILIARY MUSCLE

Ahlquist (1948)postulated that there are two types of sympathetic receptors present on smooth muscle which he designated *alpha* and *beta* receptors. Ahlquist observed that effector cells with alpha adrenoceptors have a high sensitivity to adrenaline and noradrenaline but are practically insensitive to isoprenaline whereas those having beta-receptors have a higher sensitivity to isoprenaline than other catecholamines and are generally more sensitive to adrenaline than noradrenaline (Bowman and Rand, 1980).

Beta-receptors have been sub-divided into two types on the basis of differential sensitivity to a series of beta-receptor agonists (Lands et al.,1967) . The beta-receptors of the heart and intestinal smooth muscle were designated beta-1 receptors whilst those of the bronchial, vascular and uterine smooth muscle were of another type designated beta-2 receptors.

Van Alphen et al. (1965) investigated the effect of various adrenergic blocking drugs on strips of ciliary muscle obtained from the enucleated eyes of monkeys, rabbits and cats. They found that both alpha and beta-adrenergic receptors were present in the cat ciliary muscle with beta-receptors predominating. However in the rabbit ciliary muscle the receptors were predominately alpha whist only beta-receptors were found in the monkey ciliary muscle. Kern (1970) examined human ciliary muscle obtained from 80 enucleated eyes and found the majority of adrenergic receptors to be of the beta- type. This observation was later supported by Van Alphen (1976) who summarised the distribution of adrenergic receptors as shown in Table 2.1.

TABLE 2.1 The distribution of adrenergic receptors in the ciliary muscle of various species (after Van Alphen, 1976).

CAT	mainly beta some alpha
RABBIT	mainly alpha few beta
MONKEY	exclusively beta no alpha
HUMAN	mainly beta very few or no alpha

Further pharmacological evidence for the human adrenergic receptors being of the beta subgroup comes from the studies of Hurwitz et al. (1972a and 1972b). Firstly they examined the effect of isoproterenol, a non-selective beta-adrenergic agonist, on positive accommodation produced by direct electrical stimulation of the midbrain in 23 green tail monkeys (Cercopithecus ethiops). It was observed that isoproterenol produced a significant reduction in the accommodative response. In order to verify that this observed effect was produced by local beta-activity, a non-selective beta-adrenergic antagonist, propranolol, was instilled prior to the injection of isoproterenol. It was observed that propranolol antagonised the inhibitory effect on accommodation produced by isoproterenol. These findings would indicate that beta-adrenergic activity antagonised the positve accommodation induced by direct electrical stimulation.

In a similar experiment Hurwitz et al. (1972b) examined the effect of an alpha-adrenergic agonist (levarterenol, 2.5% and 5%) on positive accommodation induced by direct stimulation of the midbrain. They noted that 2.5% levarterenol produced no change in accommodation whereas the 5% solution produced a depression in accommodative amplitude. However as levarterenol has a small beta effect in addition to its alpha action, the eye was pre-treated with propranolol prior to the instillation of levarterenol. Propranolol inhibited the induced depression in accommodative amplitude indicating that this shift was mediated via beta-activity. Hurwitz et al. also concluded that there was no local alpha sympathetic effect on positive accommodation.

Lograno and Reibaldi (1986) obtained fresh strips of human ciliary muscle and observed that these strips did not respond to adrenergic agents unless pre-treated with carbachol (a muscarinic agonist). Following this pre-treatment isoprenaline produced relaxation of the ciliary muscle whilst this effect could be antagonised by propranolol. The beta-1 selective antagonists, practolol and atenolol however had no effect on the relaxation induced by isoprenaline, suggesting that beta-2 receptors are involved in human accommodative responses. Wax and Molinoff (1987) investigated beta-adrenergic receptors in the iris and ciliary body and observed that approximately 90% of the beta-receptors demonstrated pharmacological characteristics consistent with the beta-2 subgroup. They proposed that two receptor types are present in the ciliary muscle and 30% were of the beta-1 type. This would imply that 70% of the adrenergic receptors in human ciliary muscle are of the beta-2 subgroup.

Thus the nature of sympathetic innervation to the ciliary muscle may be summarised as folows;

i) The sympathetic input is inhibitory in nature and mediated by beta-adrenergic receptors, predominantly of the beta-2 sub-group (Lograno and Reibaldi, 1986; Wax and Mollinoff, 1987).

ii) The input is relatively small in magnitude with respect to the predominant parasympathetic output (Törnqvist, 1967) and has a maximum dioptric value of around -1.5D.

iii) The time course of sympathetic activity is significantly slower than that of parasympathetic activity, taking 10-40s to reach its maximum effect (Törnqvist, 1966,1967). In contrast parasympathetically mediated responses occur around 1-2s for normal visual environments (Campbell and Westheimer, 1960).

iv) Sympathetic activity appears to be augmented by concurrent parasympathetic activity (Törnqvist, 1966, 1967; Hurwitz et al., 1972a and 1972b; Gilmartin et al., 1984; Gilmartin and Bullimore, 1987).

2.5 COMPONENTS OF ACCOMMODATION

The aggregate accommodative response is composed of a series of components which may be considered analogous to the components of vergence proposed by Maddox (1893): see section 3.7. The four components of accommodation which will be considered individually are;

i) Tonic accommodation
ii) Blur-induced accommodation
iii) Convergent accommodation
iv) Proximal accommodation

2.5A TONIC ACCOMMODATION

2.5Ai EVIDENCE FOR AN INTERMEDIATE RESTING POSITION OF ACCOMMODATION

The classical view of accommodation as proposed by Helmholtz (1909) and Fincham (1937) maintains that for the emmetropic eye, accommodation would be at rest when focused for optical infinity. However more recent work has shown that this is not the case and that in the absence of adequate visual stimuli, accommodation adopts an intermediate resting position which has been designated *tonic accommodation* (TA) (Gilmartin et al., 1984). This phenonmenon will give rise to the so called *night myopia* whereby the accommodative response tends towards this intermediate bias under degraded stimulus conditions (Leibowitz and Owens, 1975a).

This concept of night myopia was first reported in 1789 by Maskelyne, Director of the Royal Greenwich Observatory. He found that his astronomical observations at night were facilitated by the use of concave spectacle lenses. Maskelyne, who was myopic, noticed that when looking at bright stars of considerable elevation while wearing his spectacles, they appeared "without scintillation and as a small round circle of fire of a sensible magnitude". However when viewing the stars without his spectacles Maskelyne observed;

> *"They appeared to cast out rays of a determinate figure....somewhat like branches of a tree (which doubtless arise from something in the construction of the eye) and so scintillate a little, if the air be not very clear."*

Almost a century later Lord Rayleigh (1883) noted the same effect;

> *"I have found that in a nearly dark room, I am distinctly short-sighted. With concave spectacles of 36 ins negative focus my vision is rendered much sharper, and is attended with increased binocular effect. On a dark night small stars are much more evident with the aid of the spectacles than without them. In moderately good light I can detect no signs of short-sightedness."*

Otero and Duran (1941,1942) used subjective methods in order to demonstrate low luminance myopia of up to 2.0D and observed that this myopia was almost entirely eliminated following the instillation of homatropine, an antimuscarinic agent. Campbell (1953) used Purkinje image photography to demonstrate a mean increase in refractive power in darkness of 0.64D. Campbell considered that only part of the observed refractive increase was produced by night myopia, the remainder being the result of spherical and chromatic aberration.

A series of techniques including subjective coincidence optometry, infra-red retinoscopy, Purkinje image photography and infra-red optometry were employed by Heath (1962) in order to assess low-luminance myopia. He demonstrated that the levels of accommodation in total darkness were similar to those observed when the subjects were viewing a Ganzfeld field. Heath described the latter situation as "*space-myopia* ". Heath concluded that increased spherical aberration was not a major cause of low-luminance myopia.

In a review of previous work on ocular refraction at low illumination, Mellerio (1966) discussed the possible causes of night myopia. In an attempt to simultaneously measure both pupil diameter and the accommodative state, he photographed both the third Purkinje image (reflected from the anterior lens surface) and the pupil on the same photographic negative. Mellerio observed that in darkness, accommodation tended towards an intermediate value of up to 1.5D although he noted large inter-subject variation in this value of accommodation.

Leibowitz and Owens(1978) used a laser optometer to determine the accommodative response of 220 college students in total darkness. They used the term *dark focus* (DF) to describe this measurement. It will be indicated in section 2.5Aiii and in later chapters that DF may be modified by exogenous stimuli e.g. a sustained near-vision task. It appears likely that values of DF measured immediately following periods of sustained near-vision reflect both tonic accommodation and adaptive accommodative responses (see Chapter 8). For this reason the term dark focus will be adopted in this thesis to describe all measures of stimulus-free accommodation. Leibowitz and Owens observed a mean value of DF of 1.52D (sd = 0.77). The distribution of DF is illustrated in Fig. 2.5.

In an earlier paper Leibowitz and Owens (1975b) indicated that night myopia may be considered to be the passive return of the lens to a neutral or equilibrium state under darkroom conditions. Hogan (1985) also used a laser optometer to measure dark focus (referred to in his study as tonic accommodation) in 60 university students (mean age 21.6yrs) and recorded a mean value of DF of 1.58D (sd=1.11). The two studies cited above are representative of a large number which have measured dark focus using laser optometry and obtained values of DF around 1.5D e.g. (Leibowitz and Owens, 1975a;

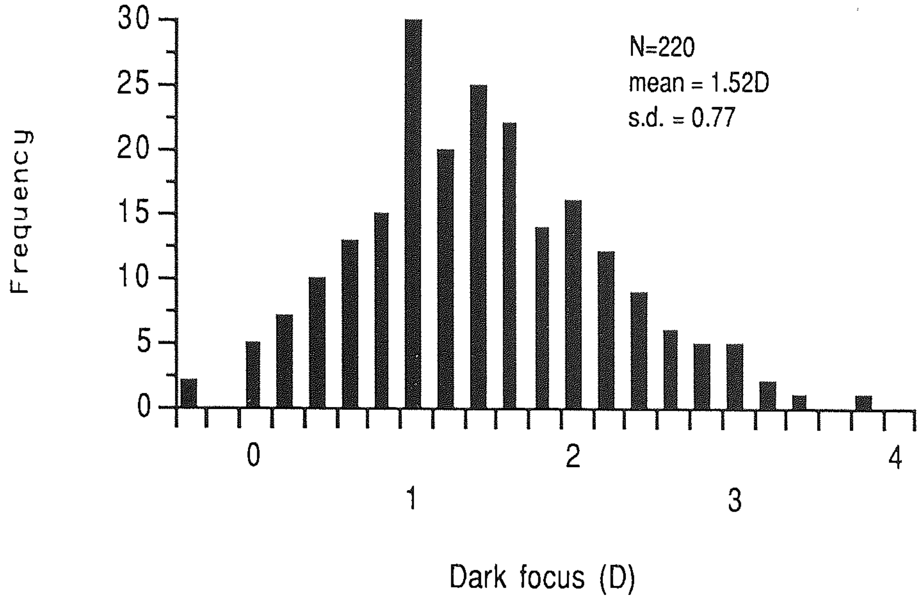

Fig. 2.5. Frequency distribution of the magnitude of dark focus measured with a laser optometer for 220 college students. (Redrawn from Leibowitz and Owens, 1978).

Leibowitz and Owens, 1975b; Owens and Leibowitz, 1976; Leibowitz and Owens 1978; Miller 1978; Mershon and Amerson 1980; Owens and Leibowitz 1980; Heron et al.,1981;Epstein et al., 1981; Maddock et al.,1981; Miller et al. 1983; Smith, 1983; Hogan and Gilmartin, 1984; Tan, 1986; Epstein et al. 1986).

Recent studies have used infra-red optometers in order to measure DF. Johnson et al. (1984) measured DF in 50 subjects aged between 18 and 31 years of age. They reported a mean value of DF of 1.10D (sd = 1.06). Johnson et al. observed that this mean value of DF is lower than those findings previously reported using laser optometry. In an accompanying paper Post et al. (1984) discussed the differences in DF obtained by laser and infra-red optometry and suggested that the laser procedure may influence the level of DF. Post et al. noted that it was unclear whether the variations in DF related to differences in mental load, arousal or other factors. However recent studies by Bullimore and Gilmartin (1987a and 1987b) have indicated that mental effort may influence measures of DF. Further discussion on the advantages of the infra-red optometer for measurement of accommodation appears in section 2.6.

2.5Aii STABILITY OF DARK FOCUS

A number of studies have demonstrated the long-term stability of DF. Miller (1978) used a laser optometer to measure DF twice a day and two days a week over a three week period. Measurements were taken on 21 undergraduate students. He observed a high level of stability, with 13 subjects (62%) showing a variability in DF of less than 1.0D. Miller also noted that 2 subjects varied by more than 2.0D during the test period and he observed that the reason for this greater variability was unclear; however he suggested that stress and changes in autonomic balance may be involved. Mershon and Amerson (1980) examined DF in 39 college-age students. For 19 subjects a second measure of DF was taken in the same experimental session as the first whereas for the remaining 20 subjects a second recording was taken 1 week later. High correlation coefficients were found between test and retest values of DF (immediate retest; $r = 0.91$; retest after 1 week; $r=0.81$). Furthermore the average change in values of DF was less than ±0.30D. Heron et al. (1981) examined the stability of DF in 30 subjects, the interval between test and retest varying between 3 and 23 weeks with a mean of 12 weeks. They found a correlation coefficient of 0.69 ($p < 0.05$) but also observed that whilst the majority of subjects showed little variation in DF, some subjects showed much larger variation with the highest change being 2.0D. However Owens and Higgins (1983) in a study of DF over a 1 year period in 5 subjects reported that the largest individual difference in DF observed was 0.66D.

It is important to note that all the studies cited above used a laser optometer in order to measure DF. It has been pointed out that this laser technique may influence measures of DF (Johnson et al., 1984; Bullimore and Gilmartin, 1987a) . Post et al. (1984) used an infra-red optometer to assess the stability of DF in trials separated by periods of a few minutes, 1 day, 1week and 2 weeks. DF was measured in 47 subjects and correlation coefficients of 0.98, 0.72, 0.75 and 0.76 were obtained for the respective test-retest intervals. These findings would indicate that DF is relatively stable over long-term periods. However several workers have reported that DF shows short-term changes following sustained visual tasks. These changes have been described as accommodative hysteresis (Ebenholtz, 1983).

2.5Aiii ACCOMMODATIVE HYSTERESIS

Ebenholtz (1983) defined accommodative hysteresis as "the incomplete relaxation of accommodation after a period of fixation, the final level of accommodation reflecting the direction and magnitude of the accommodation stimulus in force during the fixation period." Ebenholtz used a laser optometer to measure DF in 12 emmetropic subjects aged between 18 and 24 years. Following the initial assessment of DF, subjects viewed a fixation target for 8 minutes, the target being placed either at their far-point, near-point or DF position. DF was measured approximately 30s following completion of the fixation period and further measurements of DF were taken 8 and 16 minutes after completion of fixation. Ebenholtz found that near-point fixation produced a mean increase in DF of 0.34D whereas far-point fixation produced a mean decrease in DF of 0.21D. Fixation at the initial DF position produced a mean change of 0.06D which was not statistically significant. The rate of decay of the post-fixation shift in DF following near and far-point viewing were different. After 16 minutes the near-point shift in DF had only decreased to 88% of its initial value whereas the far-point shift had decayed to 33% of the initial value. Assuming an exponential decay function Ebenholtz calculated that the far-point effect would dissipate in 72 mins whereas the near-point shift would take 10.26 hours to decay.

In a later paper Ebenholtz (1985) noted that post-task shifts in DF were related to the level of pre-task DF. Thus subjects with high dioptric levels of pre-task DF showed a smaller shift in DF following near-point fixation but a large change following far-point fixation. He noted that for the far-point condition there was a correlation between the hysteresis effect and the dioptric distance between the task and the pre-task DF. However a corresponding regression was not observed for near-point fixation and Ebenholtz suggested that this may indicate the presence of a self-limiting process associated with accommodative hysteresis following sustained near-vision. Gilmartin and Hogan (1985) proposed that a possible role for sympathetic innervation to the ciliary muscle may be to attenuate the accommodative hysteresis effects which occur following periods of sustained near-vision. Further discussion on the role of inhibitory adrenergic innervation during near-vision appears in Chapter 7.

A number of other studies have also observed myopic shifts in DF following sustained near-vision tasks e.g. Östberg (1980), Schor et al.(1984), Hogan and Gilmartin (1985b), Pigion and Miller(1985), Schor et al.(1986), Tan(1986), Ebenholtz and Zander(1987), Fisher et al.(1987a, 1987b) Gilmartin and Bullimore(1987), McBrien and Millodot(1987b), Owens and Wolf-Kelly(1987) and Wolfe and O'Connell(1987). These post-task shifts in DF may represent the output of adaptive mechanisms within the accommodative response. This suggestion is discussed further in Chapters 8-10.

2.5B BLUR-INDUCED ACCOMMODATION

The role of accommodation is to provide a clear retinal image of the object of regard. Therefore the accommodative response which is initiated by the presence of a blurred retinal image will be designated *blur-induced accommodation.* Cumming and Judge (1986) defined blur-induced accommodation as "all aspects of the monocular stimulus created by a discrepancy between the accommodative stimulus and accommodative response".

Ward(1987), in a review of factors affecting accommodation, observed that a number of characteristics may affect the ability of a stimulus to elicit an accommodative response. Stimulus characteristics which may alter the resulting accommodative response include *retinal eccentricity* (Whiteside,1957; Hennessy and Leibowitz, 1972; Phillips, 1974;

Semmlow and Tinor, 1978; Bullimore and Gilmartin, 1987c); *target contrast* (Heath, 1956a; Wolfe and Owens,1981; Ciuffreda and Rumpf, 1986); *spatial frequency* (Charman and Tucker, 1977; Charman and Tucker 1978; Charman and Heron, 1979; Owens, 1980; Bour, 1981; Ciuffreda and Hokada, 1983; Raymond et al. 1984; Tucker et al., 1986; Ciuffreda et al.,1987, Tucker and Charman, 1987); *chromatic aberration* (Fincham,1951; Campbell, 1959; Kruger and Pola,1986) and *target luminance* (Wald and Griffin, 1947; Campbell, 1954; Nadell and Knoll, 1956; Alpern, 1958a; Alpern and David, 1958; Johnson, 1976).

However an attempt to determine the individual characteristics of a blur-stimulus which determine the resulting accommodative response is beyond the scope of this thesis. Blur-induced accommodation will be taken to represent the accommodative response which relates to the quality of the monocular retinal image.

2.5C CONVERGENT ACCOMMODATION

Kersten and Legge (1983) defined convergent accommodation (CA) as an accommodative response that accompanies a change in the state of convergence of the eyes. Fincham and Walton (1957) measured the convergent accommodation /convergence (CA/C) ratio in 22 subjects using a haploscope-optometer. They observed that in subjects up to 24 years of age, the induced accommodation in dioptres was equal to the convergence measured in metre angles. Fincham and Walton suggested therefore that the accommodative response in young subjects could be entirely driven by vergence cues. A more detailed discussion on CA appears in chapter 4 where the synkinetic interaction of accommodation and vergence will be considered further.

2.5D PROXIMAL ACCOMMODATION

Whilst it is generally accepted that knowledge of nearness of the object of regard will provide a stimulus to vergence (see section 3.7C) the role of proximity as a stimulus to accommodation remains unclear. A number of studies have indicated that changes in the apparent size of the object of regard will produce variations in the accommodative response. For instance Ittleson and Ames (1950) observed that changing the apparent size of a stationary target produced changes in both accommodation and vergence. However Hofstetter (1950) in a criticism of the Ittleson and Ames paper reported that the observed change in vergence was probably produced by accommodative convergence. Hofstetter therefore concluded that proximity would act as a stimulus to accommodation but not to vergence.

Fincham (1951) suggested that awareness of the proximity of an object produces "voluntary adjustments of vision". However Fincham also stated that "convergence may be the only truly voluntary component of the partnership". Fincham therefore concluded that proximity would only act as a stimulus to vergence and changes in accommodation resulted from proximal vergence stimulating convergent accommodation.

The experimental design of Ittelson and Ames (1950) was repeated by Alpern (1958b) apart from minor modifications in target luminance. Alpern measured the effect of changes in target size on both the accommodative and vergence responses, the fixation target being placed at different accommodation stimulus levels. Alpern observed in 10 subjects that variations in target size produced changes in vergence. However the mean values of accommodative response when viewing targets 2.5, 4.2 and 11.2cms in size at a viewing distance of 40 cms were 2.11, 2.16 and 2.13D respectively. Hofstetter(1942) and Morgan (1944b) also failed to demonstrate any significant change in accommodative response following alterations in target size.

Morgan (1968) examined the effect of proximity on the accommodative response by allowing subjects to view two playing cards placed at fixation distances of 33.3 and 66.7cms respectively. The cards were aligned so that they appeared to overlap. In the first viewing condition the nearer card overlaid the distant target and the accommodative response was measured using the method of stigmatoscopy. In the second condition the cards were arranged to subtend the same visual angle as in the first condition, but with the more distant card appearing to be in front of the nearer card. The experimental design is illustrated in Fig 2.6.

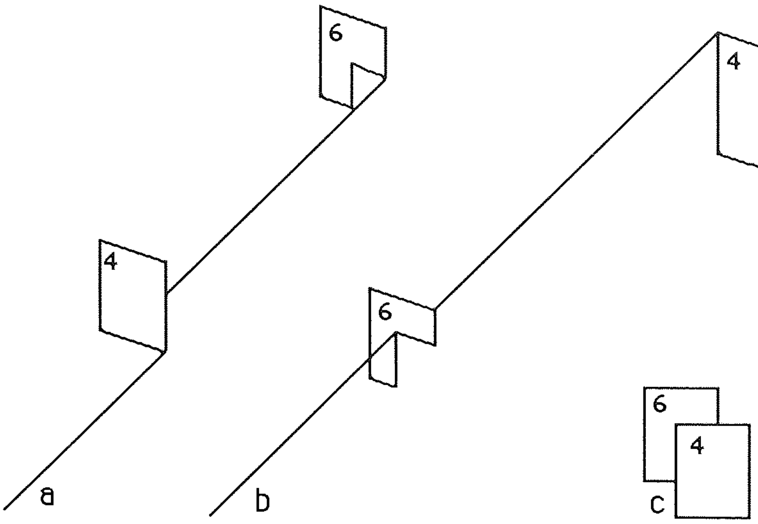

Fig. 2.6. Experimental design in order to determine the effect of apparent target distance on the accommodative response. a) the "normal" appearance of the targets; b) the "reversed" appearance. In both conditions the targets appeared to the observer as illustrated in c). Redrawn from Morgan (1968).

Morgan observed that changes in apparent viewing distance did not produce any significant change in accommodative response. This conclusion was later supported by Hennessy (1975) who used a laser optometer to measure the accommodative response while the subject viewed playing cards which appeared to be positioned at different viewing distances. Twelve emmetropic subjects viewed transparencies of a playing card which were half, twice and three times normal size. The subjects were asked to estimate the target position and additionally, in order to enhance the illusion of changes in viewing distance, the experimenter audibly moved a table to the position at which a normally sized playing card would have subtended the same visual angle. Hennessy reported that changes in apparent distance did not produce any significant effect on accommodative response.

In a recent paper Kruger and Pola (1987) examined the effect of target size on the accommodative response. Subjects viewed a Maltese cross target and three cues to accommodation were presented namely blur: the target moved both nearer and further away from the subject in a sinusoidal manner; chromatic aberration: this could be controlled by the illumination of the target using either white light or monochromatic light of 590nm and target size: changes in target size were produced by sinusoidally varying the size of an iris diaphragm so that the angle subtended by the target varied between 2 and 6°. The accommodative response was measured using an infra-red optometer in four subjects under three stimulus conditions; a) all three accommodation cues present; b) chromatic aberration was eliminated leaving size and blur changes; c) both blur and chromatic aberration were eliminated leaving change in target size as the only stimulus. Kruger and Pola found that all four subjects showed significant changes in accommodation for the size-only stimulus. They also observed that without blur-feedback the value of accommodation differed for the four subjects, ranging between 2 and 5D. Kruger and Pola suggested that these values may relate to the individual's level of DF. Additionally they noted that the change in target size produced an impression of variations in target depth and that the accommodative response may relate to the change in apparent distance rather than the change in actual size. Indeed in a footnote they indicated that pilot studies have shown that if the target does not appear to approach or recede, but instead seems to change size while remaining stationary, then the change in accommodative response may be reduced or even absent.

Clearly the role of proximal accommodation remains unclear and further work is required in order to clarify its position within the aggregate accommodative response. A discussion of proximal vergence appears in section 3.7C.

2.6 MEASUREMENT OF ACCOMMODATION

A wide variety of objective and subjective optometers have been used to measure the accommodative response ranging from relatively simple techniques such as stigmatoscopy or dynamic retinoscopy to the more complex infra-red optometers. However any optometer which uses visible light may fail to adequately control the subject's accommodation (Henson, 1983). A change in the vergence of the light emitted from the optometer will influence the accommodative stimulus. In all of the subsequent studies which will be described (Chapters 6-10), measurement of accommodation was made using an infra-red optometer (Canon Autoref R-1) which uses infra-red light to focus a target on the retina. The chromatic aberration of the eye will produce a hypermetropic shift in the refractive error of the eye when measured with infra-red light compared with that recorded in white light. In order to correct for this the manufacturers calibrate the instrument in order to give similar measures of refraction to conventional subjective techniques (Henson, 1983).

2.6A THE CANON AUTOREF R-1 INFRA-RED OPTOMETER

The major advantage of the Canon Autoref R-1 infra-red optometer is that it provides an open binocular field-of-view (18° vertically, 50° horizontally: Bullimore, 1987) through a large semi-silvered mirror, thereby allowing the introduction of a wide variety of fixation targets. The instrument is shown in Fig. 2.7. The open field-of-view also limits the contaminating effect of proximal factors and minimises instrument myopia (Hennessy, 1975). The Autoref R-1 has a power range of ±15.00D sphere and ±7.00D cylinder and measures the cylinder axis in 1° steps. The instrument may be adjusted for vertex distances of 0 or 12mm. The grating focus principle is used to determine the best focus in three meridians each separated by 60° and the sphero-cylinderical refractive error is computed by applying a sine^2 curve (Berman et al., 1984). Full details of the image analysing technique are given by Matsumura et al. (1983). A minimum pupil diameter of 2.9mm is required in order to obtain a reading. The optometer was modified so that the refractive error could be measured at approximately 1 second intervals although the

Fig. 2.7 The Canon Autoref R-1 Infra-red Optometer

actual measurement time is 0.2secs (Matsumura et al. 1983). Details of the optical layout of the instrument were presented by McBrien and Millodot (1985).

Two studies have evaluated the Autoref R-1 by comparing its findings with those of other autorefractors and also conventional retinoscopy and subjective techniques. Berman et al. (1984) compared refractive error measurements taken using the Autoref R-1, the Dioptron II autorefractor and distance streak retinoscopy in 75 subjects (150 eyes). They observed no significant difference in sphere or cylinder power between any of the techniques used although the value of the left cylinder axis showed significant variation ($p<0.05$), the standard deviation of axis readings being higher on the Autoref R-1 than for the other techniques.

McBrien and Millodot (1985) investigated the repeatability of the Autoref R-1 firstly by examining a set of 6 measurements taken in quick succession and then comparing measurements taken within a few days of each other. 186 eyes were examined and a high level of repeatability was observed although McBrien and Millodot also noted that the measurement of the cylinderical component may be slightly less valid, particularly the axis finding for astigmatism of less than 0.75D. They indicated that this may be due to the fact that the Autoref R-1 only scans 3 meridians in order to obtain a result and Long (1974) has shown that when the measurements are confined to three meridians, small measurement errors can produce large errors in computation of the final result. An increase in the number of meridians scanned would therefore improve the accuracy of the cylinder findings.

Nevertheless the optometer has been shown to provide reliable and repeatable estimates of the refractive error and has the advantages of being fully objective, requires relatively little operator skill, allows easy alignment and monitoring of fixation via the video monitor and indeed pupil measurements may be taken directly from this monitor. However a major disadvantage of the instrument is the difficulty in taking readings through spectacle lenses due to the reflections from the front surface of the lens. The manufacturers suggest that readings may be obtained by tilting the spectacle lens but it was felt that this would introduce inconsistent amounts of astigmatism depending on the degree of tilt and power of the spectacle lens. Consequently all ametropia in subsequent studies (Chapters 6-10) has been corrected using ultra-thin soft contact lenses (Hydron 06).

2.7 CONCLUSIONS

The anatomy and function of the accommodative mechanism have been considered as a separate component of the near-response. Despite extensive work over the last century a number of major areas remain unresolved particularly with regard to the stimulus to accommodation and the innervation to the ciliary muscle during periods of sustained near-vision. In Chapters 8-10 the adaptational mechanisms which affect both accommodative and vergence responses during sustained near-vision will be discussed together with the role that such processes may play in the development of ametropia. However it will be suggested in Chapter 5 that these adaptational mechanisms may involve an alteration in the synkinetic relationship between accommodation and vergence. Thus in Chapters 3 and 4 the vergence mechanism and the interaction of accommodation and vergence respectively will be considered.

CHAPTER 3

THE VERGENCE MECHANISM

3.1 INTRODUCTION

During a vergence eye movement the two eyes move in opposite directions. This is in contrast to a version movement where both eyes move in the same direction. Thus vergence movements may also be described as disjunctive eye movements. As the eyes change fixation from a distant object to a nearer object a convergence movement is made. This is illustrated in Fig. 3.1 when fixation is changed from A to B.

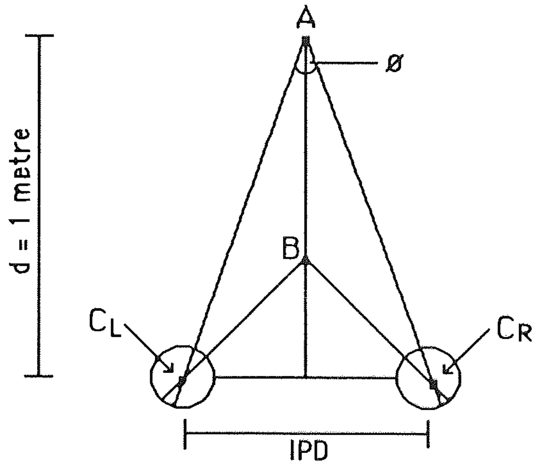

Fig. 3.1 As fixation changes from A to B a convergence movement is made. Angle ø (i.e. angle $C_L A C_R$)represents the vergence requirement. IPD = inter-pupillary distance; d = viewing distance; C_L and C_R represent the centres of rotation of the left and right eyes respectively.

It should be noted that changes in eye position may result from a combination of both vergence and version movements. Yarbus (1957) observed that when a subject changed fixation to a target which was both further away and to one side of the initial object of regard, both the vergence and version responses were clearly distinguishable. Alpern (1969) confirmed Yarbus's observation by examining the oculomotor response following the introduction of a base-out prism before one eye. The observed response is illustrated in Fig. 3.2. When a base-out prism is introduced before one eye as shown in Fig. 3.2B, the retinal image of the right eye is deviated whilst the position of the left retinal image remains unchanged. In order to regain bifoveal fixation it is only necessary for the right eye to move. However both eyes change position as illustrated in Fig. 3.2. Thus the change in eye position results from a combination of vergence and version eye movements which occur in series.

Alpern(1957) used electro-oculography in order to verify the responses illustrated in Fig. 3.2. He utilised the difference in the respective velocities of vergence and version movements in order to differentiate between these components (see section 3.8).

These eye movements illustrated in Fig. 3.2 are in accordance with Hering's law of equal innervation which stated that corresponding muscles of each eye normally receive equal innervation so that for any shift of gaze, the movements of the eyes are yoked together (Alpern, 1969).

Vergence is conventionally measured in *metre-angles (MA)* i.e. the amount of vergence required in order to fixate an object placed at a viewing distance of 1 metre. Thus the vergence requirement in metre-angles is the reciprocal of the distance of the object of regard measured in metres. This term was first introduced by Nagel (1880). In Fig. 3.1 the angle of vergence ø when viewing target A at a distance of 1 metre represents a vergence requirement of 1 metre-angle. Clearly angle ø will vary with the IPD. An advantage of this unit is that the vergence requirement is then numerically equal to the accommodation stimulus measured in dioptres. However this is not strictly accurate as convergence should be measured from the centre of rotation of the eye whilst accommodation is conventionally measured from the spectacle plane in order to facilitate arithmetic calculations (Emsley, 1953). It is also conventional to consider the

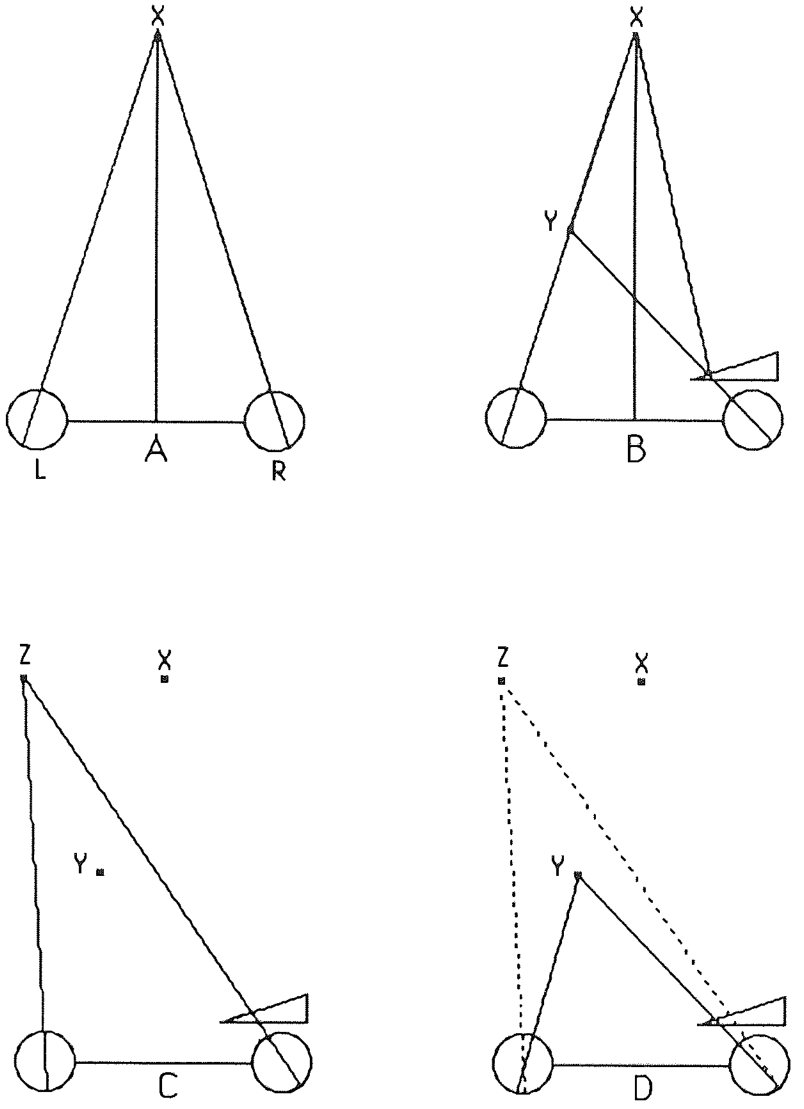

Fig.3.2 Eye movements when a base out prism is introduced before the right eye.

A. The initial position of the eyes.
B. A base-out prism is introduced before the right eye so that Y now becomes the new apparent fixation target.
C. The eyes make a version movement to fixate point Z
D. Both eyes then converge to fixate point Y.

convergence response as the angle formed between the two visual axes (von Noorden, 1985) i.e. angle ø in Fig. 3.1, rather than the vergence requirement for each individual eye.

Vergence may also be measured in *prism dioptres (Δ)* which is the tangential deviation of one centimetre at a distance of one metre. Thus from Fig. 3.1,

$$\Delta = 2\ \mathrm{Tan}\ \frac{\varnothing}{2} = \frac{(IPD)}{d}$$

where;
Δ = vergence requirement in prism dioptres
IPD = inter-pupillary distance (cms).
d = viewing distance (metres)

Now as the vergence requirement in metre angles (MA) = $\frac{1}{d}$

Then $$\Delta = (IPD).\ MA$$

Strictly the inter-ocular separation should be represented in the above equations as the distance between the centre of rotation of each eye rather than the inter-pupillary distance. However in the clinical situation it is difficult to determine the exact position of the centre of rotation and indeed Park and Park (1933) showed that the centre of rotation was not fixed but moved in a systematic way along a curved locus in space known as the space centrode. Over the range of horizontal movements of the eye, the centre of rotation moves approximately 2mm in the posterior-anterior direction and around 0.67mm horizontally (Carpenter, 1977).

3.2 GROSS ANATOMY OF THE EXTRA-OCULAR MUSCLES

The extra-ocular muscles, also referred to as the extrinsic muscles of the eye, are so called in order to distinguish them from the intra-ocular or intrinsic muscles within the globe e.g. the sphincter and dilator pupillae and the ciliary muscle.

Duke-Elder and Wybar (1973) in a review of the history of investigation into the anatomy of the extra-ocular muscles cited Gabriello Fallopio (1523-1562) as being the first to give a reasonably accurate description of the anatomy of the extra-ocular muscles. In his *Observationes anatomicae* (1561) Fallopio described the anatomy of the ocular muscles in man. Fallopio is more renowned for his observations on the human ovarian tubes (viz. Fallopian tubes). Earlier workers e.g. Galen (c.130-200 A.D.) and Aetius of Amida (c.502-575) had studied the anatomy of animal extra-ocular muscles and consequently their assumptions about human ocular musculature were inaccurate. Galen described six muscles, four to move the eye horizontally and vertically and two to rotate it, "*arranged by a kindly God*" so that man could move his eyes when he wished. However Galen also suggested that there was a seventh extra-ocular muscle, the retractor bulbi which is characteristic of the lower vertebrates (Gasson, 1986).

It is now established that the human orbit contains six extra-ocular muscles (Wolff,1976) namely the four recti (medial, lateral, superior and inferior) and the two oblique muscles (superior and inferior). The origin and insertion of these muscles are illustrated in Figs. 3.3 and 3.4. The four recti arise from a common origin, the annulus of Zinn which encircles the optic foramen and the apex of the orbit. They then pass forward to insert into the sclera at a point anterior to the equator of the globe. The superior oblique also arises from the apex of the orbit, from the body of the sphenoid bone and from the annulus of Zinn, and passes forward to a cartilaginous pulley, the trochlea, which is located just behind the orbital margin at the junction of the roof and medial wall of the orbit. The superior oblique, which takes the form of a tendon at this point, then turns at an angle of about 54° (varying between 32 ° and 64 °; Duke-Elder and Wybar,1973) to

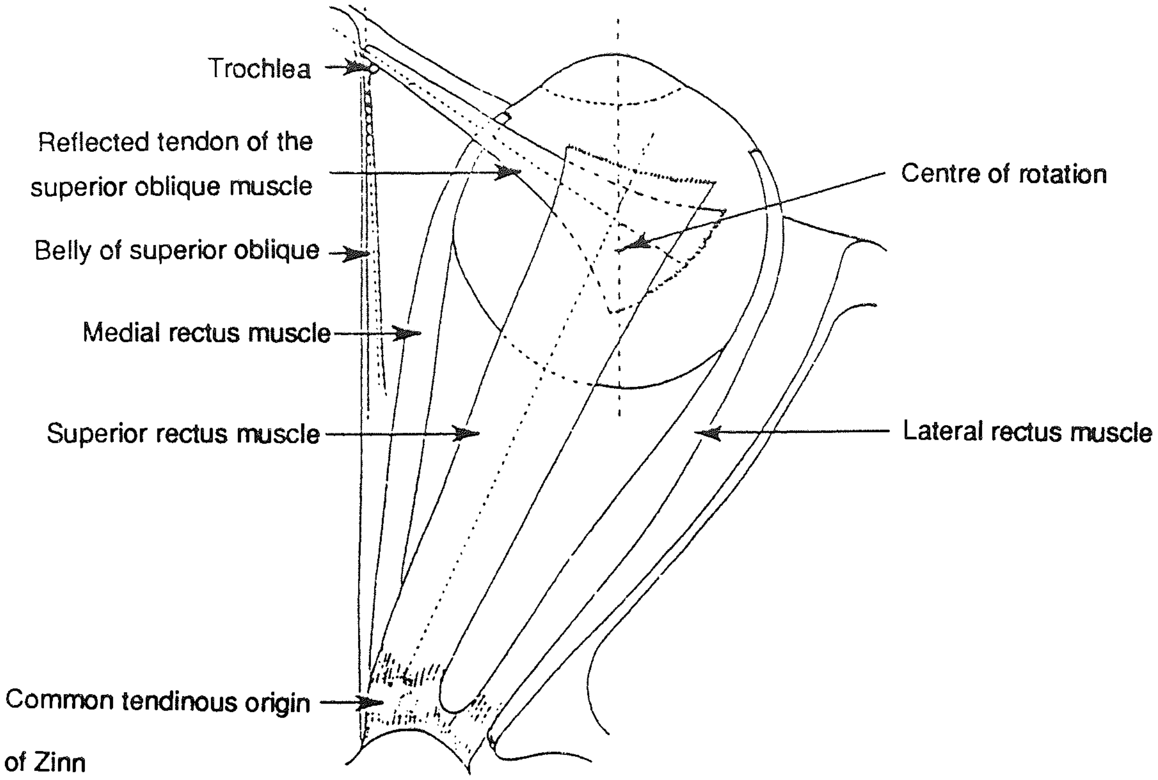

Fig. 3.3 Superior aspect of the globe and extra-ocular muscles.

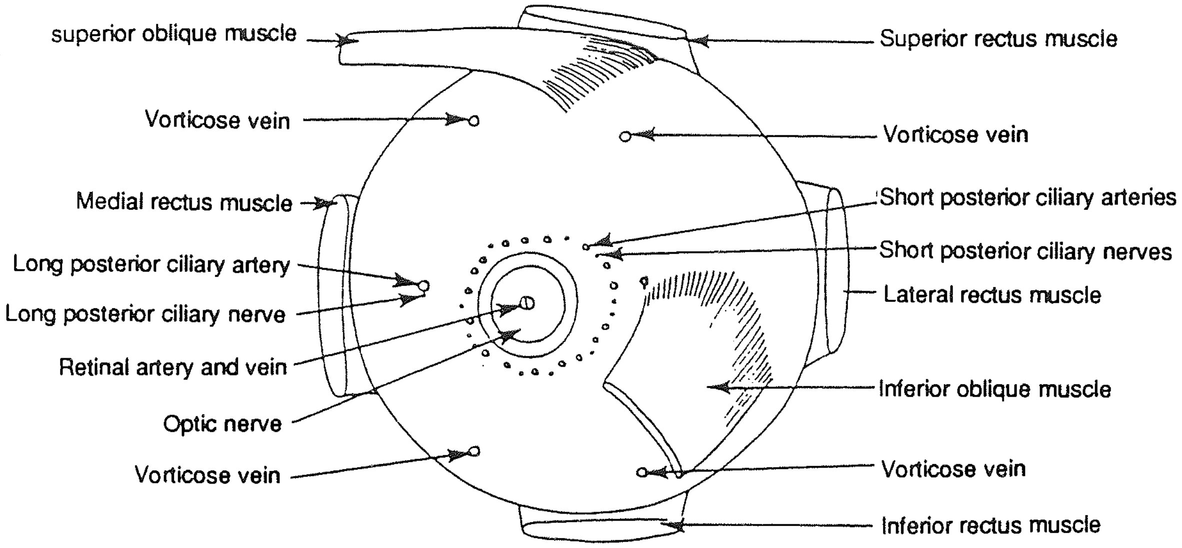

Fig.3.4 Posterior aspect of the globe.

the vertical plane of the globe to run under the superior rectus and has a fan-shaped insertion approximately 11mm in length lying obliquely on the upper part of the postero-lateral aspect of the sclera and placed behind the equator. The inferior oblique has an origin in the antero-medial corner of the floor of the orbit adjacent to the lateral aspect of the lacrimal fossa. It then passes backwards, laterally and upwards at an angle of approximately 51° (varying between 33 ° and 57 °; Duke-Elder and Wybar,1973) to the vertical plane of the globe beneath the inferior rectus, and has an insertion of around 9.5mm in length in the lower part of the postero-lateral aspect of the sclera about 5mm temporal to the optic nerve.

Each muscle is enclosed in a fascial sheath which is thickest anteriorly . The outer surface of the sheath blends with the fibro-elastic reticulum of the orbital fat and the inner surface is continuous with the perimysium of the muscle. The sheaths of the four recti are interconnected to form a fascial compartment, the muscle cone, around the globe.

3.3 STRUCTURE OF THE EXTRA-OCULAR MUSCLES

The extra-ocular muscles are composed of skeletal muscle which differs both anatomically and physiologically from the smooth muscle found for example in the ciliary muscle. Human skeletal muscle may also be described as striated muscle due to the regular pattern of transverse striations which cover the muscle cells. The dark and light stripes are denoted A- and I-bands respectively (Adler, 1987). A summary of the anatomical differences between these two muscle types is shown in Table 3.1.

Table 3.1 Summary of anatomical differences between smooth and skeletal muscle (from Silverstein, 1980).

	SKELETAL MUSCLE	SMOOTH MUSCLE
Cell type	Long cylindrical fibres arranged in bundles	Elongated tapering fibres arranged in sheets
Cell membrane	Distinct double-layered sarcolemma	Delicate sarcolemma fused with adjacent fibres
Cytoplasm	Sarcoplasm limited, organelles numerous	Small amount of sarcoplasm few organelles.
Myofibrils	Striated, fill cell	Non-striated, fill cell
Nuclei	Multiple flattened nuclei scattered over cell periphery just under sarcolemma	One oval or rod-shaped nucleus at centre of cell.
Vascular supply	Good blood supply; lymph capillaries restricted to epimysium and perimysium	Fair supply of blood and lymph capillaries
Nerve supply	Motor and sensory nerve endings	Parasympathetic and sympathetic innervation (motor) Sensory nerves (stretch receptors)

There are also differences in temporal characteristics between these two types of muscle. The latency between muscle excitation and the onset of contraction is considerably greater for smooth muscle when compared with striated muscle. Marshall (1980) stated that the excitation-contraction latency for smooth muscle (measured at 37° C) was around 200 msec while the equivalent value for striated muscle was of the order of 10 msec. Marshall pointed out that tension is developed more slowly in smooth muscle as the need for rapid activation of these muscles is generally less imperative. In contrast the extra-ocular muscles possess the fastest contraction time of any skeletal muscle in the human body, having a contraction time (measured from onset to peak of muscle tension) of less than 40 msec (Bell et al , 1980).

Differences in temporal characteristics of muscle contraction also relates to the types of motor nerve fibre supplying the muscle. The somatic efferent nerve fibres which supply skeletal muscle are generally myelinated type A (alpha) fibres. Whilst parasympathetic and pre-ganglionic sympathetic nerve fibres are also myelinated, the post-ganglionic sympathetic nerve fibres are non-myelinated and consequently have a slower propogation velocity. Details of some of the characteristics of these nerve fibres is shown in Table 3.2.

Table 3.2 Nerve fibre types in mammalian nerve (from Ganong, 1977)

Fibre type	Function	Fibre Diameter (μm)	Conduction Velocity (m/sec)	Spike Duration (msec)	Absolute Refractory period (msec)
A(alpha)	Somatic motor	12-20	70-120	0.4 - 0.5	0.4 - 1
B	Preganglionic autonomic	<3	3 - 15	1.2	1.2
C	Postganglionic sympathetic	0.3 - 1.3	0.7 - 2.3	2	2

Skeletal muscle does not normally contract in the absence of neural stimulation, lacks anatomical and functional connections between individual muscle fibres and is generally under voluntary control (Ganong, 1977). However it should be noted that only one form of vergence response may be initiated voluntarily (see Section 3.9). For a more detailed discussion on the anatomy and physiology of skeletal muscle see Ganong (1977) and Adler (1987).

The extra-ocular muscles are highly differentiated and instead of being grouped together into bundles separated by dense connective tissue, they are only loosely united. Woollard (1931) described three sizes of muscle fibres and observed that the most numerous fibres were those of medium thickness which comprise the majority of the muscle belly. The thinnest fibres tend to be located towards the peripheral parts of the muscle. Each muscle fibre has a diameter of 9-30μm (Wolff, 1976) and the intervals between the muscle fibres contain numerous nerve fibres.

Sommerkamp (1928) suggested that there were two types of extra-ocular muscle fibres which he differentiated into fast and slow fibres on the basis of their contraction velocity. Krueger (1929) demonstrated histological differences in these two types of fibres in the skeletal muscle of the frog. The fast type (called *Fibrillenstruktur* by Krueger) consist of thick fibres (diameter 11-15 µm) separated by an abundant sarcoplasm and these are probably responsible for rapid saccadic twitches. During electrical stimulation these twitch fibres show propagated impulses with non-graded contractile activity. The slow fibres (*Felderstruktur*) consist of thin fibres (diameter 9-11µm) with little sarcoplasm and poorly delineated fibrils which are not clearly separated . These slow fibrils exhibit graded contraction which is dependent upon the extent of membrane depolarization. These distinctions in extra-ocular muscle fibres were originally made on frog skeletal muscle but have subsequently been shown in the extra-ocular muscles of the guinea pig (Hess, 1961), cat (Hess and Pilar, 1963), monkey (Miller, 1967) and human (Dietert, 1965).

Alpern (1969) noted that there were two types of motor nerve endings associated with the different types of nerve fibres. The nerve endings on the thicker fibres have long varicose endings which form a sole plate at the point of contact. Alpern called these nerve endings *terminaisons en plaque.* However the thin fibres have thin delicate nerves with loop or bud-like endings which are analogous to the *terminaisons en grappe* (Tschiriew, 1879).

In an earlier paper Alpern and Wolter (1956) suggested that the histological differentiation of nerve fibres may account for the difference in velocities of vergence and version movements (see Section 3.8). They observed two types of nerve fibres by light microscopy namely;

i) Coarse, medulated nerve fibres which form typical motor end-plates and innervate the large muscle fibres only.

ii) Small non-medulated nerve fibres which form either loop-like endings close to the motor end-plate or delicate network-like endings on the muscle fibres.

Alpern and Wolter cited Boeke (1927) as being the first to describe this double innervation to the extra-ocular muscles. Boeke identified the small fibres as being part of the autonomic nervous system. Alpern and Wolter suggested that the final common pathway for saccadic movements was formed by the larger somatic nerve fibres whilst the final pathway for vergence movements was composed of thin autonomic nerve fibres. They noted out that this suggestion would account for the similar velocities of the vergence and accommodative responses, both oculomotor responses being innervated via the autonomic nervous system. Further discussion on the role of autonomic innervation to the extra-ocular muscles appears in section 3.4B.

3.4 INNERVATION OF THE EXTRA-OCULAR MUSCLES

3.4 A SOMATIC INNERVATION

The medial, superior and inferior recti and inferior oblique muscles are all innervated by the oculomotor (IIIrd) cranial nerve. The branches for the medial rectus enter the muscle belly 15mm from the origin of the muscle; those for the inferior rectus enter at the junction of the posterior and middle third of the belly, whereas those to the inferior oblique enter just after the muscle passes laterally to the inferior rectus muscle (von Noorden, 1985). These branches are all supplied from the inferior division of the oculomotor nerve. The nerve supply to the superior rectus arises from the superior division of the oculomotor nerve and enters the muscle at the junction of the posterior and middle third portions. The lateral rectus receives innervation from the abducent (VIth) cranial nerve which enters the muscle 15mm from its origin on the bulbar side. For a full description of these neural pathways see Duke-Elder and Wybar (1973).

3.4B AUTONOMIC INNERVATION

Eakins and Katz (1967) examined the effect of sympathetic stimulation on cat extra-ocular muscle. They observed that both stimulation of the cervical sympathetic nerve and the injection of epinephrine produced an increase in the resting tension of the superior rectus muscle. They noted that the response of the superior rectus to epinephrine was not always accompanied by a change in arterial blood pressure and therefore concluded that the change in muscle tension was not induced by cardiovascular changes. Furthermore they observed that topical administration of acetylcholine produced contracture of the extra-ocular muscle, whilst instillation of atropine, a muscarinic antagonist, failed to affect the contracture induced by acetylcholine. Eakins and Katz therefore concluded that there were no parasympathetic muscarinic receptors involved in the motor response.

It is unclear whether the induced changes in extra-ocular muscle tension resulted from direct stimulation of the extra-ocular muscles or as a secondary change following contraction of the intra-ocular smooth muscle. However Eakins and Katz noted that following the instillation of atropine, the response of the superior rectus to epinephrine was unaffected. Atropine blocks the muscarinic receptors in the intra-ocular smooth muscle and thus produces cycloplegia and mydriasis. The finding that atropine does not inhibit adrenergic stimulation of the extra-ocular muscle would suggest that the extra-ocular muscle contraction observed does not arise as a secondary response to intra-orbital smooth muscle changes. Kern (1968) examined the effect of sympathomimetic agents on the extra-ocular muscles of the Rhesus monkey (Macaca mulata). He observed that L-isoproterenol (a non-specific beta-adrenergic agonist) was the most potent sympathomimetic agent examined. Kern concluded that the sympathetic receptors within the extra-ocular muscles were of the beta-type.

3.5 BLOOD SUPPLY TO THE EXTRA-OCULAR MUSCLES

The extra-ocular muscles are supplied by the lateral and medial branches of the ophthalmic artery. The lateral branch supplies the superior and lateral rectus and superior oblique whilst the medial branch supplies the medial and inferior rectus and inferior oblique muscles. The inferior rectus and inferior oblique also receive a supply from the infraorbital artery. The medial rectus receives a branch of the lacrimal artery (von Noorden, 1985). The veins which provide vascular drainage from the extra-ocular muscles correspond to the arteries and drain into the superior and inferior orbital veins.

3.6 THE NATURE OF DIVERGENCE

The function of negative accommodation has been widely investigated and similarly there has been considerable discussion concerning the nature of negative vergence (divergence). The eyes are converged by active contraction of the medial recti. However a number of workers have proposed that divergence is not an active function but a passive relaxation of convergence (for a review see Toates, 1974). Verhoeff (1947) considered that divergence was merely a passive movement brought about by the relaxation of vergence effort. He stated;

> *"When I look from a near object to a distant one or voluntarily reduce my convergence, my impression is that I do so simply by relaxation of effort. When I converge my eyes as rapidly as possible it seems to me that the double images of the near object come together as rapidly as my effort can make them. But when I look as rapidly as possible from a near object to a distant one it seems that when I fully relax my effort of convergence the double images lay behind my relaxation. Such observations convince me that there is no divergence centre."*

Both Scobee and Green (1946) and Costenbader (1950) stated that divergence was a passive process which resulted from the elasticity of the orbital structures. However in a earlier paper Bruce (1935) had observed that if the elasticity of the lateral rectus was the sole divergence force then a divergent movement should be faster at the beginning of the response than at the end, with the tension being greatest initially. Bruce claimed that divergence occurred at a uniform speed (although he did not cite any evidence for this) and therefore concluded that divergence not be accounted for by a passive process.

Several workers have used clinical observations of pathological conditions to provide evidence for an active divergence mechanism. Lyle (1951) observed that lesions in the mid-brain produce divergence paralysis. He proposed that the mid-brain was the site of an active divergence centre. Adler (1958) indicated that the very existence of divergence paralysis provided evidence for an active divergence mechanism.

If divergence represents a passive relaxation of an active convergence mechanism, then the anatomical resting point i.e the position of the eyes in the absence of innervation to the extra-ocular muscles (see Section 3.7Ai) would represent the most divergent position which the eyes are able to assume. However Breinin (1957) observed in patients with intermittent exotropia that the level of divergence observed under anaesthesia is less than that observed during consciousness. This finding would indicate the presence of an active divergence mechanism during consciousness.

Recent work using electrophysiological techniques has conclusively demonstrated active divergence. Adler (1953) used an electromyographic technique previously described by Bjork (1952) in order to record the activity of the lateral rectus muscle during divergence. He observed that in divergence there was a burst of impulses from the lateral rectus which preceeded the movement of the eye by several milliseconds, indicating that this electrical activity initiated the muscle contraction. Breinin and Moldaver (1955) confirmed this observation to verify that divergence is indeed associated with active contraction of the lateral recti.

The most conclusive evidence for active divergence comes from the study of Tamler and Jampolsky (1967). They observed the activity of the lateral and medial recti using electromyographic techniques following the introduction of base-in prisms. The subjects binocularly viewed a near-target and a progressively increasing amount of base-in prism was introduced by means of a Risley rotary prism until fusion was disrupted. Tamler and Jampolsky observed increased activity in both lateral recti with increasing divergence. The increased activity was accompanied by a concomitant reduction in the activity of the medial recti. They therefore suggested that these findings provided conclusive support for the concept of an active divergence mechanism.

3.7 COMPONENTS OF VERGENCE

Maddox (1893) proposed that the total vergence response could be subdivided into independent factors which added arithmetically to produce the aggregate response.

> *"Strictly speaking, there are four elements of convergence, though the first and third are perhaps closely related. The four are: (1) Tonic; (2) Accommodative; (3) Convergence due to "knowledge of nearness", or in other words, " voluntary convergence", for we cannot, without special practice, converge the eyes voluntarily, under ordinary conditions, without doing so by thinking of a near object; (4) fusion convergence "* (p106).

A schematic representation of the Maddox classification of convergence is illustrated in Fig. 3.5.

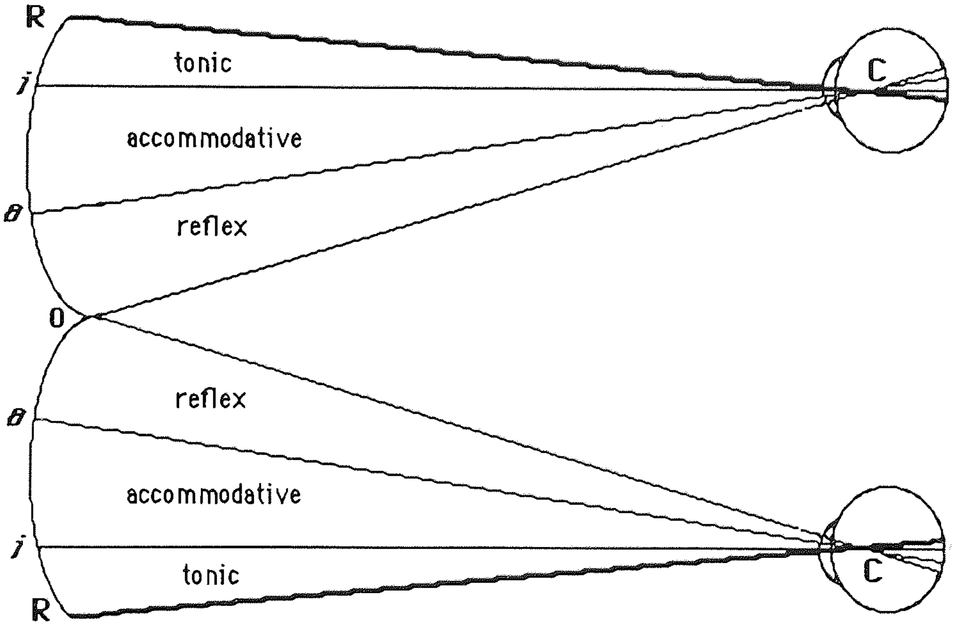

Fig. 3.5 A schematic representation of the components of convergence (redrawn from Maddox, 1893). C represents the centre of rotation of the eye. This denotation has been added to the original diagram.

It will be noted that convergence due to " knowledge of nearness" or proximal vergence is omitted from Fig. 3.5. In a review of the Maddox analysis of vergence, Morgan (1983) stated that Maddox had difficulty in placing proximal convergence within the aggregate vergence response. Maddox believed that the magnitude of tonic vergence could be affected by "persistent activity of the converging innervation" (p. 90). He listed a series of factors which could affect the magnitude of this persistent activity including sleep, drowsiness, alcohol, anaesthetic agents and knowledge of the distance of objects in space i.e. proximal vergence. Thus the reason for the omission of proximal vergence from Fig. 3.5 would appear to be due to Maddox's confusion between the tonic and proximal components of vergence.

Morgan (1983) pointed out that Maddox's intention was to provide " a series of aids to precision in the use of prisms" (p. vii) and Morgan suggests that the Maddox classification still provides a useful basis for clinical analysis of binocular vision problems. Further discussion concerning the individual vergence components described by Maddox appears in subsequent sections of this chapter.

3.7A TONIC VERGENCE

Hebbard (1952) reviewed various definitions of tonus with regard to the term *tonic vergence*. One definition which he cited was that of Carlson and Johnson (1942) who defined tonus as;

> *" The low degree of continuous activity which exists in muscles or nerves when they are at rest."*

Hebbard pointed out that the major difficulty which arises from this definition is to clarify what represents the position of rest of the vergence system. Maddox (1893) stated that tonic convergence represented the difference between "the anatomical position of rest" and the position of "physiological rest". He suggested that the ocular muscles possess a *physiological tone*, similar to that of other skeletal muscles. Tonic vergence is represented in Fig. 3.5 by angle R C i . Maddox observed that the eyes of alert subjects do not diverge when viewing a distant object under conditions of total dissociation but generally maintain a parallel or slightly convergent posture. He concluded that this position resulted from the activity of tonic vergence. The additional convergence which was required in order to binocularly fixate a near-target was produced by the added components of accommodative and reflex vergence.

Maddox recognised that tonic vergence varied between individuals and he suggested that such differences may relate to their oculomotor balance. He stated that the primary stimulus to tonic vergence was visual i.e. the desire to look at something and the necessity of imaging the object of regard on the fovea. However Maddox indicated two additional non-visual factors which could influence tonic vergence namely persistent activity of the convergence mechanism (see section 3.7) and the normal tonus of striated muscle. Recent research has confirmed that tonic vergence is indeed susceptible to adaptational changes during periods of sustained near-vision.

Maddox stated that excessive tonic vergence would produce latent overconvergence (esophoria) whilst deficient tonic vergence produces latent underconvergence (exophoria). In order to maintain normal binocular vision it is necessary to overcome these tendencies by the recruitment of additional reflex vergence which he assumed to be stressful and would therefore lead to asthenopia. Maddox also noted that tonic vergence can be altered by training; observing that viewing through base-out prisms produced an increase in tonic vergence (increased esophoria). Furthermore he observed that the use of plus lenses for near-viewing produced a reduction in exophoria at near which he attributed to increased tonic vergence. Owens and Leibowitz (1983), in a review of tonic vergence, suggested that the ability to produce changes in tonic vergence may facilitate adaptational effects during sustained near-vision. This facility is discussed in greater detail in Chapters 8-10.

3.7A i THE ANATOMICAL POSITION OF REST

Alpern (1969) defined the anatomical position of rest as;

> *" the position of the eyes if all of the extraocular muscles were devoid of all sources of innervation"*

Evidence for a divergent anatomical position of rest has come from examination of cadavers e.g. Grut (1889) cited the work of Volkman who examined the interpupillary distance (IPD) in fresh cadavers and observed that the mean IPD was greater for cadavers than for living subjects. Majoras (1935) also stated that the post-mortem posture of the eyes was usually that of divergence.

Other workers have investigated the effect of general anaesthetics and muscle relaxants on eye position in an attempt to determine the anatomical position of rest. Meyers (1951) assessed the lateral displacement of the eyes under general anaesthesia by measuring the distance between the limbus and the medial canthus in 37 anaesthetized patients. A significant level of divergence was observed in 65% of the patients examined, the mean value being 22° of divergence. Meyers also noted that those patients who were normally esophoric exhibited a nearly parallel position of the eyes. However there was no correlation between the habitual degree of heterophoria and the deviation observed under general anaesthesia. In a later paper Drucker et al (1951) evaluated the effect of d-tubocurare (a muscle relaxant) on the extra-ocular muscles in normal adult volunteers. They observed ptosis and progressive paresis of the extra-ocular muscles; the eyes adopting an upward and outward resting position. Duncalf and Jampel (1961) evaluated the effects of d-tubocurare on 26 patients who were about to have corrective surgery for strabismus. They estimated the deviation of the eyes by judging the position of the corneal reflexes (i.e Hirschberg method) and observed that the angle of divergence under complete ophthalmoplegia was of the order of 15-20°.

Abraham (1951) noted that the anatomical position of rest would vary throughout life as the structures which control the primary position are changed by growth of the eyes and surrounding tissues. In particular Abraham pointed out that the muscles are changed by either their activity or inactivity. This is based upon the principle that use of an organ leads to hypertrophy whilst disuse leads to atrophy. In later life therefore the anatomical position of rest changes from 45° divergent (Abraham, 1949) to around 20° of divergence due to the physiological activity of the extra-ocular muscles during life.

3.7A ii THE PHYSIOLOGICAL POSITION OF REST

Alpern (1969) stated that it is impossible to determine the absolute value of tonic vergence in a given subject as one cannot assess the anatomical position of rest. However an estimation of the value of tonic vergence may be obtained from the physiological position of rest. Such an estimation clearly assumes that the range of values for the anatomical position of rest would not be large. Alpern defined the physiological position of rest as the angle formed between the line of sight of the two eyes while viewing monocular targets under conditions where all stimuli to fusion have been obviated. The angle formed under these conditions is the *heterophoria*. However it should be noted that the value of heterophoria gives an indication of the level of tonic vergence only when the output of the other vergence components, namely proximal and accommodative vergence, is zero. Such a situation exists when vergence is measured under stimulus-free conditions. The most convenient stimulus-free environment is that of total darkness. The term *dark vergence (DV)* has been adopted (Owens and Leibowitz, 1976) to describe the value of vergence measured under darkroom conditions.

3.7A iii DARK VERGENCE

In the studies of Ivanoff and Bourdy (1954) and Ivanoff (1955) a nonius alignment method was used to measure the vergence response for a large letter M which was presented in the inferior visual field at a range of luminances. They measured binocular convergence in 9 subjects at test luminances varying from 1 to 10^{-6} cd.m^{-2}. Vergence responses remained fairly accurate until luminance reached scotopic conditions when increasing fixation disparities were observed for both distance and near stimuli. Eight of the nine subjects exhibited an increasingly convergent (eso) fixation disparity for the distance stimulus and an increasingly divergent (exo) fixation disparity for the near stimulus. The ninth subject's vergence responses tended towards a parallel posture at the lowest luminances. Individual vergences in darkness ranged between 0.05 and 4 MA with a mean of 1.79MA (Ivanoff and Bourdy, 1954).

Fincham (1962) used infra-red photography to measure the position of vergence in 31 subjects in total darkness. He observed that when the subjects were instructed to look into the distance they exhibited a mean convergence of 0.41MA (sd= 0.72; range +2.1 to -1.0 MA). Levy (1969) used a perimeter to present pairs of briefly flashed monocular stimuli at various positions along the principal meridian in an otherwise dark room. The subject observed the light for one second, followed by three seconds of darkness and then the light was displayed for a further second. The subject reported the position of the second stimulus with respect to the first. As the stimuli were in the same position, Levy suggested that the eye would drift towards its resting position during the period in darkness. Therefore the second flash would appear to be displaced relative to the first. Levy's results gave a value for dark vergence of 2.6 MA. Owens and Leibowitz (1983) suggested that the response strategies of the task requirement in Levy's method may have been contaminated by proximal vergence and this might account for the increased value of dark vergence when compared with the findings of Ivanoff and Bourdy (1954) and Fincham (1962).

Owens and Leibowitz (1980) used a laser nonius alignment device to measure dark vergence in 60 subjects, the dichoptic bars being flashed for a period of 125msec. This stimulus duration is shorter than the response time for either accommodation or vergence (Rashbass and Westheimer, 1961). The distribution of dark vergence found by Owens and Leibowitz is illustrated in Fig. 3.6.

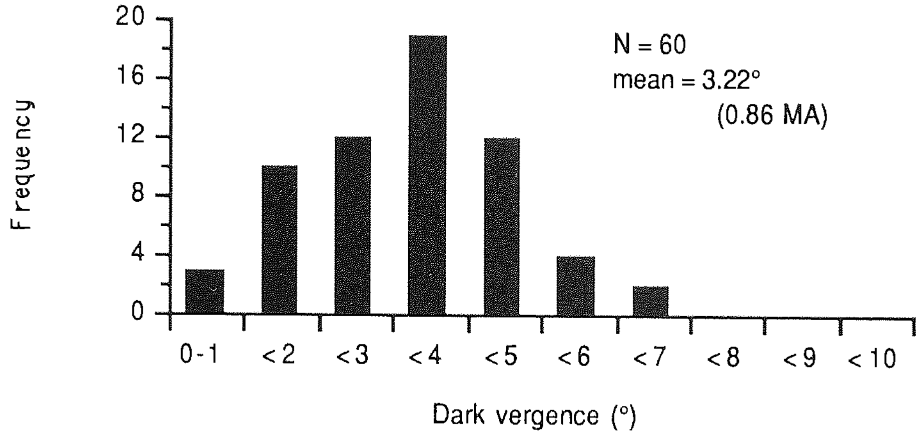

Fig. 3.6 Frequency distribution of dark vergence for 60 college-age subjects (Redrawn from Owens and Leibowitz, 1980).

In a more recent study Owens and Wolf-Kelly (1987) measured dark vergence in 28 college students using two dichoptic stimuli which were flashed for 100 msec in an otherwise dark room. A Maddox rod was placed before the left eye and the subject reported the position of the streak relative to the spot seen with the right eye. This light source was then moved until alignment was achieved. The mean value of dark vergence recorded was 1.20 MA.

Hogan (1985) recorded dark vergence (referred to in his study as tonic vergence) using a nonius alignment device in which the subject observed the alignment of the two monocular vertical lines. The targets consisted of a bank of light emitting diodes which were energised for only 125msec in order to prevent a fusional response. Tonic (dark) vergence was examined in 60 subjects and a mean value of 0.93 MA was obtained.

3.7B ACCOMMODATIVE VERGENCE

Accommodative vergence refers to a blur-driven change in the horizontal position of the visual axes (Ciuffreda and Kenyon, 1983). This synkinesis between accommodation and vergence was described by Mueller (1826). Accommodative vergence is conventionally referred to in the literature as accommodative convergence (AC) although it may be positive (producing convergence) or negative (divergence). In accordance with convention the term accommodative convergence will be adopted for all values of accommodative vergence. A more detailed discussion on AC appears in Chapter 4 in which the synkinetic interaction of accommodation and vergence is considered further.

3.7C PROXIMAL VERGENCE

"The awareness of a near object may give rise to an appropriate degree of convergence which is generally called *proximal convergence* " (Duke-Elder and Wybar, 1973). Maddox's original classification referred to this component as the vergence induced by "knowledge of nearness" (see section 3.7). As a result of the intimate association between accommodation and vergence, it may be difficult to determine whether a change in the vergence response results directly from proximal vergence or from proximal accommodation driving accommodative convergence. Conversely proximal accommodation may arise from proximal vergence stimulating convergent accommodation. The role of proximal accommodation has been discussed in Section 2.5D. Whilst evidence exists for a proximal input to the near-response, the exact location of this input within the oculomotor system remains unclear.

Asher (1952) examined the role of proximal factors on accommodative convergence in 12 subjects reporting asthenopic symptoms and 22 asymptomatic subjects. Changes in accommodation were stimulated by three different methods;

i) By the introduction of negative spherical lenses whilst the subject viewed a target placed at a distance of 6m.

ii) Fixating targets placed at different viewing distances.

iii) The target was placed at a viewing distance of 20 cms and positive spherical lenses were used to relax accommodation.

The vergence response was measured for the changes in accommodation produced by the three methods described above. Subjects were then classified into 3 groups depending on their response to the various accommodative stimuli.

a) Accommodative: the relationship between accommodation and vergence remains approximately the same whether the observer is viewing the target directly or a virtual image of the target. Thus methods i) and ii) above will give similar results. In these subjects vergence appears to be solely induced by the degree of accommodative effort.

b) Perceptual: no convergence is induced by the use of negative lenses, but a convergence response is recorded when the target position is changed (i.e. method ii).

c) Intermediate: lying between types a) and b).

Asher observed that in 22 asymptomatic subjects, 2 were placed in the accommodative group, 5 in the perceptual group and 15 in the intermediate group. However in 12 asthenopic subjects none fell into the accommodative catagory, 11 were placed in the perceptual group with 1 subject being classified as intermediate. Asher concluded that the proximal component dominates the vergence response in patients having asthenopic symptoms.

Alpern (1955) examined the effect of testing distance on the AC/A ratio using a haploscope in order to assess changes in heterophoria. AC/A ratios were determined over an accommodation stimulus range of 0-4.50D and at testing distances ranging between 20 and 590 cms. The accommodative response was plotted against vergence for 11 young adult subjects and the reciprocal of the slope calculated in order to give the AC/A ratio. Alpern concluded that there was no consistent variation in AC/A with testing distance.

In a later paper Ogle and Martens (1957) noted that measures of accommodative convergence vary depending on whether the change in accommodative stimulus is induced by alteration of target distance or by the introduction of negative spherical lenses. They attributed this difference to proximal factors. In order to quantify this parameter Ogle and Martens examined accommodative convergence/accommodation (AC/A) ratios in which the change in the accommodative stimulus was produced by the two methods described above. Heterophoria was assessed either by the use of a Maddox rod or using the fixation disparity technique. These methods were used to calculate the proximal convergence/accommodation (PC/A) ratio. Ogle and Martens reported a mean value of PC/A using the Maddox rod technique (N=28) of 0.9Δ/D (sd = ±0.9). However when using the fixation disparity method to assess vergence changes, the mean value of PC/A in 104 subjects was 1.52Δ/D (sd = ±1.62). Ogle and Martens pointed out that the differences in PC/A by the two methods of measurement may relate to the different degrees of binocularity, a Maddox rod producing total dissociation of the eyes while fixation disparity allows a more binocular view. They suggested that this larger binocular field may enhance the stimulus for psychic awareness of distance. It is also of interest to note that in the 104 subjects examined by the fixation disparity method, there was no significant variation of PC/A with refractive error. This observation may be significant when considering accommodation-vergence synkinesis in different refractive groups (see Section 5.2Fiic).

Alpern (1958b) examined the effect of target size on the vergence response by measuring the change in vergence while viewing targets of differing sizes. The size of the target varied between 2.5 and 11.2 cms and the accommodation and vergence responses were measured using a haploscope-optometer. Alpern observed that changes in target size produced a significant increase in the vergence response. However Alpern also noted that the changes in target size may be independent of variations in perceived distance and it may incorrect to assume that the observed changes in vergence response were produced by proximal factors.

A review of previous studies on proximal vergence was presented in tabular form by Hokoda and Ciuffreda (1983) and is reproduced in Table 3.3.

TABLE 3.3 Summary of previous investigations into proximal vergence. (After Hokoda and Ciuffreda, 1983).

AUTHORS	**SUBJECT DETAILS**	**METHOD**	**ACCOM. MEASUREMENT (S=accom. stimulus; R= accom. response)**	**PC/T† (Δ/D) [mean ± 1 sd]**
Tait (1933)	18-30yr N=200	Zero accommodative level phoria at 33.3 cms minus 6m phoria and near fusion demand for binocular fixation	S	1.87±2.39
Hofstetter (1942)	28 young adults	34.5 cm gradient AC/A minus 5m gradient AC/A. Haploscope measures	R	0.73±0.57
Morgan (1944b)	20-30yr N=50	Near fusion demand for binocular fixation (40 cm) minus tonicity, AC and fusional vergence Haploscope measures	R	1.20±0.8
Morgan (1950)	413 non-presbyopes	Calculated AC/A (6m and 40 cms) minus gradient AC/A (+1.00D at 40cms).	S	0.53±1.17
Shapero & Levy (1953)	24-35yr N=8	Phoria compared across same accom. demand (0-3D) for different distances (6m-33cms); prism effectivity correction	S	0.87
Manas & Schulman (1954)	22 young adults	Calculated AC/A (6m and 40 cms) minus gradient AC/A (+1.00D at 40 cms	S	0.53±1.17
Alpern (1955)	11 young adults	Zero accommodative level phoria at different distances (5.9m-20cms)	R	0.71
Ogle & Martens (1957)	19-50yrs (mean=27yr) N=28	Calculated AC/A (4.4m-14cms) minus 40 cm gradient AC/A; prism effectivity correction	S	0.9±0.9
Ogle & Martens (1957)	14-72yrs (mean=31yr) N=104	Calculated AC/A (associated phorias at 4.4m and 40cm) minus fixation disparity derived AC/A at 40cms; prism effectivity correction	S	1.52±1.62
Hofstetter (1951)	20-27yr (mean=23yr) N=21	33.3cm gradient AC/A minus 6m gradient AC/A; prism effectivity correction	S	0.87

AUTHORS	**SUBJECT DETAILS**	**METHOD**	**ACCOM. MEASUREMENT (S=accom. stimulus; R= accom. response)**	**PC/T† (Δ/D) [mean ± 1 sd]**
Ogle et al (1967)	11-79yr (mean=32yr) N=256	Calculated AC/A (associated phorias at 2.5m and 33.3cms) minus fixation disparity derived AC/A at 33.3cms; prism effectivity correction	S	1.81±1.95
Franceschetti & Burian (1970a)	95 unspecified age	Calculated AC/A minus 40cm gradient AC/A	S	2.03
Sheedy & Saladin (1975)	22-39yr N=13	Zero accommodative level phoria at 40cm minus distance phoria and near fusion demand for binocular fixation	S	1.96±1.72
Hokoda * (1982)	6-47yr (mean=29yr) N=106	Calculated AC/A (4.5m and 40cm); minus gradient AC/A (40cm).	S	1.70±1.72
Wick (1985)	14-36yrs (mean=25.2) N=20	Calculated from near and distance heterophoria	S	2.56

† PC/T : Ratio of proximal convergence / testing distance measured in dioptres

* unpublished data.

Wick (1985) attempted to assess the contribution of proximal vergence to the aggregate vergence response. He measured distance and near (40cm viewing distance) heterophoria, AC/A ratio and the accommodative response. From this data he calculated the output of accommodative and fusional vergence and assumed that the remainder of the response would be made up of proximal vergence. Wick concluded that the contribution of proximal vergence to the combined response would exceed that of AC, the mean values observed being 6.4Δ and 5.18Δ respectively . However a number of points should be noted from Wick's paper. Firstly the stimulus AC/A ratio calculated from Wick's data would only be 2.07Δ/D, considerably lower than the mean value of 4.0Δ/D obtained by Morgan (1968). It may be that in those subjects having low values of AC, there is a greater contribution from proximal vergence. Furthermore the role of tonic vergence within Wick's calculation is somewhat unclear. It would appear that he assumed that the output of tonic vergence would remain unchanged for both distance and near viewing. However the target used in the assessment of the near heterophoria may have induced changes in tonic vergence (see Section3.7Aiii).

In the same paper Wick presented a model of the vergence system which included a proximal component (see Section 4.9). He suggested that the input from proximal vergence would be located in front of the CA/C cross-link so that proximal vergence would drive CA. However this would also imply that proximal accommodation would stimulate AC and clearly further work is required in order to determine the respective roles of proximal accommodation and vergence within the aggregate near-response.

3.7D FUSIONAL (DISPARITY) VERGENCE

A vergence response may be initiated when the images of the object of regard fall on non-corresponding points on the two retinae. Such vergence movements are called fusional vergence movements (Westheimer and Mitchell, 1956). Tyler (1983) defined corresponding retinal points in terms of ocular geometry, suggesting that corresponding points would lie at the same distance, both horizontally and vertically, from the centre of the fovea of each eye; this distance being measured in terms of visual direction i.e. units of arc. Corresponding points have the perceptual characteristic of giving rise to identical visual directions (Jones, 1983). Furthermore Jones noted that Hering (1868) described corresponding retinal points as "cover points", the implication being that if the two retinae were placed on top of one another so that the two fovea are in alignment, then corresponding points would be juxtaposed.

Alpern (1969) defined the stimulus for fusional movements thus;

> *"The stimulus for fusional movements in the horizontal plane is a disparity in the egocentric localizations of the visual fields of the two eyes which is associated with a disjunctive movement of the eyes independent of change in their refractive power".*

The phrase " egocentric localizations" refers to the projection into the visual field of the corresponding retinal points. However this relatively complex definition adds little to the initial sentence of this section (3.7D) except to emphasize that the change in vergence response is not a consequence of a change in accommodative response. It should be noted however that disparity-vergence will initiate convergent accommodation (see Chapter 4). Perhaps a better definition comes from the work of Stark et al. (1980) who defined this vergence component as;

> *"The eye movement response when the vergence system acts as a closed loop visual feedback control system to remove disparity error."*

If the two images of an object of regard should fall on non-corresponding retinal areas in each eye, then that object will be simultaneously localised in two separate visual directions resulting in diplopia and confusion. It is this disparity between the position of the retinal images which acts as the stimulus to fusional vergence (Leigh and Zee, 1983). Thus diplopia is not necessary in order to elicit such a vergence response (Stark et al,1980). Alpern (1969) noted that the introduction of a weak prism before one eye will produce a vergence response although the subject will not be consciously aware of any diplopia.

Stewart (1961) stated that the fusion response can be divided into two components namely motor and sensory . The motor component produces correct alignment of the two eyes so that images of the object of regard fall on corresponding points on the two retinae. This then allows sensory fusion to take place, i.e. the integration of information received at the cortex from the two eyes into a single image.

Stark et al (1980) suggested that as it is retinal disparity rather than the presence of diplopia which produces a vergence response, the term *disparity-vergence* is most suitable to describe these movements and this term will be adopted in this thesis. However it should also be noted that the perception of diplopia is a sensory process and it is likely that during the initiation of disparity-vergence, some degree of sensory suppression will take place (similar to that which occurs during a saccadic eye movement). This would prevent the subject from perceiving diplopia while the retinal images fall on non-corresponding points.

According to the Maddox classification of vergence, the disparity-vergence response serves to compensate for any error of alignment of the two eyes which remains after the other components of vergence, namely tonic, accommodative and proximal have taken effect. However the work of Semmlow and Heerema (1979) has indicated that this may not strictly be the case; this point is discussed further in section 4.8A.

3.8 TEMPORAL CHARACTERISTICS OF THE VERGENCE RESPONSE

Whereas the response latency of vergence and version eye movements is similar at around 120-200 msec, the velocity of vergence eye movements is much slower. Westheimer and Mitchell (1956) observed that the maximum velocity for horizontal fusional movements of 5.5° was 21.43°/sec whilst Adler (1987) noted that the velocity of version eye movements could be up to 400°/sec. The temporal aspects of disparity-vergence will be considered in section 3.8A; for a consideration of temporal aspects of accommodative convergence see section 4.7A.

3.8A TEMPORAL CHARACTERISTICS OF DISPARITY-VERGENCE

The time-course of disparity-vergence movements has been studied photographically by Tani et al (1956), Westheimer and Mitchell (1956), Stewart (1961) and by Alpern (1957) using electro-oculography. These workers all observed the relatively slow velocity of these movements. Stewart (1961) noted that disparity-vergence movements reach a maximum velocity of around 10 °/sec. As the extra-ocular muscles are capable of producing saccadic eye movements up to 400 °/sec (Adler, 1987) , then the slower disparity-vergence velocity must relate to a delay in innervation to the muscles rather than to any delay in the action of the muscles themselves.

Rashbass and Westheimer (1961) observed that when a 2° target disparity was introduced, the reaction time was typically around 160 msec. Similar durations of reaction time have also been reported by Westheimer and Mitchell (1956 and 1969). Rashbass and Westheimer noted that a constant velocity of vergence movement was quickly established and maintained for about 200 msec. The velocity then falls off until the final vergence position is reached. Larger disparity stimuli however produce a higher maximum velocity.

3.9 VOLUNTARY VERGENCE

Duke-Elder and Wybar (1973) suggested that in addition to the Maddox classification of vergence a further component may be added namely *voluntary vergence*. They defined voluntary vergence as, " vergence initiated in the cerebral cortex by a volitional effort". It should be noted that this is not the same as the voluntary vergence component suggested by Maddox (1893) which actually referred to proximal vergence (see Section 3.7). Furthermore Duke-Elder and Wybar noted that voluntary convergence is still associated with accommodation and pupil miosis.

Voluntary vergence is the only disjunctive eye movement which may be produced at will. Eskridge (1971) examined voluntary convergence using a haploscope-optometer. In order to stimulate voluntary convergence the arms of the haploscope were placed at various vergence stimuli and the targets were superimposed by a voluntary vergence effort. When fusion occurred, the accommodative response was measured using the optometer. In addition the subject's accommodative convergence was examined. Eskridge observed that the levels of accommodative convergence and voluntary convergence were identical and therefore concluded that voluntary convergence was initiated via the voluntary stimulation of accommodative convergence. It is difficult to be certain that the vergence responses were in fact voluntary convergence and not fusional vergence. Eskridge stated in his paper that these two components could be differentiated by voluntarily diverging the eyes to the maximum and then adjusting the haploscope arms until the targets were superimposed. However it must be questioned whether the subject would be able to sustain the output of voluntary convergence once a fusional stimulus was introduced, i.e. the presence of two monocular targets falling on non-corresponding points.

Fry (1959b) noted that subjects viewing monocular targets via a haploscope-optometer were able to exert additional convergence when the maximum level of accommodative effort had been reached. He suggested that this extra vergence output represented accommodative vergence produced by voluntary alignment of the targets. However it should be noted that in this situation the vergence response which is described as voluntary is again responding to retinal disparity. It would seem likely that true voluntary convergence can only be examined under stimulus-free conditions since only under this condition can contamination from fusional and proximal vergence be eliminated. Under such conditions it would be possible to determine whether voluntary vergence is entirely composed of accommodative convergence or whether it is an additional component of the vergence response.

3.10 CONCLUSIONS

The function of the vergence system is to align the visual axes of the two eyes so that an image of the object of regard falls on corresponding points of the two retinae. This eliminates retinal disparity and therefore avoids diplopia and confusion. However under normal binocular viewing conditions, vergence and accommodation interact closely to produce a clear single image of the object of regard. Therefore in Chapter 4 the synkinetic relationship between accommodation and vergence is examined further.

CHAPTER 4

ACCOMMODATION-VERGENCE SYNKINESIS

4.1 INTRODUCTION

In Chapters 2 and 3 accommodation and vergence were considered as separate components of the near-response. However accommodation and vergence do not operate independently but interact so that under closed-loop conditions, where negative feedback mechanisms are allowed to operate, accommodation will initiate a vergence response [i.e. accommodative convergence (AC)] and conversely vergence will drive accommodation [i.e. convergent accommodation (CA)].

4.2 ACCOMMODATIVE CONVERGENCE.

Accommodative convergence (AC) has been defined as a blur-driven change in the horizontal position of the eyes (Ciuffreda and Kenyon, 1983). Mueller (1826) is frequently cited as being the first to demonstrate this synkinesis between accommodation and vergence. In a monocular experiment he observed that when a target was moved inwards along the line of sight of the viewing eye, there was a slow inward movement of the occluded eye. This experiment was later repeated by Alpern and Ellen (1956a) who used electro-oculography (EOG) in order to objectively measure the vergence response. They confirmed Mueller's findings and furthermore observed that the fixating eye remained stationary during the convergence movement. This observation would not be in accordance with Hering's law of equal innervation which states that: "corresponding muscles of each eye normally receive equal innervation so that for any shift of gaze the movements of the two eyes are yoked together" (Alpern, 1969). Alpern and Ellen stated that the failure of the vergence system to conform to Hering's law resulted from the "predominance of the fixation system". However Kenyon et al. (1978) used a low-noise, high bandwidth infra-red monitoring system to examine the vergence response to a monocular accommodative stimulus of 2D. They observed that both the occluded and fixating eyes do converge and recorded a mean response in the fixating eye of 0.41° (sd = ±0.22°) . The mean vergence response of the occluded eye was 3.5° (sd = ±0.91°). Kenyon et al. suggested that the inherent noise level of the EOG technique used by Alpern and Ellen could obscure such small eye movements and this was why they had not been previously observed. The findings of Kenyon et al. would indicate that the change in AC is a binocular response and the movements occur in the direction (although not the amplitude) predicted by Hering's law of equal innervation. They also noted that the movement may start as an equal binocular response which is modified by feedback control processes into an unequal, but still binocular movement in order to maintain target fixation.

The gain* of AC is reflected in the accommodative convergence/ accommodation (AC/A) ratio (Schor, 1986). A number of studies have quantified this ratio by placing the vergence system into an open-loop state. This may be achieved by dissociating the two eyes in order to eliminate the stimulus to fusion. An increase in the accommodative response will induce a rise in AC. Under closed-loop conditions, it is likely that this increase in AC would be accompanied by a decrease in disparity-induced vergence in order to maintain the aggregate vergence response and thereby avoid diplopia and confusion. However by totally dissociating the two eyes, the increase in AC does not induce diplopia or confusion and therefore does not require a compensatory change in disparity-vergence. Thus opening the vergence loop allows the increase in AC to become manifest.

If the open-loop vergence response is measured at two different accommodation levels, then any change in vergence will have been produced by variation in AC providing the other vergence components namely tonic and proximal vergence are kept constant. For a review of techniques employed to assess the AC/A ratio see Borish (1970). The three

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* gain: the ratio of output magnitude to input magnitude (Hung and Ciuffreda, 1983).

principal methods used to measure the ratio are;

i) Heterophoria method
ii) Gradient test
iii) Fixation disparity method

4.2A HETEROPHORIA METHOD

In this technique the value of AC/A is derived from the difference between the heterophoria recorded when viewing a distant target and that recorded when viewing a near target (Duke-Elder and Wybar, 1973). The assumption is made that the difference in vergence response between the two values of heterophoria is solely due to the change in AC. Clearly variations in target distance will not only produce an alteration in AC but also in proximal cues to accommodation and vergence and therefore any technique involving a change in target distance will not give an absolute value of AC/A.

4.2B GRADIENT TEST

In this technique, the AC/A ratio is determined by measuring the heterophoria at two different accommodative stimulus levels, the change in accommodation being produced by the use of spherical lenses rather than a change in target distance. This reduces the contaminating effect of proximal vergence. However it should be noted that variation in lens power will alter the spectacle magnification and the induced change in the apparent size of the target may drive proximal accommodation (see section 2.5D). Using this method;

$$\mathbf{AC/A = (P_2 - P_1)/\Delta D}$$

where P2 = heterophoria at higher accommodative stimulus
P1 = heterophoria at lower accommodative stimulus
ΔD = change in accommodation

The term ΔD may be taken as either the change in the accommodative stimulus or the change in the accommodative response. The former will compute the *stimulus AC/A* ratio whilst the latter allows the calculation of the *response AC/A* ratio. Further discussion on the difference between these two forms of AC/A appears in section 4.3.

4.2C FIXATION DISPARITY METHOD

This method was described by Ogle et al. (1967). The AC/A ratio is derived by dividing the value of prism required to produce a given fixation disparity by the value of spherical lens power which produces the same fixation disparity. Ogle et al. list six advantages of this technique;

1) Same target stimulus }
2) Same level of light adaptation } Under both
3) Same accommodation stimulus } measurement conditions
4) Same task requirements }
5) Fusion is maintained
6)Test provides a measure of the prism-induced oculomotor imbalance.

Clearly a number of these advantages also apply to the gradient test although point #5 will be discussed further in section 4.3A. A previous study (Rosenfield, 1984) observed that this technique requires good patient co-operation and accurate observation. The Mallett fixation disparity unit (viewing distance 6m) was used to determine the AC/A ratio in 17 optometry students and the mean value of AC/A obtained was 3.28Δ/D (sd = 1.37). The ability of untrained observers to perform this test was questioned because of the extremely vigilant observation which is required in order to determine the exact point at which a disparity occurs.

4.3 DISTRIBUTION OF AC/A

Typical distributions of stimulus AC/A taken from the studies of Ogle et al. (1967) and Franceshetti and Burian (1970b) are illustrated in Figs. 4.1 and 4.2 respectively.

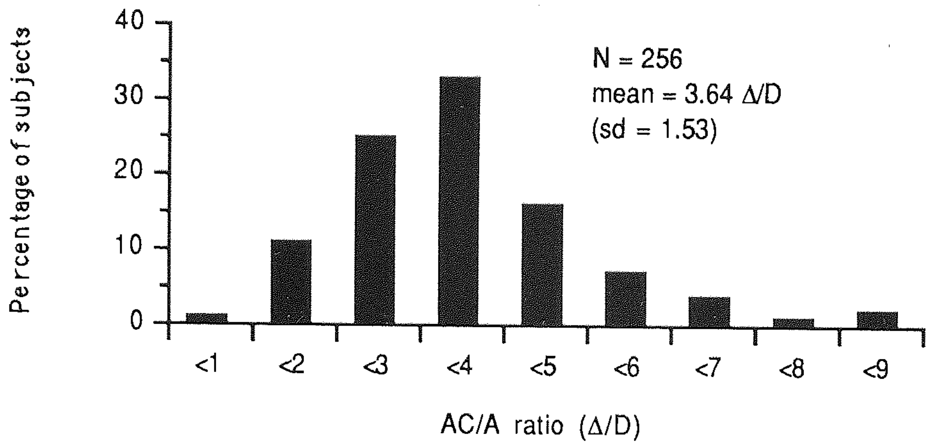

Fig. 4.1 Distribution of stimulus AC/A ratios in a "normal" (age range 11-79 years) population. AC/A measured using fixation disparity technique. (Redrawn from Ogle et al., 1967)

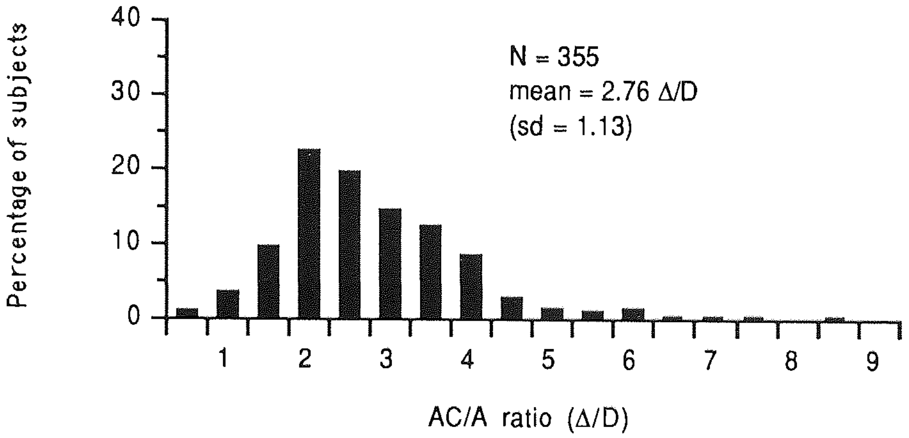

Fig. 4.2 Distribution of stimulus AC/A ratios in a "random" (age range not specified) population. AC/A measured using gradient method. (Redrawn from Franceshetti and Burian, 1970b)

Whilst the two distributions of AC/A illustrated in Figs. 4.1 and 4.2 are similar, it should be noted that the mean value of AC/A is lower for the gradient (dissociated) technique of measurement when compared with the fixation disparity (associated) method. Further discussion on the differences between these two methods of assessement appears in Section 4.3A. Several studies have reported mean values of stimulus AC/A between 3-5Δ/D (e.g. Morgan, 1944b; Morgan and Peters, 1951). Again it should be emphasized that the denominator for these ratios is the level of accommodative stimulus. However it has been demonstrated by a number of workers including Morgan(1944b), Heath (1956b), Westheimer (1966) and Ramsdale (1979) that the accommodative stimulus and accommodative response are unequal apart from one specific value of accommodative stimulus. This is illustrated in Fig. 4.3. This inequality of accommodative stimulus and response produces an accommodative "lead" at the lower end of the stimulus range and an accommodative "lag" for the upper portion of the range. Alpern (1958c) observed that AC is related to the effort of accommodation and therefore in order to obtain a reliable estimate of AC/A, the accommodative response must be measured and used as the denominator in the equation. This procedure will allow calculation of the response AC/A (AC/A_R) as opposed to the stimulus AC/A (AC/A_S). Mean values of AC/A_R are generally higher than AC/A_S and are of the order of 4-6Δ/D (Manas, 1955; Flom and Takahashi, 1962; Rosenfield and Gilmartin, 1987a). However in the clinical situation it is difficult to accurately assess the accommodative response and the AC/A_S will still provide useful information with regard to the oculomotor balance. For example the observation of a high AC/A_S may aid diagnosis of a binocular abnormality such as convergence excess.

4.3A DIFFERENCES IN AC/A RECORDED BY GRADIENT (DISSOCIATED) AND FIXATION-DISPARITY (ASSOCIATED) TECHNIQUES

A number of workers (e.g. Martens and Ogle, 1959; Hebbard, 1960) have observed differences in the value of the AC/A ratio depending on the degree of dissociation of the two eyes imposed during the measurement. When using the gradient method the eyes are totally dissociated and therefore all stimuli to fusion are eliminated. The fixation disparity technique however permits normal binocular vision except for two monocular nonius lines positioned within the central visual field. At a viewing distance of 40cms the vertical and horizontal angular sizes of these lines are 35' 14" and 12' 33" respectively (Pickwell et al., 1988). In the fixation disparity method fusion is allowed apart from a small

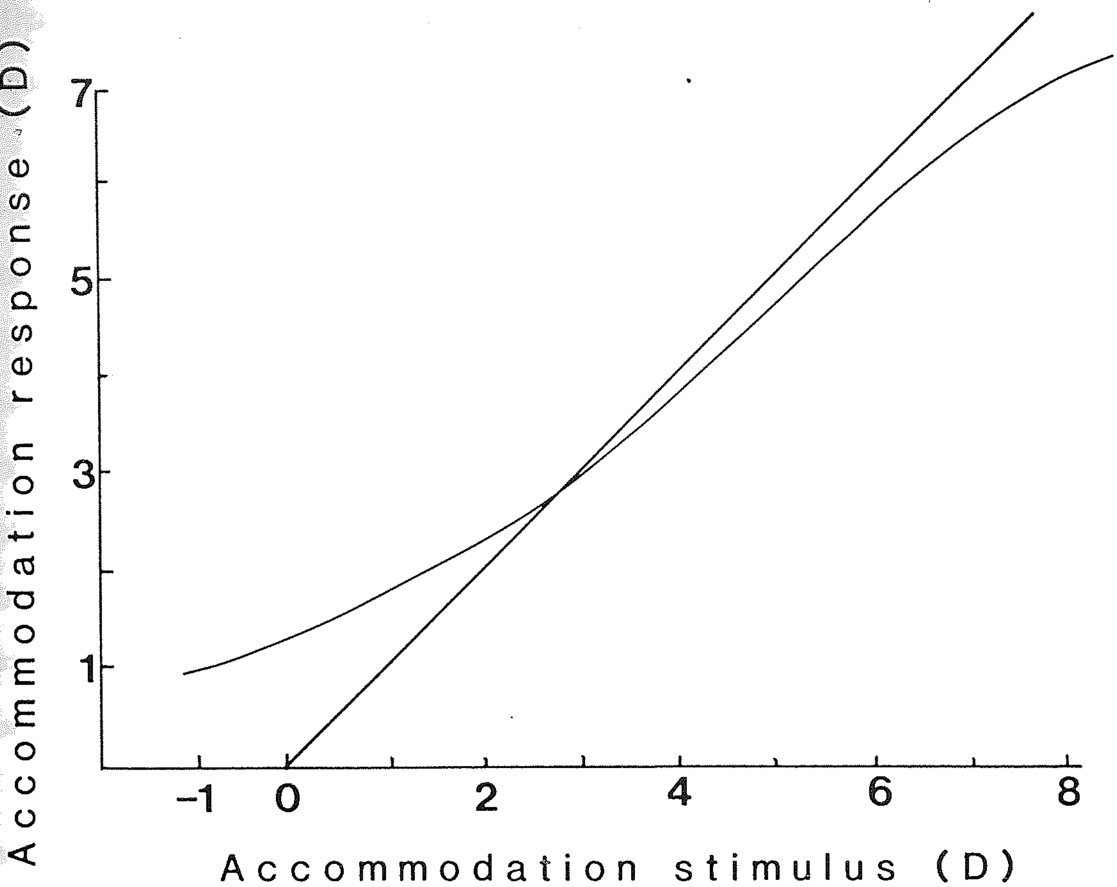

Fig. 4.3 The accommodative response as a function of the stimulus to accommodation. The straight line represents the unit-ratio (Donders) line (redrawn from Morgan, 1944b). It should be noted that Morgan described this graph as "a typical example" drawn from a study of 50 college students aged betwen 20-30 years.

area of the central visual field and the vergence system is not therefore open-loop. Thus one may be unable to differentiate AC from other components of the vergence response e.g. disparity-vergence.

Hebbard (1960) reported a poor correlation between measurement of AC/A determined by the gradient method and the fixation disparity technique. A study on one subject indicated a non-linear AC/A ratio when calculated by the fixation disparity technique whereas the gradient method revealed a linear ratio for the same subject. Further discussion on the linearity of the AC/A ratio appears in Section 4.4. Hebbard also observed differences in the magnitude of the AC/A ratio, a value of 9Δ/D being obtained by a gradient method using a haploscope, whilst the fixation disparity technique gave a value of AC/A ranging between 3.3 and 43Δ/D depending on the graphical method used to calculate the ratio.

In 1967 Ogle et al. reported values of AC/A ratio measured by the fixation disparity (associated) and gradient (dissociated) methods in one subject of 6.3Δ/D and 4.0Δ/D respectively. They suggested that the difference between these values resulted from the greater stimulus to both accommodation and disparity-vergence during binocular viewing. However Ramsdale (1979) measured the steady state accommodative response under monocular and binocular viewing conditions in 9 subjects, using a laser optometer, and noted only marginal differences between the two responses. Furthermore Schor (1983a) stated that it is unlikely that differences between dissociated and associated measures of AC/A can be accounted for by variations in the accommodative response under monocular and binocular viewing conditions. He indicated that in some cases the accommodative response would have to double under binocular conditions when compared with monocular viewing in order to account for the differences in AC/A. Schor suggested that a change in the output of CA may explain the difference between dissociated and associated measures of AC/A. To provide evidence for this suggestion, Schor cited the work of Semmlow and Hung (1979) who compared fixation disparity curves in 4 subjects for increasing vergence stimuli; accommodation being either open-loop or closed-loop. The accommodation loop was opened by subjects viewing the target through a 1mm diameter pinhole. Semmlow and Hung observed that under open-loop conditions there was a significant reduction in fixation disparity at higher vergence stimulus levels when compared with closed-loop viewing. They concluded that under closed-loop conditions the introduction of a vergence stimulus produces an increase in disparity-vergence which in turn will produce an increase in CA. The rise in CA will be accompanied by a fall in blur-driven accommodation in order to maintain the aggregate accommodative response and the fall in blur-driven accommodation will result in a decrease in AC. This reduction in the output of AC will produce a exo shift in fixation disparity. Opening the accommodation feedback loop eliminates the necessity to compensate for the increase in CA and there is no resulting change in AC. Therefore with accommodation open-loop, there is a reduction in the fixation disparity induced by an increase in vergence stimulus. Schor (1983a) concluded that the synkinesis between accommodation and vergence is "complicated by CA during binocular viewing conditions". The increased level of CA when using the associated method of measurement produces a reduction in blur-driven accommodation. The fall in the output of blur-induced accommodation will result in a reduction in the level of AC and hence produces a decrease in AC/A.

Judge (1985) examined mathematically the variations between associated and dissociated AC/A ratios in order to investigate the proposal that CA could account for these differences. Using equations for accommodation and vergence responses derived from the Schor (1983a) model of accommodation-vergence interaction, Judge concluded that variations in CA could not account for the differences in AC/A findings. However Judge provided no alternative explanation in his paper for the observed discrepancies.

The use of the terms disparity stimulus and fixation disparity in Judge's paper is somewhat confusing. In this thesis the term fixation disparity is taken to represent the vergence error which may exist under conditions of clear, binocular single vision (i.e. analogous to the dead-space of accommodation or steady-state error; see section 4.9). These errors do not produce diplopia providing they fall within the limits of Panum's fusional areas (Panum, 1858). However if we consider equation #1 in Judge's paper, he stated that when fixation disparity is induced by supplementary prisms then;

$$\mathbf{P + v_s - d = d.k_v + b.k_a.k_{ac}}$$

where; P = power of prism

v_s = vergence stimulus in the absence of prism

d = fixation disparity

k_v = vergence controller gain

b = blur associated with prism viewing

k_a = accommodative controller gain

k_{ac} = accommodative convergence gain

The left hand side of the equation represents the new vergence stimulus immediately following the introduction of the prism. The right hand side of the equation should represent the resulting vergence response induced by the prism. However,

$$\mathrm{NVS} = \mathrm{NVR} + d \quad \ldots\ldots 1$$

where NVS = net vergence stimulus

NVR = net vergence response

d = fixation disparity (steady state error)

Thus from equation 1 above,

$$\mathrm{NVS} - d = \mathrm{NVR} \quad \ldots\ldots 2$$

When a prism is introduced

$$\mathrm{NVS} = v_S + P$$

where v_S = vergence stimulus in the absence of the prism

P = power of prism

Therefore from equation 2

$$NVR = P + vs - d \quad \text{.......} \quad 3$$

The change in vergence response may be considered as being composed of two components, disparity-vergence and accommodative convergence. Judge did not consider proximal effects in his paper. The output of accommodative convergence may be given by the function $\mathbf{b.k_a.ka_c}$, where b = blur associated with prism viewing; k_a = accommodative controller gain; k_{ac} = accommodative convergence gain (AC/A ratio).

The output of disparity-vergence is given by $\mathbf{k_v(DV)}$ where k_v = vergence controller gain, DV = disparity-vergence stimulus.

$$\text{Thus } NVR = k_v (DV) + b.k_a.k_{ac} \quad \text{.......} \quad 4$$

Equating equations 3 and 4 we obtain;

$$\mathbf{P + v_s - d = (DV).k_v + b.k_a.k_{ac}}$$

It will be observed that the right hand side of this equation differs from that proposed by Judge.

4.3B EFFECT OF AGE ON THE AC/A RATIO

The differences between AC/A_S and AC/A_R are most clearly demonstrated in a review of the literature on the effects of age on the AC/A ratio. Studies on the effect of presbyopia on the AC/A_S (e.g. Morgan and Peters, 1951; Davis and Jobe, 1957; Alpern and Hirsch, 1960; Ogle et al., 1967) have all indicated that the onset of presbyopia produces no significant change in AC/A_S. A summary of these studies is shown in Table 4.1.

Table 4.1. **MEAN VALUE OF STIMULUS AC/A IN A PRESBYOPIC POPULATION**

Study	Method of testing	N=	Mean AC/A (Δ/D)
Morgan & Peters (1951)	Gradient	200	3.8
Davis & Jobe (1957)	Gradient (Orthorater)	10,000	4.8
Alpern & Hirsch (1960)	Heterophoria	1,202	4.0
Ogle et al. (1957)	Fixation disparity	23	6.0

Studies on the effect of age on the AC/A_R however have indicated a large increase in AC/A_R between 40 and 50 years of age. Fry (1959a) measured his own AC/A_R using a haploscope-optometer and noted that it increased from 5.7 Δ/D at age 29 years to 31.5Δ/D at age 50 years. In a later study Breinin and Chin (1973) compared AC/A_S and AC/A_R in 28 patients aged between 16 and 60 years. They showed that while AC/A_S remained relatively constant with age, AC/A_R showed a marked increase concurrent with the onset of presbyopic symptoms. These differences are illustrated in Fig.4.4. In presbyopic subjects a discrepancy will occur between accommodation stimulus and accommodative response and this difference will be reflected in the large variation between AC/A_S and AC/A_R.

4.4 LINEARITY OF THE AC/A RATIO

A number of studies have provided evidence for a linear AC/A ratio within an intermediate accommodation stimulus range. Westheimer (1955a) examined the AC/A_R using a haploscope-optometer in two near-emmetropes for accommodation stimuli ranging between 0 and 5D. He reported that one of the subjects showed a linear AC/A_R ratio whilst the other subject exhibited a non-linear relationship for this stimulus range.

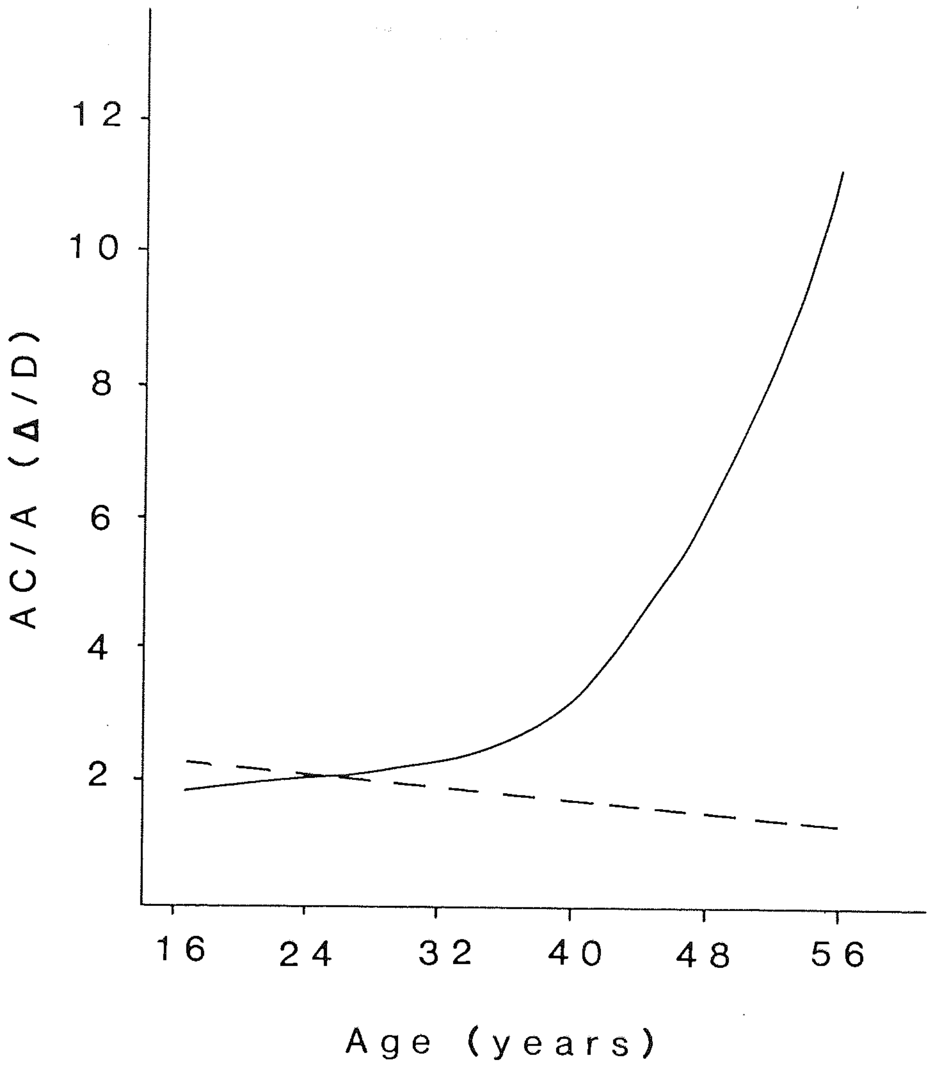

Fig. 4.4. The effect of age on the response AC/A (solid line) and the stimulus AC/A (broken line). Data from Breinin and Chin (1973). Figure is redrawn from Ciuffreda and Kenyon (1983).

The curvilinear relationship which was observed in the latter subject was both significant (i.e. significantly different from a straight line) and remained constant over the 4 month testing period.

Ogle and Martens (1957) examined the linearity of the AC/A_S in 28 subjects using both the gradient and heterophoria methods. They observed significant non-linearity in approximately 50% of their subjects when using the gradient method to assess the AC/A_S over an accommodative stimulus range of -1 to +7D. However the non-linearity occurred when plus lenses were used to relax accommodation. Ogle and Martens therefore suggested that only minus lenses should be used in the determination of the AC/A ratio. When the heterophoria method was used to determine the AC/A_S over an accommodation stimulus range of 0.22-7.0D, a linear AC/A_S was observed throughout. However Ogle and Martens noted the contamination of the vergence response by proximal factors when employing the heterophoria method (see section 4.2A) so that this linear response does not represent pure AC. In a later paper Martens and Ogle (1959) used the fixation disparity method to determine the AC/A_S for approximately 250 subjects. They observed a linear response over the accommodation stimulus range ±3.0D in 92% of subjects. However there was no consistent pattern of non-linearity in the remaining 8% of subjects; for instance 8 subjects showed a decrease in AC/As when plus lenses were used to relax accommodation whereas other subjects showed an increase in AC/As with plus lenses (3 examples of the latter category were shown although the total number of patients in this sub-group was not specified). Martens and Ogle noted that those subjects exhibiting a non-linear relationship tended to have more complicated oculomotor and asthenopic symptoms when compared with the average patient. There was also a higher incidence of intermittent heterotropias in the non-linear group.

In a later study Alpern et al. (1959) measured both AC/A_S and AC/A_R over an accommodation stimulus range of -4 to +11D using a haploscope-optometer. These ratios were computed for four pre-presbyopic subjects. They observed linear AC/A_R and AC/A_S relationships over the central portion of the stimulus range (≈ +1 to +5D) with significant non-linearity outside this range.

Flom (1960a) examined the linearity of both the stimulus and response AC/A ratio in 12 college students for an accommodative stimulus range of 0-3.5D (stimulus AC/A) and 0-6.25D (response AC/A). Ten of the twelve subjects exhibited significant non-linearity in response AC/A measures and 5 subjects showed non-linearity in the stimulus AC/A. However in a discussion on this study, Ciuffreda and Kenyon (1983) stated that when the different techniques of measurement were compared, only one subject exhibited a non-linear AC/A ratio for all methods of assessment. Ciuffreda and Kenyon also noted that the correlation coefficients between convergence and accommodation were extremely high (mean value of r=0.98) suggesting only a small degree of non-linearity. Furthermore they found that if the lowest stimulus level was removed from the data, this would produce a further reduction in non-linearity.

Westheimer (1955a) proposed two hypotheses which might account for a linear relationship between accommodation and AC. Firstly he suggested that a neural linkage may exist so that a vergence response is activated each time an accommodative response is sought. In order for such a system to produce a linear relationship it would be necessary for either the two effector systems i.e. accommodation and vergence to be linear throughout or alternatively possess a series of non-linearities which cancelled each other out.

Clearly such a system would be unlikely to be sufficiently robust to cope with the changes in the oculomotor system that occur throughout life or with the adaptational changes which may occur during periods of sustained near-vision (see Chapters 7-9). Westheimer's second hypothesis proposed a negative feedback system in order to maintain the constancy of the AC/A ratio. Thus a change in the output of one function would be compensated for by a corresponding alteration of the alternate component in order to maintain the ratio of outputs at a constant level.

It is feasible that both of the above hypotheses could account for the linearity of the AC/A ratio. Westheimer's suggestion that negative feedback circuits monitor and sustain the output of both accommodation and vergence is discussed further in both section 4.9 and subsequent chapters.

In 1959 Brecher commented on what he considered to be the remarkable nature of the linear relationship between accommodation and vergence. He pointed out that a visual stimulus produces a change in two motor outputs, one of which is directed to the ciliary smooth muscle and the other to the extra-ocular striated muscles. Brecher observed that it is surprising that non-linearity should exist in relatively few subjects. He concluded that the linear relationship must be developed by control feedback systems. Further discussion of these feedback mechanisms appears in Section 4.9.

4.5 STABILITY OF THE AC/A RATIO

Manas and Shulman (1954) examined the stimulus AC/A ratio in 22 optometry students. Each student was examined three times per week at approximately two-day intervals until twenty values of AC/A were obtained for each subject. AC/A ratios were determined using both the heterophoria and gradient techniques. It should be noted that +1.00DS lenses were used for the gradient test which may have induced significant non-linearities into the AC/A ratio (see Section 4.4).

The mean values of AC/A_S calculated by the heterophoria and gradient methods were 4.7Δ/D (sd=0.78) and 4.1Δ/D (sd=1.66) respectively. Furthermore the AC/A calculated using the gradient method exhibited approximately twice the variability of the findings derived from the heterophoria technique. Manas and Shulman concluded that as values of heterophoria do not remain constant, then the AC/A ratio, which is a function of heterophoria, cannot remain constant either. They stated that the AC/A ratio is a psycho-physiological variable which will fluctuate " depending upon the exigencies of the day and the demands of the environment".

Hirsch (1954) proposed in an editorial footnote to the Manas and Shulman paper that the reported variability of AC/A may represent the variation normally evident in repeated measures of a physiological parameter. In a later paper, Manas (1955) suggested that the AC/A ratio was unstable because accommodation and vergence are not rigidly linked. Furthermore AC/A ratios have been shown to vary with age and ametropia (see section 4.5A). However Manas's arguments were concerned with measures of AC/A_S and clearly only values of AC/A_R are applicable to a discussion on the interactions between accommodation and vergence. Westheimer (1955b) in response to the Manas (1955) paper stated that the variability of AC/A may relate to the deficiencies in techniques of measurement.

Later Morris (1957) also criticised a number of the arguments proposed by Manas (1955) as evidence for instability of the AC/A ratio. Morris used graphical analysis in order to determine both AC/A_S and AC/A_R (accommodation and vergence being measured using a haploscope-optometer) and concluded that both AC/A ratios were usually stable when computed by this technique.

Flom (1960b) examined AC/A_S and AC/A_R in four optometry students using refractor head / Risley prism and haploscope-optometer methods respectively. He determined the AC/A ratios for an accommodative stimulus range of 0-3.5D over a nine week period.

The standard deviations of the AC/A ratios recorded over this period were;

Haploscope (AC/A_R)	=	0.13
Haploscope (AC/A_S)	=	0.10
Risley prism (AC/A_S)	=	0.18

The relative stability of the ratios obtained is illustrated in Fig. 4.5 for one subject. A learning effect on the measured AC/A ratio was also noted in one subject, the AC/A_S measured using the refractor head / Risley prism was seen to decrease over the test period. However Flom stated that it was not possible to determine whether the observed variability in AC/A results from changes in observational characteristics or from neuromuscular variations.

Ogle (1966) examined the AC/A_S using the fixation disparity technique over a period of six weeks in one subject and observed that the AC/A_S had a mean value of 3.62Δ/D with a standard deviation of ±0.25Δ/D. Ogle suggested that this small standard deviation was evidence for the stable nature of the ratio. However a number of studies have indicated that the AC/A ratio is susceptible to induced changes by a variety of factors, these are discussed in section 4.5A.

4.5A ADAPTATION PROPERTIES OF THE AC/A RATIO

It has previously been noted that the AC/A_R exhibits a marked increase around 45 years of age(see Section 4.3B) due to the increased effort required in order to produce a unit change in accommodation. Variations in ametropia have also been shown to produce changes in AC/A, the AC/A_R in myopes is reduced as they adapt to a full minus spectacle correction (Flom and Takahashi, 1962). For a fuller discussion on the relationship between ametropia and AC/A see Chapter 6.

A number of studies have examined the effects of both ocular and systemic drugs on

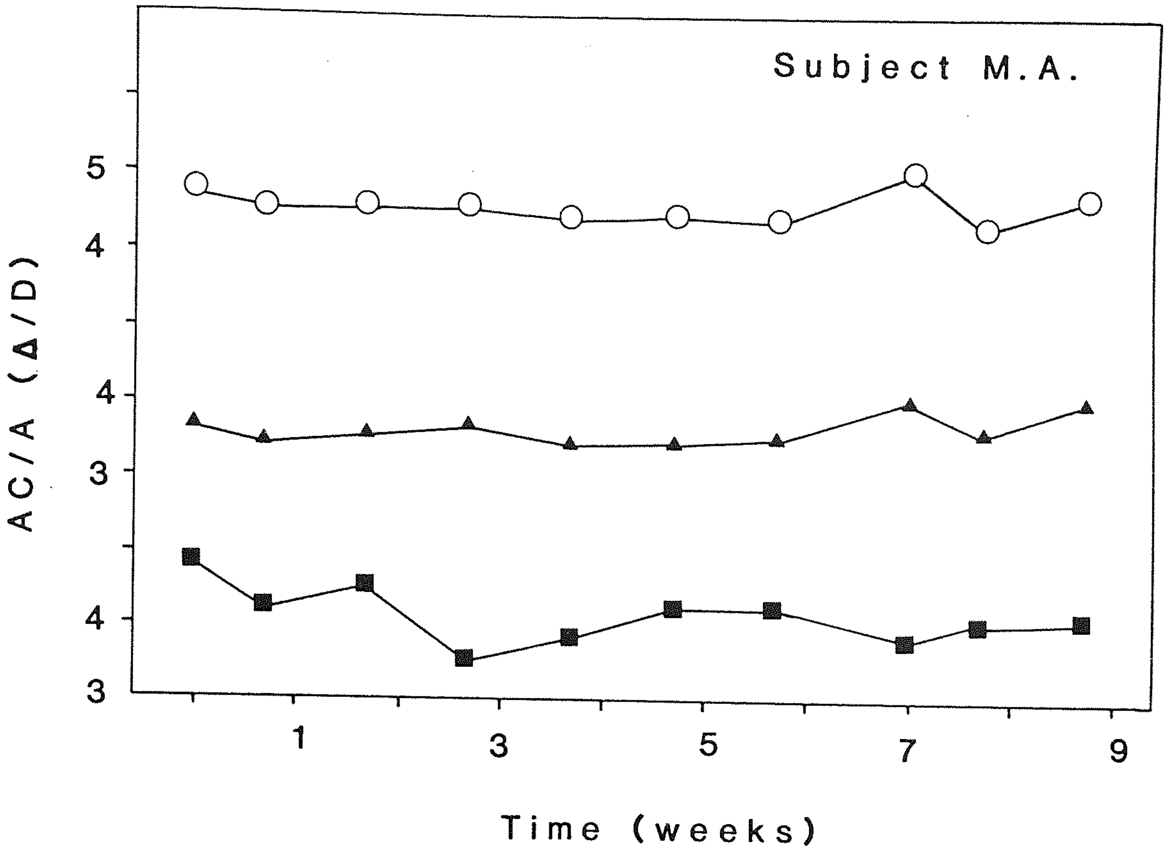

Fig. 4.5 AC/A ratio plotted as a function of time. Circles indicate response AC/A determined using haploscope-optometer. Triangles: stimulus AC/A measured with haploscope. Squares: AC/A recorded with Risley prism/refractor head. Each point represents the reciprocal of the slope of the straight line fitted by least squares to 20 data points over an accommodative range of 0-3.5D (redrawn from Flom, 1960b).

the AC/A ratio. For a review of this work see Ogle et al. (1967) and Ciuffreda and Kenyon (1983). A broad range of drugs including barbiturates (Westheimer and Rashbass, 1961; Westheimer, 1963), ethyl alcohol (Cohen and Alpern, 1969; Hogan and Linfield, 1983; Hogan and Gilmartin, 1985a) cycloplegics (Christoferson and Ogle, 1956; Alpern and Larson, 1960; Westheimer, 1963) and parasympathomimetics (Ripps et al., 1962) have been shown to produce changes in AC/A ratio.

Both Ogle et al. (1967) and Ciuffreda and Kenyon (1983) have also reviewed the effects of other factors on the AC/A ratio, notably orthoptic exercises and surgery and have indicated that the AC/A ratio may be modified by both of these methods. Thus the AC/A ratio has been shown to be adaptable by external factors. This property of adaptation is examined further in later sections which deal with the effects of sustained near-vision on the near-response mechanism.

4.6 CONVERGENT ACCOMMODATION

Kersten and Legge (1983) defined convergent accommodation (CA) as an accommodative response that accompanies a change in the state of convergence of the eyes. An earlier definition by Fry (1940) described CA as, "that amount of accommodation which is fully associated with convergence when the need for exact focusing has been eliminated". CA may be demonstrated by placing the accommodation system into an open-loop condition. This may be achieved by the subject viewing a target through a pinhole. The pinhole will produce an increase in depth-of-focus which in turn will render ineffective the stimulus to accommodation derived from a blurred image.

If the open-loop accommodative response is measured at two vergence stimulus levels, the increased vergence response will produce a rise in CA. Under closed-loop conditions it is likely that this increase in CA would be accompanied by a decrease in blur-induced accommodation in order to maintain the aggregate accommodative response constant, and thereby maintain a clear retinal image. However by opening the accommodation loop, the increase in CA does not require a compensatory reduction in blur-induced accommodation. Thus the increase in CA can become manifest.

In a review of CA, Kersten and Legge cited Porterfield (1759) as being one of the first workers to indicate an interaction between vergence and accommodation. Donders (1864) noted that the state of accommodation of the eye corresponds to a definite convergence of the visual axes. However Donders observed that both Porterfield (1759) and Mueller (1826) assumed that this relationship was absolute and causal i.e. a fixed amount of accommodation being always associated with a given degree of convergence. Donders indicated that such a rigid relationship does not exist, evidence for this being derived from the existence of positive and negative relative accommodation and vergence. Thus a given vergence response may be accompanied by a range of accommodative responses while single, clear binocular vision is maintained.

CA has not received as much attention as AC due to the practical difficulty in measuring open-loop accommodative responses. Fincham and Walton (1957) examined CA using a haploscope-optometer in 22 subjects. The accommodation-loop was opened by subjects viewing the target through 0.5mm diameter pinholes. They noted that up to the age of 24 years the induced accommodation in dioptres was equal to the convergence measured in metre-angles (MA). Above 24 years of age however there is a steady decrease in the convergent accommodation/convergence (CA/C) ratio. This is in contrast to the AC/A_R ratio which has been shown to be relatively stable up to 45 years of age (see section 4.3B). For a review of methods of CA/C assessment see Kent (1958) and Balsam and Fry (1959). Further discussion on both the measurement of the CA/C ratio and adaptation of this cross-link during periods of sustained near-vision appears in Chapter 9.

4.7 TEMPORAL CHARACTERISTICS OF ACCOMMODATIVE CONVERGENCE AND CONVERGENT ACCOMMODATION

4.7A DYNAMICS OF ACCOMMODATIVE CONVERGENCE

Semmlow and Wetzel (1979) measured the latency and time constant for both AC and disparity-vergence in 5 subjects and obtained the mean values shown in Table 4.2. Disparity-vergence was isolated by measuring the vergence response while the subject was viewing through a 1mm diameter pinhole (i.e. open-loop accommodative response).

Table 4.2 Comparison of vergence dynamics for isolated disparity-vergence and accommodative convergence. Positive and negative refer to convergent and divergent stimuli respectively. T = time constant *, LAT = latency. All measurements in seconds (From Semmlow and Wetzel, 1979)

	POSITIVE		NEGATIVE	
	T	LAT	T	LAT
ACCOMMODATIVE CONVERGENCE	0.43	0.30	0.66	0.38
DISPARITY-VERGENCE	0.20	0.18	0.29	0.32

* Time constant is the time for the response to reach 63% of its final value.

These values of latency and time constant for AC are similar to those reported in previous studies e.g. Allen (1953); Alpern and Ellen (1956b); Wilson (1972); Semmlow and Venkiteswaren (1976); Krishnan et al. (1977). The studies of both Semmlow and Wetzel (1979) and Hung et al. (1983) observed that the increased latency of AC would prevent this component from contributing to the initial stages of a vergence response. Furthermore Hung et al. noted that the initial accommodation and vergence stimulus consists of a blurred retinal image falling on an eccentric portion of the retina. Semmlow and Tinor (1978) reported that increasing target eccentricity reduces the effectivity of a target to initiate an accommodative response and hence AC. However as disparity-vergence brings the target image closer to the fovea, the contributions of accommodation and AC are progressively increased. Hung et al. therefore suggested that the increased latency of AC when compared with disparity-vergence may relate to the reduced effectivity of an eccentric stimulus.

4.7B DYNAMICS OF CONVERGENT ACCOMMODATION

Krishnan et al. (1977) observed that dynamic measures of CA are difficult to obtain as globe rotation interferes with the measurement of accommodation. However they described the use of a dynamic optometer which measures the position of the third Purkinje image (reflected from the anterior surface of the crystalline lens) in order to quantify the accommodative response. Krishnan et al. verified that this optometer was not sensitive to eye movements less than 5° and was therefore able to measure the dynamics of CA responses for small step changes in disparity. The accommodation loop was opened by maintaining a high level of target blur. Krishnan et al. observed that CA has a latency of 0.25-0.30s (mean for 2 subjects) following initiation of a step stimulus and the response was completed 0.90-1.1s after stimulus onset. Divergent accommodation (i.e. negative CA) however was slower than CA both in terms of latency and response velocity.

This latency of CA indicated by Krishnan et al. lies between the reported latencies of disparity-vergence (mean ≈ 0.16s; Westheimer and Mitchell, 1956; Rashbass and Westheimer, 1961) and blur-induced accommodation (mean ≈ 0.34s; Campbell and Westheimer, 1960; Tucker and Charman, 1979). Allen (1953) stated that the faster reponse of vergence when compared with accommodation was due to the increased latency of the ciliary muscle. However this would fail to explain the faster response of CA compared with blur-induced accommodation. It would seem that the near-response reacts faster to disparity stimuli than to blur stimuli, possibly due to the previously reported observation that the initial stimulus falls on an eccentric portion of the retina and target eccentricity degrades the blur- stimulus to accommodation.

4.8 SYNKINESIS OF ACCOMMODATIVE CONVERGENCE (AC) AND CONVERGENT ACCOMMODATION (CA)

Accommodation and vergence are individual components of the oculomotor response which are both capable of operating in isolation. However under normal binocular viewing conditions these two functions interact via the simultaneous operation of the cross-links AC and CA. In this section the interaction between these cross-links will be discussed in an attempt to quantify their contributions to the closed-loop near-response.

Semmlow and Hung (1980) observed that a major difficulty encountered in investigation of the human vergence system is the inability to measure the oculomotor constituents which combine to produce the net vergence response (see section 3.7). Whilst similar difficulties also arise in investigation of the accommodative system, a number of studies have provided information relating to the relative proportion of an individual oculomotor component by placing either accommodation or vergence into an open-loop state. These studies will be discussed further in subsequent chapters but it is clear that opening of one of the oculomotor loops will affect the synkinetic link between accommodation and vergence. Other studies have attempted to investigate the actions of individual components of the near-response either by demonstrating differences in response latencies (see section 4.7) or by examining their effects at the limits of clear single binocular vision.

4.8A THE ROLE OF CONVERGENT ACCOMMODATION WITHIN THE AGGREGATE ACCOMMODATION RESPONSE

Recent work (e.g. Toates, 1969; Hung and Semmlow, 1980; Semmlow and Hung, 1980; Schor, 1983b and 1985; Schor and Kotulak, 1986)has indicated that dual-interactions exist between accommodation and vergence so that the two oculomotor functions mutually interact under normal binocular viewing conditions. This dual-interaction theory contrasts with the Maddox classification of vergence (see section

3.7) which failed to consider the role of CA . The Maddox hypothesis represented a single interactive model as it included AC but not CA. Conversely Fincham and Walton (1957) proposed a single interactive model where retinal disparity was the dominant stimulus. Evidence for dual interaction comes from the study of Semmlow and Heerema (1979) who measured the value of fusional vergence while a subject binocularly viewed a stimulus placed at their heterophoria position. According to the Maddox single interaction theory, the output of fusional vergence under these conditions would be zero. However Semmlow and Heerema observed that when one eye was suddenly occluded, there was a small divergence movement followed by a return to the initial eye position. They concluded that this initial divergence movement was caused by a relaxation of fusional vergence. Thus under binocular (associated) viewing conditions the fusional requirement differs from that under dissociated conditions. Semmlow and Heerema suggested that this difference can be explained by the increased output of CA under binocular viewing. Increased CA may require a reduction in the output of blur-driven accommodation in order to maintain the aggregate accommodative response constant. This reduction in blur-driven accommodation will then be reflected as a fall in AC. The reduced level of AC under binocular viewing conditions will require increased disparity-vergence in order to avoid diplopia and confusion.

4.8B THE ROLE OF ACCOMMODATIVE CONVERGENCE WITHIN THE AGGREGATE VERGENCE RESPONSE

Semmlow and Wetzel (1979) examined the closed-loop vergence response to a target stimulus placed at a viewing distance of 33cms. Vergence was assessed with accommodation either closed- or open-loop. The former condition will give a measure of the normal net vergence response whilst the latter condition represents the response of disparity-vergence alone. The accommodation loop was opened by the subject viewing the target through 1mm diameter pinholes. The difference between the two vergence responses represents the output of AC. Semmlow and Wetzel observed that the initial portion of the net vergence response resulted from disparity-vergence whilst

AC only contributed to the final part of the movement. Furthermore they noted that the closed-loop vergence response was less than the sum of the two isolated components (disparity-vergence and AC). Semmlow and Wetzel postulated that the output of either disparity-vergence or AC may adopt an intermediate level, i.e. only contribute a proportion of their potential response. Further discussion on the contribution of individual elements of accommodation and vergence to the closed-loop oculomotor response appears in Chapters 8-10.

4.9 MODELS OF ACCOMMODATION-VERGENCE INTERACTION

A number of workers have described the inter-relationship of accommodation and vergence in terms of control theory in an attempt to clarify the synkinetic relationship between the two oculomotor components. Control theory attempts to portray the function of a system using a model in order to explain the characteristics of that system. One may then compare the behaviour of the model with that of the real system. Control theory has been applied in a wide number of disciplines including biology, applied mathematics, branches of engineering and psychology.

Toates (1975) defined a model as a theory which describes the function of a system in terms which are unambiguous. In a series of papers Toates attempted to simulate the accommodative and vergence functions by control systems, initially considering each system in isolation and subsequently examining the interaction of the two functions.

Both accommodation and vergence may be considered as negative feedback control systems whereby a negative feedback loop provides information relating to the output of the system and therefore allows monitoring of the relationship between the system's output and input. An example of a negative feedback system is illustrated in Fig. 4.6.

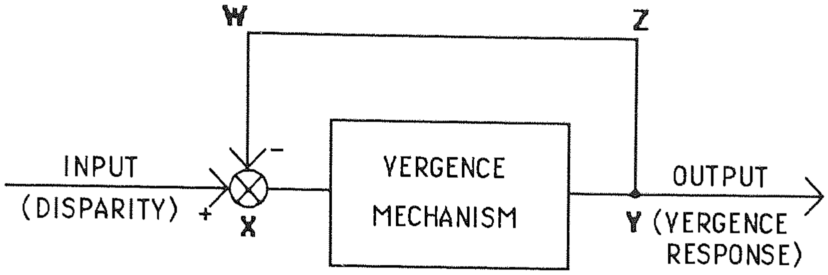

Fig. 4.6 Disparity-vergence illustrated as a simple negative-feedback control system. The input to the system is retinal disparity and the output is a disparity-vergence response. The negative feedback loop YZWX allows monitoring of the error signal i.e. discrepancy between output and input.

In the simple control system illustrated in Fig. 4.6, retinal disparity is detected as an error between the output of the system, the vergence response, and the input to the system, retinal disparity. When input and output are unequal, an error signal is set up which initiates a vergence response. The increase in output thereby reduces the error signal. When input and output match i.e. stimulus and response are equal, then the error signal is zero and no further response is sought. The relationship between output and input, and hence the error detector, is monitored by the feedback loop YZWX shown in Fig. 4.6. Since an increase in output reduces the stimulus to the input, i.e. lowers the error signal, then this is known as *negative feedback.* If an increase in output produced an increase in the error signal then this would be an example of *positive feedback.* However the vast majority of physiological systems operate by the self-limiting action of negative feedback (Guyton, 1971).

Toates (1974) described control-theory models of blur-induced accommodation and disparity-vergence and these are illustrated in Fig.4.7a and 4.7b respectively. In the

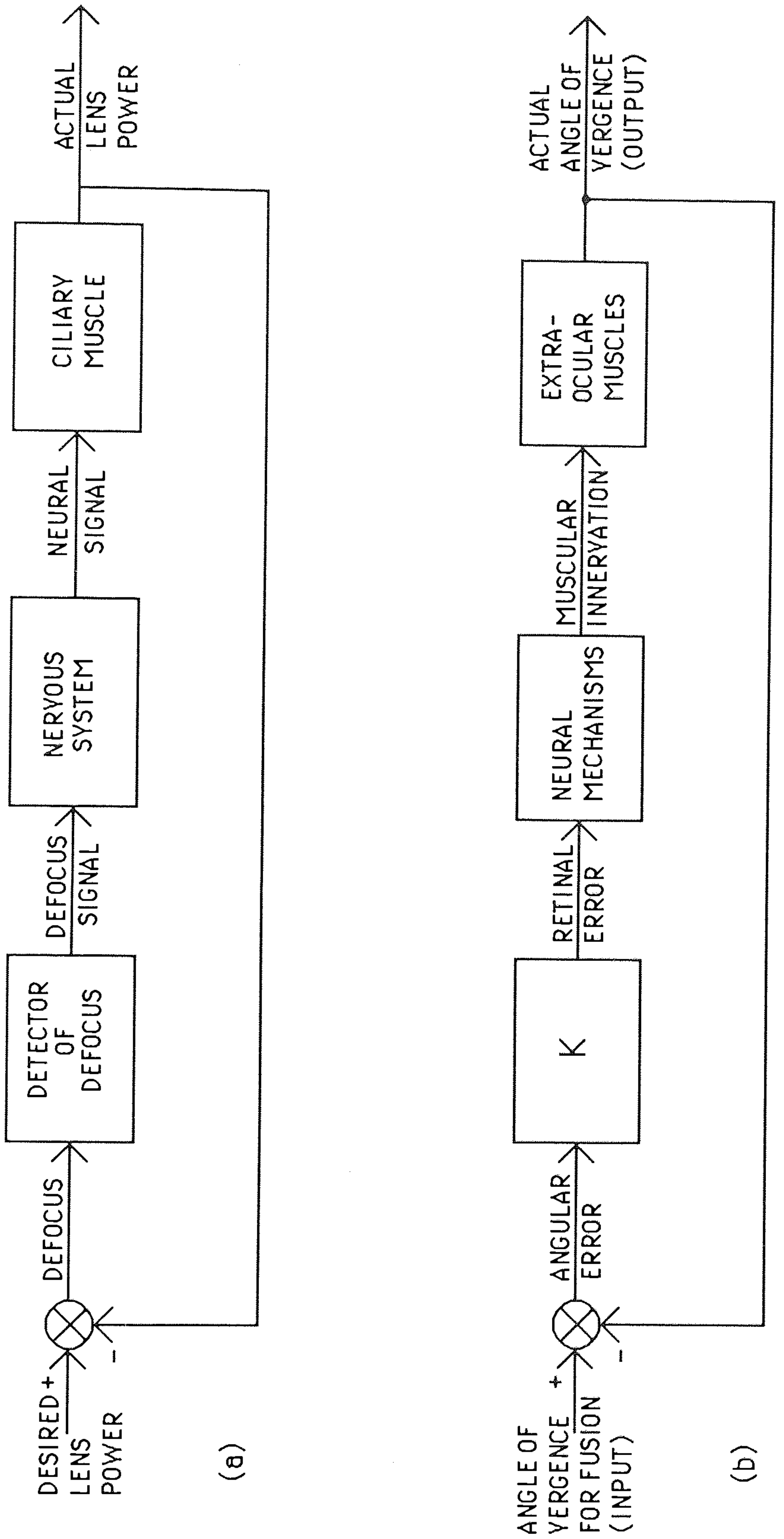

Fig.4.7 Control-theory models of a) blur-induced accommodation; b) disparity-vergence. K is a constant given by the ratio between retinal-disparity and the angular error. (Redrawn from Toates, 1974).

blur-driven accommodation model (Fig. 4.7a), following the detection of an error signal i.e. defocus, a signal is sent forward to the nervous system and the neural signal produces a change at the ciliary muscle resulting in an alteration of lens power. As the accommodation output increases, this serves to decrease the error signal via the negative feedback loop. However Toates (1972) noted that the accommodative mechanism exhibits a steady-state error, that is the error signal under steady state conditions is not zero. This is illustrated in a typical accommodation stimulus-response curve (see fig. 4.3) which indicated that except for one specific value, accommodation stimulus and response are unequal.

The presence of this steady-state error may provide evidence for a particular type of feedback control mechanism being present in the accommodative system. Toates (1972) described two possible relationships which are illustrated in Fig. 4.8.

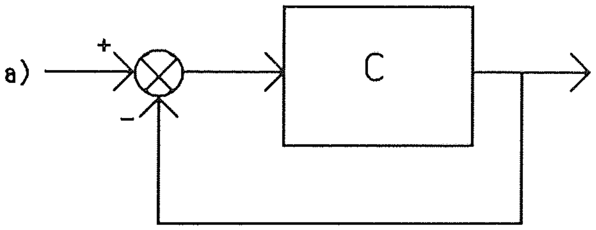

Fig. 4.8 a Proportional negative feedback control system

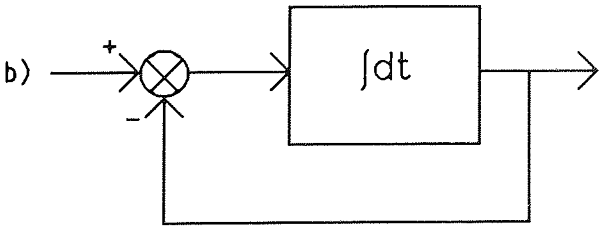

Fig. 4.8 b Integral negative feedback control system

In Fig. 4.8a , the output of the system is proportional to the error signal. Thus;

$$\text{output} = C.\text{error}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathbf{A}$$

where C is a constant.

In Fig. 4.8b however the output is a function of the integral of the error signal and is given by the equation;

$$\text{output} = \int_{o}^{t} \text{error}.\ \ dt\ldots\ldots\ldots\ldots\ldots\ldots\mathbf{B}$$

where t = time

In equation B, if any error exists then the integral (i.e. the output) would have a finite value. However a constant output can only occur when the error signal is zero. A constant (steady-state) output cannot co-exist with an error. As the accommodative system has been shown to exhibit a steady-state error (see Fig. 4.3), Toates concluded that accommodation must act as a proportional controller since integral control would not allow a steady-state error to exist. The suggestion that the relationship between output and error might be described by the function shown in equation **A** above is clearly an oversimplification in view of the observed relationship between accommodative stimulus and response. It might be deduced from the typical S-shape of the stimulus-response curve that a polynomial function would provide a better description of this relationship.

In consideration of the type of control system which may best describe the vergence function, Toates (1974) noted the conflicting opinions on the presence of a steady-state error within the vergence mechanism. He cited the work of Ogle et al. (1967) which suggested that fixation-disparity is a steady-state error whose amplitude falls within the values of Panum's areas. Toates suggested that fixation disparity may act as the error signal in order to induce a vergence response. Schor (1980) supported this view describing fixation disparity as a steady-state error which acts as a stimulus to maintain vergence under binocular viewing conditions. This would imply that vergence may act a proportional control system. However Toates (1974) suggested that vergence exhibits many of the characteristics of an integral controller but his arguments regarding the presence of a steady-state error are somewhat unclear. The work of Schor and co-workers would appear to verify that fixation disparity acts as a steady-state error which would presumably exclude the possibility that vergence could possess an integral control system.

The control models described previously have examined accommodation or vergence in isolation. Westheimer (1963) produced the first block diagram to include both accommodation and vergence feedback control systems and this is illustrated in Fig. 4.9. The interactions AC and CA are shown as cross-links between the two primary oculomotor functions. It should be noted that this and all subsequent models of accommodation-vergence interaction which will be discussed adopt the dual interaction theory (see Section 4.8) as it is now accepted that AC and CA show mutual interactions. This is in conflict with the single interactive theories proposed by Maddox (1893) and Fincham and Walton (1957).

A more detailed model of accommodation -vergence interaction was proposed by Hung and Semmlow (1980). This model is illustrated in Fig. 4.10. Hung and Semmlow stated that their model simulated static behaviour of accommodation and vergence and made no attempt to simulate dynamic responses. Thus no account is made of the adaptive processes which may occur following periods of sustained near-vision (see chapters 7-10).

In order to test their model Hung and Semmlow collected responses from all stimulus-response combinations in four subjects. As there are two feedback-controlled

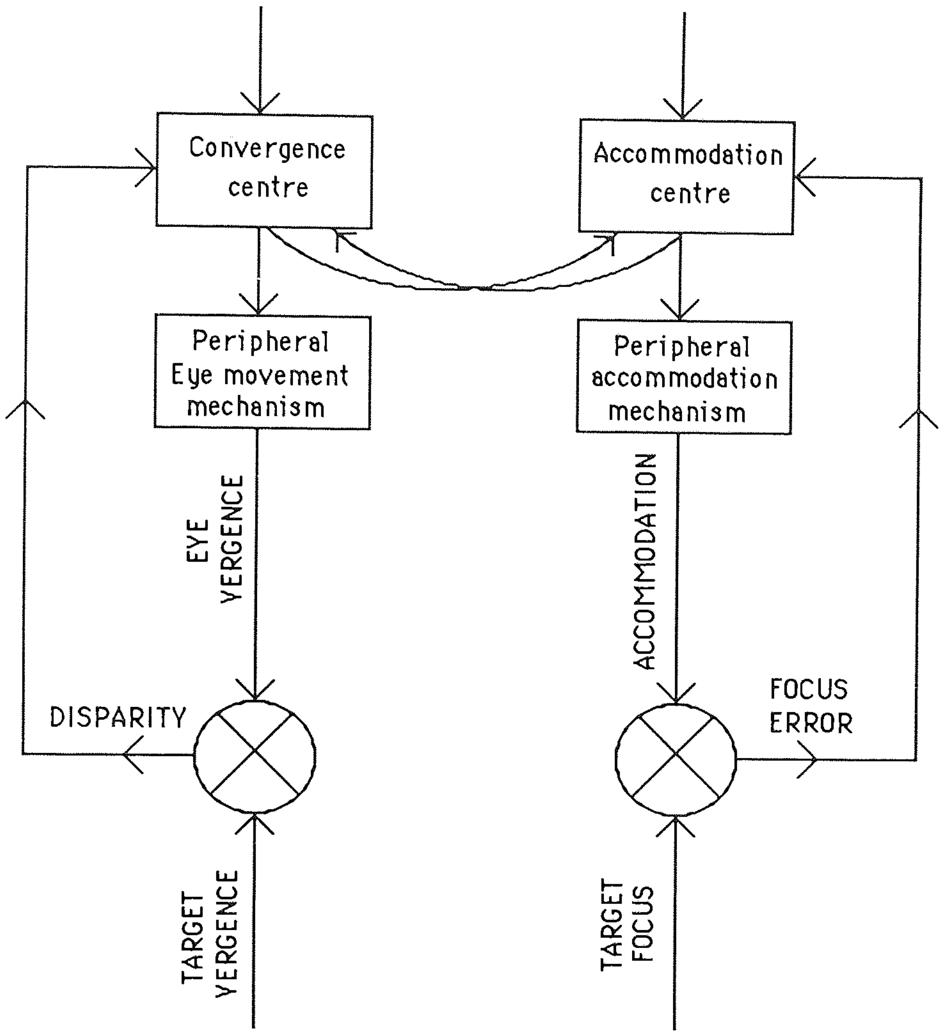

Fig. 4.9 Westheimer (1963) model of accommodation-vergence synkinesis. Focus error and disparity-stimulus result from a comparison of the difference between respective accommodation and vergence stimulus and response.

motor responses (accommodation and vergence), two primary stimuli (blur and disparity) and each feedback system can be either open or closed-loop, this produces eight possible combinations. However they failed to consider proximal cues as an independent stimulus to either accommodation or vergence. Results were compared with model simulations and good correlations were obtained. The mean values obtained for the model parameters indicated in Fig. 4.10 are shown in Table 4.3. The model suggested that both blur and disparity contribute to the near-response and that both cross-link interactions, AC and CA contribute to the aggregate response.

Table 4.3 Linear parameters for Hung-Semmlow model of accommodation-vergence interaction. Mean values from 4 subjects (mean age 27 yrs). Figures in parentheses represent one standard deviation. (from Hung and Semmlow, 1980).

Tonic accommodation (ABIAS)	1.27D	(0.83)
Tonic vergence (VBIAS)	0.38MA	(0.76)
Vergence controller gain (VCG)	182	(76.1)
Accommodative controller gain† (ACG)	6.04	(4.23)
Convergent accommodation (CA)	0.62D/MA	(0.17)
Accommodative convergence (AC)	1.00MA/D	(0.58)

† ACG measured for positive accommodative error.

It is of interest to note that in the Hung-Semmlow model the dead-space of accommodation is illustrated (corresponding to the accommodative lag) but no corresponding dead-space is indicated on the vergence system. This is despite the fact that reference is made in the text of their paper to the work of Ogle et al. (1967) relating to fixation disparity, a characteristic which Hung and Semmlow described as " vergence error versus vergence stimulus ". The value of their model would be improved if a vergence dead-space were included.

Further discussion on accommodation-vergence interaction, with particular regard to adaptational effects during periods of sustained near-vision, appears in later chapters of this thesis.

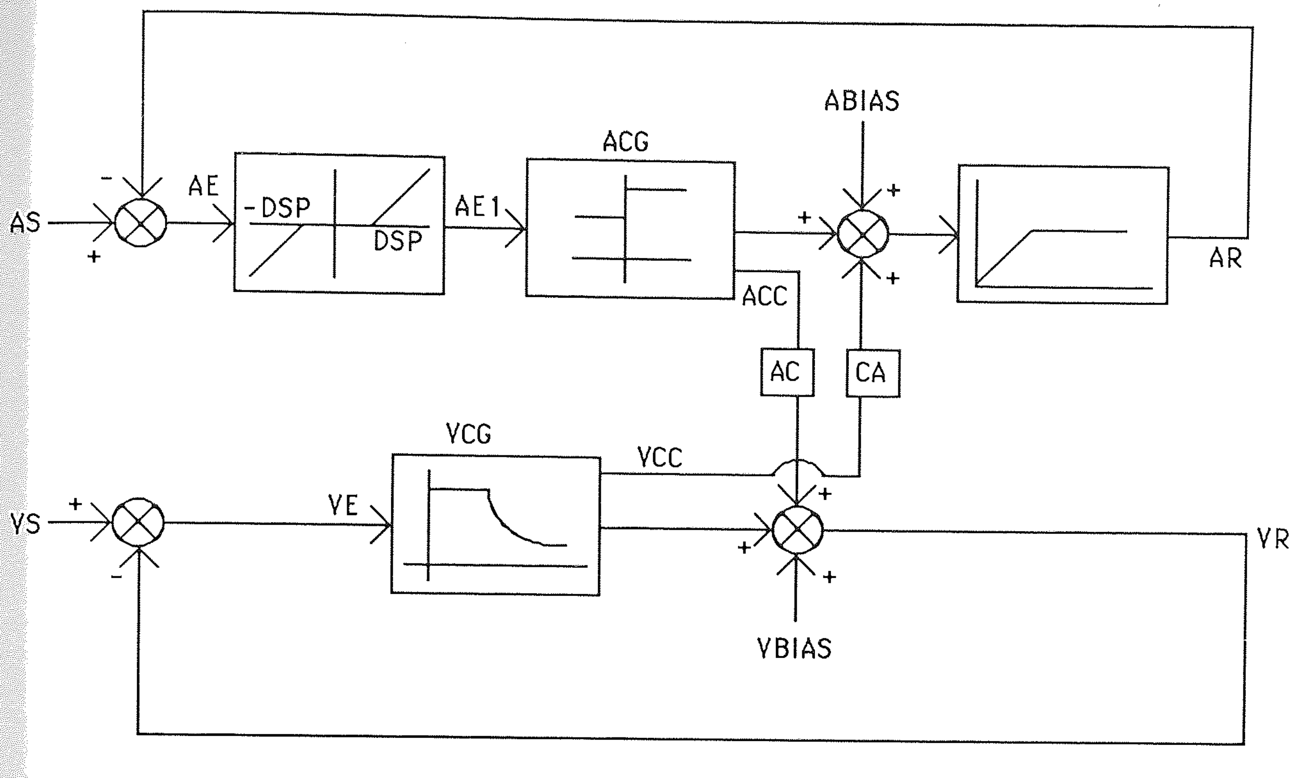

Fig. 4.10a Hung-Semmlow (1980) model of accommodation-vergence interaction.
Key:
AS: accommodation stimulus
AE: accommodative error
AR: accommodation response
DSP: dead space of accommodation
AE1: accommodation error after consideration of dead space
ACG: accommodative controller gain
ABIAS: tonic accommodation
ACC: stimulus for accommodative convergence
AC: accommodative convergence
CA: convergent accommodation
VBIAS: tonic vergence
VCG: vergence controller gain
VCC: stimulus for convergent accommodation
VS: vergence stimulus
VE: vergence error
VR: vergence response

The schematic figures are explained in Fig. 4.10b.

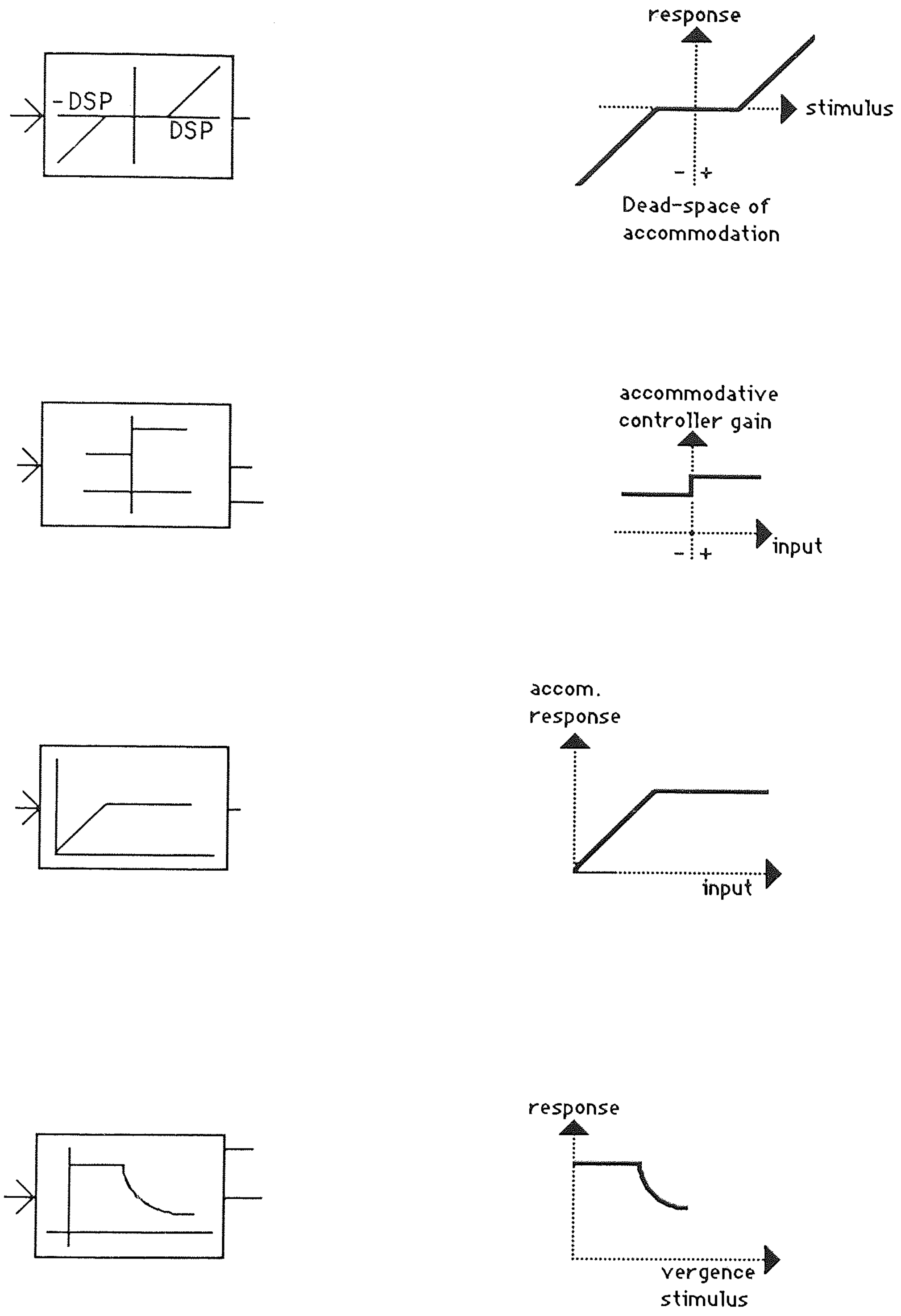

Fig. 4.10b. Symbols used in Hung-Semmlow (1980) model of accommodation-vergence interaction

4.10 CONCLUSIONS

The synkinesis between accommodation and vergence has been considered with particular reference to the cross-link interactions designated accommodative convergence (AC) and convergent accommodation (CA). It is suggested that under closed-loop conditions CA and AC interact with the other components of the accommodation and vergence responses respectively in order to produce the combined response. A negative feedback loop has been proposed as a mechanism whereby the stimulus-response relationship (i.e. error signal) may be monitored for both accommodation and vergence. Furthermore control-theory models have been illustrated which attempt to clarify accommodation-vergence synkinesis and may allow the application of mathematical equations in an attempt to determine the relative proportions of various components within the near-response. Chapter 5 considers the proposal that the development of environmentally-induced myopia may relate to a relative change in the proportions of one or more components of the near-response, thus altering the synkinetic relationship between accommodation and vergence.

CHAPTER 5

THE ROLE OF NEAR-VISION IN THE DEVELOPMENT OF ENVIRONMENTALLY-INDUCED MYOPIA

5.1 INTRODUCTION

"Myopia (short-sight) is that form of refractive error wherein parallel rays of light come to a focus in front of the sentient layer of the retina when the eye is at rest" (Duke-Elder and Abrams, 1970). In simple myopia i.e. optical and non-pathological myopia (Emsley, 1953) this refractive change is produced by variations in the optical system of the eye, either by increased power of the refractive components or an increase in the axial length of the globe.

Aristotle (384-322 B.C.) is credited with first distinguishing shortsight (Goldschmidt, 1968). However the term myopia was derived by Galen (131-201 A.D.) from the words *myein* (to close) and *ops* (eye). Galen observed that shortsighted people partially closed their eyes in order to see better. Galen's theory of vision involved visual spirits called *pneuma*. The pneuma originated in the brain and filled the anterior chamber. In normal vision the pneuma passed from the eye to distant objects so that they might be observed. A deficiency of pneuma would reduce the ability to perceive distant objects resulting in myopia. The ancient Romans considered myopia to be a permanent visual handicap called *Vicium Perpetuum* which if found in a slave considerably lessened his value (Gasson, 1986).

Kepler in 1604 was the first to recognise that a focused retinal image was a prerequisite of clear sight. Furthermore Kepler stated that people who used their eyes a great deal for reading and writing became myopic. Later Ramazzini (1713) reported that prolonged near work produced "weakness of vision" including myopia and additionally caused changes in " tonus of the membranes and fibres of the eye". This latter statement is remarkable in the light of recent work suggesting a relationship between ciliary muscle tone and environmentally-induced myopia (see Section 5.2Fiii).

Donders (1864) stated ;

> *"The distribution of myopia, chiefly in the cultivated ranks, points directly to its principal cause: tension of the eyes for near objects. Respecting this fact there can be no doubt"* (p343).

Donders observed that myopia might be a permanent state resulting from frequent and repeated periods of accommodation; the refractive change resulting from a failure to fully relax the accommodative response. However Donders stated that myopia which was caused by an increase in axial length could not be explained by repeated periods of accommodation. He cited three factors which could contribute to an increase in axial length namely;

i) Pressure of the extra-ocular muscles on the eyeball during strong convergence of the visual axes.

ii) Increased pressure of the fluids, resulting from accumulation of blood in the eyes while in the stooping position.

iii) Congestive processes in the fundus oculi, which lead to softening and extension of the membranes. The fact that under increased pressure extension of the globe occurs principally at the posterior pole is explained by the lack of support from the extra-ocular muscles of the eye at that point.

The theories which suggest that envionmentally-induced myopia results from either the actions of the vergence system or from raised pressure within the globe will be discussed in more detail in subsequent sections of this chapter.

5.2 CLASSIFICATION OF MYOPIA

In a review of methods for the classification of myopia, Grosvenor (1987) observed that a large number of systems have been proposed over the last 150 years. The alternative suggestions providing a basis for a classification may be grouped under the following broad headings;

i) Rate of myopia progression
ii) Anatomical features of myopia
iii) Degree of myopia
iv) Physiological and pathological myopia
v) Hereditary and environmentally -induced myopia.
vi) Theory of myopia development
vii) Age of myopia onset

5.2A RATE OF MYOPIA PROGRESSION

Donders (1864) classified myopia on the basis of its rate of progression. He described three categories of myopia namely stationary, temporarily progressive and permanently progressive myopia.

Stationary myopia is generally of low degree (1.50-2.00D) and arises, "in the years of development". The degree of myopia remains stationary during adulthood and may occasionally diminish with the approach of old age. However Donders suggested that this apparent reduction in myopia with increasing age is probably related to the increased pupil miosis observed in elderly people which will produce increased depth-of-focus.

Temporarily progressive myopia generally arises in the early teens and continues to progress until the late twenties. After this age the rate of myopia progression approaches zero. Interestingly Donders noted, in a discussion of this form of myopia, that it is rare for myopia to develop after 15 years of age in previously normal eyes and it never develops after the 20th year of life. This observation is discussed in section 5.2G.

Permanently progressive myopia ascends rapidly up to 25-35 years of age and thereafter advances more slowly. Subsequent increases in myopia are said to occur "in jumps" rather than in a smooth progression. Donders observed that in these cases it is rare at 60 years of age "to find a tolerably useful eye" due to such conditions as retinal detachment and macula degeneration.

5.2B ANATOMICAL FEATURES OF MYOPIA

Borish (1970) stated that the myopia aetiology could be;

i) Axial i.e. the eye is relatively too long for its refractive status.

ii) Refractive i.e. the refractive system is too strong for the axial length of the eye.

An increase in axial length may occur either in the anterior or posterior portions of the globe or throughout the eye. The site of elongation may have implications in determining the aetiology of the myopia e.g. it has been suggested that expansion of the posterior portion of the globe may relate to the actions of the superior and inferior oblique muscles (see section 5.2Fiib).

Borish subdivided refractive myopia into;

a) Index myopia i.e. where the refractive indices of the media are anomalous.

b) Curvature myopia. Reduced radius of curvature of one or more refractive surfaces producing increased refractive power.

c) Aqueous chamber. A decrease in anterior chamber depth will increase the refractive power of the eye.

Further discussion on the nature of environmentally-induced myopia appears in section 5.2Eiv.

5.2C DEGREE OF MYOPIA

A classification on the basis of the degree of myopia is frequently associated with other factors e.g. age of myopia onset (Goldschmidt, 1968). Hirsch (1950) examined the refractive error of 562 eyes having 1D or more of myopia in patients aged between 18 and 60 years of age. Hirsch divided the population into three groups on the basis of the degree of myopia which he designated alpha, beta and gamma respectively. Using inferential statistics he concluded that the alpha group followed a normal distribution curve and had a theoretical peak at +0.50D. The beta group was represented by a second normal distribution curve which had a peak around -4.00D. Hirsch suggested that the myopia in this group may be hereditary in origin (see Section 5.2Ei). The gamma group ranged from -9.00 to -15.00D. and were described by Hirsch as malignant, pathological, degenerative or congenital. Sorsby et al. (1957) in an investigation of 341 eyes aged between 20 and 60 years concluded that 95% of refractive errors fell within the range ±4.00 D. They also suggested that myopia less than 4.00D had a different aetiology (see section 5.2Fi) compared with myopia exceeding 4.00D.

5.2D PHYSIOLOGICAL AND PATHOLOGICAL MYOPIA

Physiological myopia was defined by Curtin (1985) as that myopia where each component of refraction lies within the normal distribution for that population. Thus the myopia arises from a failure of correlation (see section 5.2Fi) between the refractive components. However Bate (1975) defined physiological as "relating to natural processes, as distinct from pathological ones". Therefore physiological myopia is simply and more accurately defined as non-pathological myopia.

Duke-Elder and Abrams (1970) defined pathological refractive errors as "those refractive anomalies determined by the presence in the optical system of the eye of an element which lies outside the limits of the normal biological variations". *Pathological myopia* may also be described as malignant myopia or degenerative myopia (Duke-Elder and Abrams, 1970). They adopted the term degenerative myopia to describe that myopia which is accompanied by degenerative changes particularly in the posterior segment of the globe. This is most frequently found in high degrees of myopia (greater than 6.00D) but Duke-Elder and Abrams suggested that a classification merely by degree of ametropia is inappropriate since degenerative changes may occur in cases of low myopia. Additionally Harman (1913) described a case of more than 17D of myopia without pathological changes being present.

5.2E HEREDITARY AND ENVIRONMENTALLY-INDUCED MYOPIA

Whilst this thesis is primarily concerned with environmentally-induced myopia, it would be inappropriate to ignore the evidence for a hereditary influence on the aetiology of myopia. It is frequently impossible to distinguish between environmental and hereditary influences and hence other means of classification have been adopted (e.g. age of onset or degree of myopia) in an attempt to provide additional information regarding the aetiology of refractive error development.

5.2Ei EVIDENCE FOR HEREDITARY INFLUENCES ON THE DEVELOPMENT OF MYOPIA

The clearest evidence for hereditary influences on myopia development arises from two sources namely;

i) the incidence of myopia in uniovular twins

ii) the incidence of myopia within ethnic populations.

5.2Eii UNIOVULAR TWIN STUDIES

A number of workers have compared the incidence of myopia in uniovular and binovular twins in an attempt to determine hereditary influences on the incidence of myopia. These studies have been reviewed by Goldschmidt (1968); Borish (1970) and Karlsson (1974). The two largest studies which will be discussed in more detail are those of Waardenberg (1950) and Sorsby et al. (1963).

Waardenberg (1950) examined the refractive error in 300 pairs of uniovular twins and 225 pairs of binovular twins. Subjects with high myopia were excluded from this study. 90% of the uniovular twins had less than 1.00D difference in refractive error (measured for the vertical meridian) and 74% of these twins showed a difference of less than 0.50D. However the binovular twins showed significantly larger differences in refractive error.

Sorsby et al. (1963) determined the refractive error in 78 pairs of uniovular twins, 40 pairs of binovular twins and 48 unrelated control pairs. In the control group both of the subjects were the same sex and approximately the same age . Additionally the control group was selected in order to give the same sex distribution, age range and range of refractive error as the group of uniovular twins. Sorsby et al. found 70.5% of the uniovular twins had vertical refractions within 0.50D of their partners whilst only 30% of the binovular twins and 29.2% of the control pairs exhibited such close agreement. The level of concordance was significantly higher in the uniovular twins than in the binovular twins, with no significant difference being observed between the binovular twins and the control group.

Uniovular twin studies have clearly indicated that inherited factors play a part in the development of refractive error. Further evidence for this observation comes from studies of the incidence of myopia amongst different ethnic populations.

5.2Eiii POPULATION STUDIES

The incidence of myopia has been shown to vary widely between different ethnic populations, for a review see Borish (1970). Crawford and Hammar (1949) examined the incidence of myopia amongst various ethnic groups in Hawaii and observed that 17% of the Chinese population were myopic. This compared with an incidence of myopia of only 3% amongst the indigenous Hawaiian population. It is clearly impossible to eliminate environmental factors from population studies and one ethnic group may well indulge in a greater number of activities which may lead to the development of myopia (e.g.reading) when compared with another. Nevertheless the increased incidence of myopia amongst certain ethnic groups (e.g. Chinese, Japanese, Egyptians, Germans, Jews and Middle Eastern peoples) may provide further evidence for inherited factors playing a role in the aetiology of myopia.

5.2Eiv ENVIRONMENTALLY-INDUCED MYOPIA

> *" Throughout all this maze of theorizing, much of it mutually contradictory and most of it fanciful, there run two main threads of thought linking the onset and progress of myopia with environmental constitutional factors - excessive close work and general debility"*
> (Duke-Elder, 1970; p340)

Cohn (1867) examined the incidence of myopia in 10,060 schoolchildren in Breslau and other German cities. He observed that in the youngest schoolchildren there was little myopia but the incidence increased with age. Cohn concluded that as the increased incidence of myopia occurred during the educational process, and consequently when a substantial portion of the time was spent reading and involved in other close work, the onset of myopia was related to increased near-visual activity. This became known as the *use-abuse theory* since Cohn suggested that myopia onset was an adaptation to use or abuse of the eyes during sustained near-vision.

A number of workers have indicated a higher incidence of myopia in subjects whose occupations involve a substantial amount of close-work when compared with other occupations. Tscherning (1882) classified Danish conscripts into six categories based upon their previous occupation. These categories and the incidence of myopia observed are indicated in Table 5.1. Tscherning evaluated 7,523 men with 260 men in the smallest category (good but not university education). Later Goldschmidt (1968) repeated Tscherning's study but used subjective refraction in order to determine the refractive error rather than the ophthalmoscopic estimation of refraction used by

Tscherning. Goldschmidt tried to match the occupational categories as closely as possible and examined 3,651 men with 144 men in the smallest category (again those having a good but not university education). The incidence of myopia observed by Goldschmidt is also indicated in Table 5.1.

Table 5.1. Incidence of myopia (percentage) amongst various occupations. Data from Tscherning (1882) and Goldschmidt (1968).

	Tscherning (1882)	Goldschmidt (1968)
Mainly university students	32.4	30.1
Mainly clerks	15.8	11.8
Those with a good (but not university) education	13.3	13.9
Fine work craftsmen	11.7	9.1
Heavy work craftsmen	5.24	4.3
Farm and unskilled labourers and seamen.	2.45	2.9

Duke-Elder (1930) examined the refractive error of 244 pupils at the London School of Printing who were involved in a variety of occupations. He observed that the incidence of myopia was higher in those subjects undertaking occupations which involved a high level of near-work (e.g. compositors, myopia incidence = 42.5%) when compared with those subjects performing less near-work (e.g. warehousemen, myopia incidence = 27%). In an earlier paper Sydenstricker and Britten (1927) observed a higher incidence of visual defects in young (aged between 20-24 years) business and professional workers (36.4%) compared with agricultural workers(21%). However these visual defects were not analysed into myopia or hypermetropia.

Young (1961) demonstrated that when adult monkeys are restricted to a near-visual environment, they exhibit significant increases in myopia. Nine pigtail monkeys (Macaca nemestrina) were placed in restraining chairs and enclosed within hoods which prevented vision beyond 20 inches. The restricted monkeys showed a mean increase in myopia of approximately 0.75D within 6 months of being placed under the hoods. In later studies Young observed that if adolescent monkeys * are placed in the restricted visual environment, there were no significant changes in refraction for the initial 3-4 months but this was followed by a rapid myopic shift which averages approximately 2D following one year of visual restriction (Young, 1965). When infant and very young monkeys were placed in a restricted visual environment, there was an even longer period before the development of myopia, but the myopic shift which ensues was more rapid than for adolescent monkeys and a greater degree of myopia resulted (Young, 1963). Young (1977) suggested that the higher levels of myopia which develop in the younger monkeys may relate to greater elasticity in the tunics of the younger eye when compared with older monkey eyes.

In a further attempt to determine the effect of near-vision upon myopia development, Young et al. (1969) examined the incidence of myopia amongst Eskimo families. They investigated 41 family units in Barrow, Alaska comprising 197 subjects. It was noted that the Eskimo families consisted of parents who were illiterate whilst their children had learned to read and were required to attend schools comparable to those in the U.S.A. Young et al. observed that out of 130 parents, only two were myopic and one of those had a refractive error of only -0.25D. The remaining parents had refractive errors between plano and +3.00D with the majority having hypermetropia greater than +1.50D. However around 60% of the schoolchildren examined were myopic. Clearly other factors besides schoolwork may be related to the increased incidence of myopia in the Eskimo children e.g. the introduction of a Western type diet. Young et al. suggested that as the refractive changes occur in the offspring but not in the parents then it is

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* Young (1965) stated that the exact ages of the pigtail monkeys was unknown but calculations based upon the monkey's height and weight would indicate that the males were aged between 2.5-3 years and the females were aged between 3-4 years. These ages fall in the prepubertal range and are developmentally equivalent to human children aged between 7 and 12 years.

unlikely that a change in diet plays a major role in myopia development. However it should be noted that degree of susceptibility to refractive error development will vary between adults and children (as illustrated by Young's monkey studies) hence this study does not provide conclusive evidence for the role of near-work in myopia development.

In a study of a different Arctic population, Alsbirk (1979) examined the incidence of refractive errors amongst West Greenland Eskimos. These subjects were literate, having been taught a written Eskimo language. They noted that 36.3% of subjects aged between 15 and 39 years (N=208) were myopic with 4.6% having myopia greater than 2D. Interestingly 28% of subjects over 60 years of age were shown to be myopic in this population. This is a considerably higher incidence of myopia when compared with that amongst the illiterate Alaska Eskimos (Young et al., 1969).

Later Richler and Bear (1980a and 1980b) examined both the ocular refraction and the number of hours per day spent performing near-visual activities in the population of Western Newfoundland. A significant correlation was observed between hours of near-vision and the degree of myopia for all age ranges. Richler and Bear suggested that this finding must be interpreted with caution but it may provide further evidence for an association between near-vision and myopia. Goldschmidt (1968) pointed out that if intelligence, height or social position were substituted for quantity of close work, a significant correlation may still be observed. Possible mechanisms for the development of environmentally-induced myopia are discussed in section 5.2F.

5.2F THEORY OF MYOPIA DEVELOPMENT

In a review of refractive error development, McBrien and Barnes (1984) described three major theories of myopia development namely;

i) Biological-statistical theory
ii) Use-abuse theory
iii) Theory of emmetropization

5.2Fi BIOLOGICAL-STATISTICAL THEORY

Steiger (1913) introduced the concept which considered emmetropia as a status occupying a position between myopia and hypermetropia along a biological continuum. Steiger measured the radius of curvature of 5000 corneae using the Javal-Schiotz ophthalmometer and observed that values of corneal radii were normally distributed. Steiger suggested that all of the ocular components of the eye, e.g. axial length, corneal curvature, anterior chamber depth, would be characterised by their own frequency distribution curve. As the refractive state of the eye results from the interaction of these components, then the distribution of refractive error should reflect the distribution of the individual components. This became known as the biological variability theory or more simply the *biological theory* for development of refractive error.

Data from Stenstrom (1946) and Sorsby et al. (1957) indicated that the distribution of refractive error is not normal but showed leptokurtosis in the emmetropic region and is skewed towards the myopic side. This would appear to disprove the theory of free association between the refractive components suggested by Steiger as free association would have predicted a lower incidence of emmetropia compared with that actually observed. This difference is illustrated in Fig. 5.1.

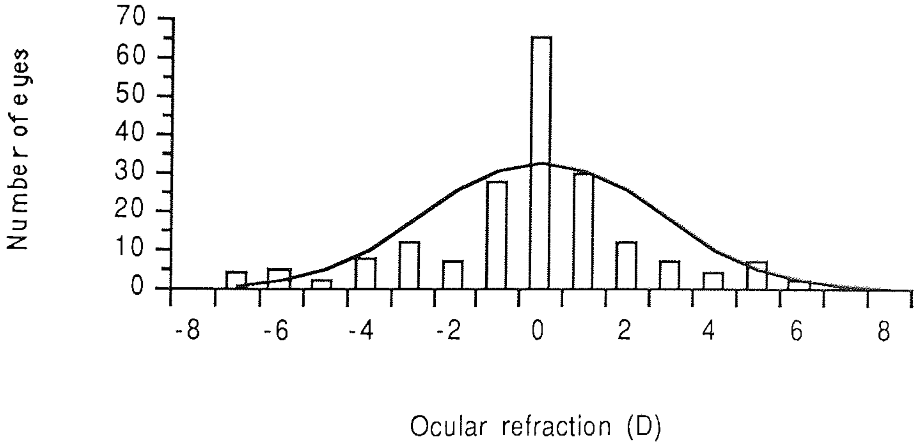

Fig. 5.1 Distribution of refractive error in 194 adult eyes (Redrawn from Sorsby et al., 1957). The line represents the theoretical normal distribution and it may be clearly seen that the observed distribution of refractive error is markedly leptokurtotic.

Sorsby et al. (1957) noted that within the range of refractive errors between ±4.00D, a broad distribution of ocular components may be observed. Within this refractive range, axial lengths of 21-26mm, corneal powers of 38-48D and lens powers of 17-26D were found. In a study of 341 eyes, it was demonstrated that 98% of eyes fell within this range of refractive error. Sorsby et al. suggested two co-ordinating mechanisms in the emmetropic eye which may compensate for these variations in ocular components, namely between axial length and either corneal curvature or crystalline lens power. In the first co-ordinating mechanism, an increase in axial length was accompanied by an increase in corneal radius. Alternatively increased axial length may be accompanied by a flatter crystalline lens. Further discussion on the processes of emmetropization appears in section 5.2Fiii. Sorsby et al. (1957) stated that normally the components of the eye are well correlated, and that this results in emmetropia. However a failure of correlation would produce varying degress of ametropia which he described as *correlation ametropia* since it was the correlation rather than the value of the individual ocular component which resulted in development of the refractive error. For a review of the normal range of values of refractive components see Borish (1970).

McBrien and Barnes (1984) summarised Sorsby's conclusions by stating that the determination of the refractive error involved the correlation of four normally varying components; axial length, corneal power, lens power and anterior chamber depth. It was the optimum correlation of these components which produced emmetropic or near-emmetropic eyes. Correlation ametropia resulted from a failure of this correlation and only rarely did ametropia result from an abnormal refractive component i.e. where the value of the component fell outside the range observed in emmetropic eyes. This abnormal component was most commonly axial length but ametropia may also result from abnormal corneal or lenticular parameters. However Sorsby stated that the components of ametropia were genetically determined and consequently he did not consider the effect of environmental factors on refractive error.

5.2Fii THE USE-ABUSE THEORY

The so called use-abuse theory was first described by Cohn (1867) who stated that the onset of myopia was an adaptation to use or abuse of the eyes during sustained near-vision. Evidence for a relationship between myopia and near-vision has been presented in section 5.2Eiv. However whilst such evidence exists, this theory has been unable to provide a satisfactory explanation of how close-work leads to axial elongation (Goldschmidt, 1968).

It also remains unclear whether the development of myopia results from the changes in the accommodative system, the vergence system or an alteration of the synkinesis between accommodation and vergence. These possibilities are considered in subsequent sections.

5.2Fiia EXCESSIVE ACCOMMODATION PRODUCES MYOPIA

In a review of this topic Stansbury (1948) cited a number of workers including Ware (1813) and von Arlt (1856) as stating that myopia was produced by raised intra-ocular tension during accommodation. This observation has been confirmed in more recent work by Young (1975) who implanted a radiosonde pressure transducer into the vitreous chamber in two Macaca nemestrina monkeys. Young demonstrated an increase in vitreous pressure as the fixation distance reduced. The increase in vitreous pressure was approximately 6mm of mercury when viewing a target at a fixation distance of 12 inches. Furthermore this increase in pressure was maintained as long as the accommodation response was sustained but decreased when accommodation relaxed. It should be noted that the monkey viewed the fixation target binocularly and consequently changes in both accommodation and vergence were stimulated. It therefore remains unclear whether the alteration in vitreous pressure results from increased accommodation, vergence or may relate to the combined effect of the two oculomotor responses.

The suggestion that myopia resulted from an increased accommodative response was made by Newman (1929) who suggested that excessive accommodation would pull on the elastic membrane of the choroid, producing an increase in choroidal tension and a consequent decrease in its nutrition. This would lead to degenerative changes resulting in a posterior staphyloma. However Hensen and Volkers (1873) showed that needles inserted into the choroid behind the equator remained relatively stationary during periods of increased accommodation and furthermore needles inserted into the choroid at the posterior pole did not move at all.

Bedrossian (1966) stated that accommodation was the primary causative factor in myopia and he demonstrated that when atropine was instilled into one eye and the other eye used as a control, there was a reduction in myopia in the atropinized eye of around 0.50D per year while myopia progression continued in the other eye at a rate of approximately 0.63D per year. It should be noted however that the use of a monocular cycloplegic will cause total dissociation of the eyes for near-vision, resulting in a change in fusional requirements and hence affect the vergence response.

Young (1965) investigated the effect of atropine in eight Macaca nemestrina (pigtailed) monkeys in whom myopia had already been induced by restricting their visual environment (see section 5.2Eiv). After a 0.50D increase in myopia had been produced, 1% atropine was instilled three times a day for two months. Following the two month instillation period the myopia progression reversed slightly and appeared to stabilize although the monkeys were still kept in the restricted visual environment.

A number of workers have induced myopia in a variety of species by suturing the animal's eye-lids in order to prevent detailed form-vision. Lid-suture techniques have been shown to induce myopic shifts in monkeys (Somers et al., 1978; Raviola and Wiesel,1985), chickens (Wallman et al.,1978; Yinon et al., 1980; Wallman and Gottlieb, 1987; Wildsoet and Pettigrew, 1987; Pickett-Seltner et al., 1988), cats (Gollender et al., 1979; Smith et al., 1980) and tree-shrews (Sherman et al., 1977; McKanna and Casagrande, 1985; McBrien and Norton, 1987). Raviola and Wiesel (1985) observed that surgical suturing of the eye lids in infant rhesus and stump-tailed macaque monkeys produced a myopic shift mediated via an increase in vitreous chamber depth. In order to determine the effects of accommodation on the induced myopia development they examined the effect of atropine on lid-suture myopia. They observed that in the stump-tailed monkeys (Macaca arctoides), instillation of atropine inhibited myopia development. However in the rhesus monkey (Macaca mulatta) atropine did not affect the degree of lid-suture myopia. This would indicate that the role of accommodation in myopia development varied between these two species of monkey. Raviola and Wiesel suggested that the fact that atropine produced no inhibition of myopia development in the rhesus monkeys may relate to a reduced efficacy of atropine as a cycloplegic in these animals. In order to investigate this proposal, they removed the ciliary ganglion in one rhesus monkey and thereby interrupted the parasympathetic innervation to the ciliary muscle. However this surgical procedure did not inhibit the development of lid-suture myopia. This finding would indicate that accommodation does not play a part in the development of lid-suture myopia in the rhesus monkey. The observed variation in the role of accommodation in myopia development between different species of monkey would indicate that any attempt to infer conclusions on human myopia development from animal studies must be viewed with caution.

5.2Fiib EXCESSIVE VERGENCE PRODUCES MYOPIA

A number of workers have suggested that increased axial length may be related to the action of the extra-ocular muscles on the globe. Thus the forces inducing myopia development may arise from the external aspects of the globe rather than internally.

Stansbury (1948) cited Von Graefe(1854) as being the earliest to indicate that the medial and lateral rectus muscles may cause stretching and distension of the eyes during sustained near-vision . In a later paper, Von Arlt (1876) also suggested that myopia may be produced by excessive vergence. He postulated that the pressure of the extra-ocular muscles during convergence impeded blood outflow through the vortex veins, leading to congestion and increased intra-ocular tension.

The notion that the action of the superior oblique muscle was responsible for myopia development was proposed by Stilling (1891). He stated that myopia varied with the anatomical position of the trochlea, a low (presumably meaning inferior) pulley position would result in globe compression. However a number of other workers (see Stansbury,1948) were unable to verify the theory that refractive error varied with the position of the trochlea in the orbit.

Jackson (1931) reported that " excessive convergence in the majority of cases starts the myopia and keeps it progressive". In an attempt to verify Jackson's statement, Luedde (1932) investigated the effect of monocular cycloplegia (atropine) on myopia progression. Luedde indicated that total dissociation of the eyes at near would reduce the vergence demand. He observed a reduction in myopia progression in one subject and claimed that this was evidence for the role of vergence in the development of myopia. It should be noted that Luedde carried out exactly the same experiment as that performed later by Bedrossian (1966); see section 5.2Fiia. However their interpretation of similar results differed, Luedde claiming that excessive vergence produced myopia whereas Bedrossian suggested that it was due to the effects of excessive accommodation.

Both Donders (1864) and Linder (1944) observed that there was a lower incidence of myopia in watchmakers than might have been predicted in view of the amount of near-vision involved in this occupation. Donders suggested that the reduced incidence of myopia may relate to the use of monocular loupes which would reduce the vergence demand. It should be noted however that the magnifying effect of the loupe may also lower the accommodative stimulus.

Further evidence for excessive vergence being the precursor of myopia comes from the study of Mohan et al. (1977) who showed that the myopia development which could be induced in rabbits by applying raised temperature and intra-ocular pressure (Maurice and Mushin, 1966; Tokoro, 1970) depended strongly upon extra-ocular muscle tension. They observed that myopia development increased following resection of the four recti, while free tenotomy of the recti resulted in a reduction in development.

Greene (1980) stated that extension of the posterior portion of the globe could result from the action of the oblique muscles, these being the only extra-ocular muscles which insert into the posterior half of the globe (see Fig. 3.4). Greene stated that the peak force capabilities of the extra-ocular muscles were 250 times greater than that of the ciliary muscle, suggesting that vergence must mechanically dominate accommodation. Greene also noted that whilst changes in accommodation may indirectly affect intra-ocular pressure (IOP) via choroidal tension (Van Alphen, 1961 and 1986), the potential IOP changes which may be induced by vergence are larger and may be transmitted directly to the sclera by the extra-ocular muscles.

5.2Fiic VARIATIONS IN ACCOMMODATION-VERGENCE SYNKINESIS PRODUCES MYOPIA

It is clear from the evidence cited in Sections 5.2Fiia and 5.2Fiib that it is difficult to differentiate between the actions of the accommodative and vergence mechanisms in the development of myopia. Therefore whilst there is a substantial amount of evidence linking near-vision and myopia, it remains inconclusive as to which component is responsible for the myopic shift. As a consequence of the negative feedback mechanisms which have been shown to exist between accommodation and vergence (see section 4.9), an alteration in the output of either accommodation or vergence is likely to induce changes in the other component. The findings which will be discussed in subsequent chapters suggest that myopia may develop from an alteration of the synkinesis between accommodation and vergence and indeed myopia itself may be an adaptation in order to maintain this synkinetic relationship (see chapters 8-9).

5.2Fiii THEORY OF EMMETROPIZATION

It was indicated in section 5.2Fi that the number of emmetropes in the population exceeds that which might have been predicted on statistical grounds. The process which is responsible for this relatively high incidence of emmetropia has been described as *emmetropization* (Straub, 1909). Nadel et al. (1957) considered emmetropization to be an example of the principle of allometric growth commonly encountered in biologic phenomena. Presumably they regarded emmetropia as resulting from the independent parallel growth of the ocular components. This would imply that emmetropia results purely by chance rather than as a result of any specific interaction between the ocular components. Hofstetter (1969) suggested that the leptokurtosis of the frequency distribution of refractive error is the normal result of an inherent structural condition in the design of the human eye. Thus the distribution of refractive error should be considered in terms of its deviation from the expected leptokurtosis rather than considering the deviation from a normal distribution. Hofstetter stated that the dispersion of refractive error away from perfect leptokurtosis is compatible with the normal distribution of the optical components of the eye, and the occasional variation of individual refractive elements produced by effects unrelated to normal growth and development.

The most substantial work to date on the process of emmetropization was the study of Van Alphen (1961). He reanalysed data from the work of Stenstrom (1946) who had measured the optical elements of 1000 right eyes in 315 women and 685 men aged between 20 and 35 years. Stenstrom measured the ocular refraction, corneal power, anterior chamber depth and axial length of these eyes and used the data to calculate the crystalline lens power. Van Alphen found 10 statistically significant intercorrelations between these optical elements which are indicated in Table 5.2.

Table 5.2 Simple correlation coefficients* from 1000 eyes (from Van Alphen, 1961).

	Rx	AL	ACD	CP	LP
Ocular refraction (Rx)		-0.76	-0.34	-0.18	0.00
Axial length (AL)			+0.44	-0.31	-0.36
Ant. chamber depth (ACD)				+0.10	-0.27
Corneal Power (CP)					-0.12
Lens Power (LP)					

* Levels of significance; 5%, r = 0.06: 1%, r = 0.08.

An attempt to fit all of the ten correlations into one scheme would result in contradictory findings e.g. myopes have a greater axial length than hypermetropes and an increased axial length is generally associated with flatter corneae. However it has been demonstrated that myopes have steeper corneae than hypermetropes. Thus Van Alphen considered that these 10 intercorrelations were essentially the result of a few independently acting factors as one factor could affect a number of variables and thereby alter several intercorrelations. He suggested that in emmetropic subjects there needed to be at least two independent factors namely;

i) A factor determining the relationship between corneal power and axial length (denoted S).

ii) A factor grouping axial length, lens power and anterior chamber depth (denoted P).

Van Alphen noted that factor S operates in corneal power and axial length but does not contribute to the variability of the other three parameters. Thus there is a trend for larger eyes to have flatter corneae, and this trend is essentially independent of refractive error. Factor P represents an underlying influence which tends to produce deeper anterior chambers and flatter lenses in larger eyes.

However in consideration of ametropia, a third factor (denoted R) was introduced. Factor R was associated with the resistance to intra-ocular pressure offered by the ciliary muscle- choroid layer.

Van Alphen suggested that intra-ocular pressure was of significance in the determination of both corneal curvature and axial length of the eye. If the intra-ocular pressure is countered by both choroidal tension and scleral elasticity, then choroidal tension will be a factor in the determination of the axial length. Van Alphen considered the ciliary muscle-choroid combination as a functional unit which could behave physiologically as a continuous sheet of smooth muscle. He noted that the ciliary muscle originates from the scleral spur and inserts into the supra-choroid. Hence contraction of the ciliary muscle will pull the choroid forward. As the choroid and ciliary muscle were considered to be functionally continuous, the resistance to changes in intra-ocular pressure will therefore be dependent upon ciliary muscle tonus. Therefore high ciliary muscle tone will lower the tension on the sclera whereas low ciliary muscle tone will result in scleral strech.

Van Alphen proposed that the process of emmetropization was achieved by a negative feedback, self-focusing control system. If a photocell was imagined to be placed at the macula, then a self-focusing mechanism would adjust the position of the photocell in order to lie at the focus of the refractive system. He proposed two possible self-focusing mechanisms. Firstly a comparator could compare the present output of the photocell with a memory store for previous outputs. This is illustrated in Fig. 5.1. Secondly if the crystalline lens was allowed to oscillate, the correlation between photocell output and lens oscillation could be computed. This is illustrated in Fig. 5.2. Either of these two methods would allow computation of the error signal. By feeding back the output of the photocell to the pressure regulator and inserting a device which detects the direction of the error signal, a self-focusing mechanism is achieved.

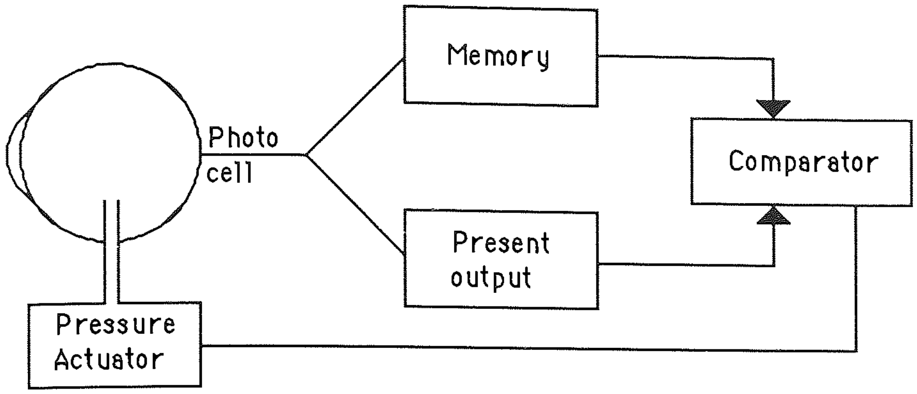

Fig 5.2 Self-focusing mechanism where the output of the photocell (macula) is compared with previous output information (redrawn after Van Alphen, 1961).

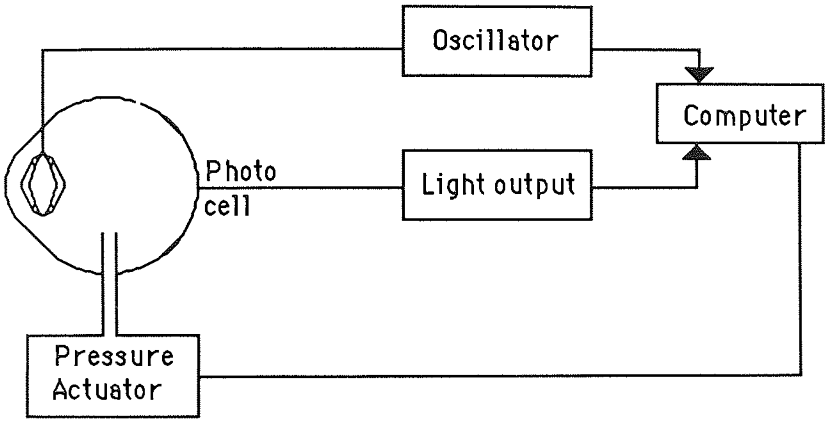

Fig. 5.3 Self-focusing mechanism where lens oscillation and photocell (macula) output are correlated. (redrawn after Van Alphen, 1961)

Whiteside (1957) and Campbell et al. (1959) have verified that crystalline lens oscillation does indeed occur, being of the order of ±0.25D at 2Hz. However in a recent review by Charman and Heron (1988), it was suggested that lower frequency components (<0.5Hz) may be of more significance in the function of accommodation. The self-focusing model requires a link between the macula (photocell) and the ciliary muscle (elasticity regulator). Van Alphen suggested that the stimulus to accommodation forms this link between the output from the macula and the input to the ciliary muscle.

Van Alphen observed that variations in ciliary muscle tone could produce changes in refractive error by interfering with this self-focusing mechanism. He noted that at birth the eye was generally hypermetropic. The development of refractive error may then proceed in three directions. If there was no adjustment of the parasympathetic overactivity in the eye, then tension in the ciliary muscle and choroid remains high, the pressure on the sclera is diminished, the globe does not expand and the eye will remain hypermetropic. However if the parasympathetic tone is released by adjustment from higher centres, then the globe will expand until emmetropia is reached and this state will be maintained by feedback between the macula and the ciliary muscle. However further loss of parasympathetic tone will lead to further expansion and elongation of the globe resulting in myopia.

Thus eyes of any size (Factor S) which are hypermetropic at birth, will have to stretch (Factor P) in order to become emmetropic. In this process axial length is adjusted to the total refractive power. The degree of adjustment (Factor R) determines the refraction and the shape of the globe. Thus Factor R represents the degree of ametropization i.e. the degree of adjustment of factor P with respect to Factor S.

In a discussion on school myopia Van Alphen observed that not all sustained near-vision tasks result in myopia. He suggested that learning, as opposed to mere close work, has a more complicated psycho-visual mechanism. Learning may induce stress and anxiety which may not be present in other forms of close work. Van Alphen suggested that the emotional state may affect autonomic balance and this alteration might affect ciliary muscle innervation and thereby influence the determination of refractive error. A discussion on the influences of emotional and psychological factors on refractive error development is beyond the scope of this thesis. However a consideration of the relationship between sympathetic innervation to the ciliary muscle and the AC/A ratio appears in Chapter 7.

5.2G AGE OF MYOPIA ONSET

A large number of studies have classified myopia on the basis of the subject's age at the time of reported myopia onset. In a recent paper Grosvenor (1987) classified myopia into the following categories;

i) Congenital myopia. Those children who are myopic at birth and where the myopia persists through infancy.

ii) Youth-onset myopia. The form of myopia which has its onset during the period between 6 years of age and the early teens.

iii) Early adult-onset myopia. Myopia onset between 20 and 40 years of age.

iv) Late adult-onset myopia. Myopia onset after 40 years of age.

Clearly a major difficulty in any attempt to classify myopia in terms of age of onset is that the subject's recall of their myopia onset will probably relate to their first refractive correction whereas symptoms of reduced distance vision may have occurred at a previously undetermined time. Rosenberg and Goldschmidt (1981) investigated the development of myopia in 280 Danish schoolchildren and stated that the pre-myopic period and initial myopia development were so variable in terms of duration, symptomatology and progression that it is not possible to determine the exact onset of myopia. They observed that marked differences exist in adaptation to reduced distance visual acuity, noting that some children had symptoms when only 0.50D of myopia or less was present while other children had between 1 and 2D of myopia yet presented without any visual symptoms.

Several studies have used the age of myopia onset in an attempt to differentiate between environmentally-induced myopia and that myopia which relates to inherited factors (see section 5.2E). Studies on the growth of the ocular components have indicated that the eye reaches its adult axial length by 13 years of age (Sorsby et al., 1961; Sorsby and Leary, 1970; Larsen, 1971). Furthermore it has been demonstrated that the other refractive components of the eye have attained their adult values by 13-15 years of age (for review see McBrien and Millodot, 1987a).

Studies on the development of refractive error in children (e.g. Brown, 1938 and 1942; Slataper, 1950) have indicated that stabilization of the refractive error normally occurs around 15 years of age. Morgan (1958) observed that by the age of 16 years most children have attained their adult refraction which will remain nearly constant for the next three decades. However Hirsch (1964) noted that a small percentage of people exhibit changes in refractive error after 16 years of age and it is this late-onset myopia which will be discussed in section 5.2Gi.

5.2Gi LATE-ONSET MYOPIA

Goldschmidt (1968) described a type of myopia which develops after the cessation of bodily growth. He adopted the term " *Spatmyopie* " to describe this myopia. Goldschmidt stated that this myopia may be environmentally determined and is likely to relate to high levels of near-vision. He also observed that subjects who become myopic during the period of bodily growth may develop *spatmyopie* in addition to their initial myopia if they should choose an occupation which requires high levels of close work. Goldschmidt concluded that whereas "common low myopia", which develops during periods of bodily growth, has its aetiology " in the genetic substance", another type of myopia exists which develops after cessation of bodily growth and is principally found in people undertaking fatiguing close work. Goldschmidt stated that this type of myopia was therefore environmental in origin.

Goss and Winkler (1983) examined the refractive records of 299 patients, all of whom had at least four examinations between the ages of 6 and 24 years and had at least 0.50D of myopia during this period. They observed that although there was a great deal of individual variability, the mean age of myopia cessation was 15.53 years. It was also noted that myopia stops increasing earlier in female subjects when compared with males. In a later paper Goss et al. (1985) examined longitudinal data on 559 myopic patients although only 108 patients had been examined on three or more occasions. They categorized the change in myopia during adulthood (i.e. above 18 years of age) into three groups namely;

i) Adult stabilization. Here rapid increases in myopia during early adolescence are followed by stabilization during early adulthood. Minor adjustment of the refractive error may occur after stabilization but these changes are generally small and of the order of ±0.25D. 68% of male subjects and 87% of female subjects fell into this category.

ii) Adult continuation. In this group the rapid myopic progression seen during adolescence continues through adulthood. This pattern represented 25% of male subjects and 13% of females.

iii) Adult acceleration. This was the least common pattern; myopia progression increases after adolescence. 6.3% of males and no female subjects fell into this group.

Goss et al. reviewed a series of papers which described cases of myopia onset in young adulthood. Several studies have observed an increase in myopia amongst students of military academies (e.g. Hayden, 1941; Hynes, 1956; Sutton and Ditmars, 1970; Shotwell, 1981 and 1984) which varied with the amount of time spent undertaking near-vision tasks. Riffenburgh (1965) presented nine cases of myopia onset after 20 years of age and he suggested that the myopia which becomes manifest in adulthood has a different form from that which appears in childhood and that this adult-onset myopia is associated with close-work. Young (1977) stated that approximately 8% of the myopic subjects in graduate and professional schools became myopic in their twenties. Stevenson (1984) described two types of myopia, developmental myopia where the age of onset is between 6 and 9 years and environmental myopia developing between 15 and 17 years of age.

Goss et al. (1985) and Goss and Erickson (1987) described cases of late-onset myopia which were induced by a decrease in the radius of corneal curvature. Goss et al. observed increases in both myopia and corneal steepening in 32 subjects with an overall correlation coefficient of 0.58. Goss and Erickson observed a significant correlation between changes in refractive error and corneal steepening in 37 patients who had three or more refractions at 18 years of age and older. However it should be noted from the Goss and Erickson study that the mean changes in refractive error were small (mean for male subjects -0.06D; for females -0.02D) and some subjects showed increased hypermetropia during the test period.

In a recent paper Adams (1987) presented his own case of late-onset myopia in which the refractive error changed from -0.25D at 19 years of age to -4.75D at 42 years of age. Whilst there was no significant change in corneal curvature, his axial length at 42 years of age was 25.8 mm, 1.8mm longer than the mean given by Stenstrom (1946) for an adult population. Taking 0.234D of myopia for each additional 0.1mm of axial length (Van Alphen, 1961) this equates to 4.2D of myopia produced by the increase in axial length.

McBrien and Millodot (1987a) compared the ocular biometric components of 30 late-onset myopes (myopia onset after 15 years of age) and 30 emmetropic subjects who were age and sex matched. Using A-scan ultrasonography and keratometry they observed that late-onset myopes had a significantly increased axial length. Both anterior and vitreous chamber depth were significantly longer in the late-onset myopes while there was no significant difference in corneal curvature. These findings indicate that late-onset myopia results from axial elongation rather than corneal or lenticular changes. Rosenfield and Gilmartin (1987c) also found (see section 7.6) no significant variation in corneal curvature with refractive error in a population consisting of 20 early-onset myopes (i.e. myopia onset prior to 15 years of age), 20 late-onset myopes (myopia onset at 15 years of age or later) and 20 emmetropes.

5.3 CONCLUSIONS

Evidence from a wide range of experimental studies has indicated an association between near-vision and myopia although the actual mechanism which leads to the increase in refractive error remains unclear. The processes of both accommodation and vergence have been implicated in the development of environmentally-induced myopia. An additional proposal is that myopia development relates to an alteration in the synkinetic relationship between accommodation and vergence. In Chapter 6 this synkinesis will be examined via the AC/A ratio in a population consisting of myopic and emmetropic subjects.

CHAPTER 6

THE EFFECT OF A NEAR-VISION TASK ON THE RESPONSE ACCOMMODATIVE CONVERGENCE/ACCOMMODATION (AC/A) RATIO OF A MYOPIC POPULATION

6.1 INTRODUCTION

In Chapter 5, evidence was presented for an association between near-vision and myopia. However it remains unclear whether the development of environmentally -induced myopia relates to the action of accommodation, the action of vergence or an alteration in the synkinetic relationship between the two. In order to investigate the interaction of accommodation and vergence, the accommodative convergence/ accommodation (AC/A) ratio was examined during the course of a sustained near-vision task in a population consisting of myopic and emmetropic subjects.

Goldschmidt (1968) stated that the myopia which develops after the cessation of bodily growth is more likely to be envionmental in origin when compared with the myopia which evolves earlier in life (see Section 5.2G). Furthermore he observed that this myopia, which is relatively late in onset, was related to high levels of near-vision. This study has subdivided subjects on the basis of age of myopia onset. It has been reported that stabilization of the refractive error normally occurs at around 15 years of age (Brown, 1938 and 1942; Slataper, 1950; Goss and Winkler, 1983). Accordingly myopic subjects were divided into *late-onset myopes* (LOMs) i.e. myopia onset at 15 years of age or later and *early-onset myopes* (EOMs) i.e. myopia onset prior to 15 years of age.

The aim of this study was to determine whether differences in accommodation -vergence synkinesis occur between the two myopic groups. In addition a third group of emmetropic subjects was included as a control. If the aetiology of environmentally-induced myopia is related to an alteration in accommodation-vergence interaction, then this may be reflected as a change in the response AC/A ratio*.

6.2 METHOD

Response AC/A, vergence changes and accommodation response were measured for three accommodation stimulus levels, 3.0, 3.9 and 4.6D respectively, the latter two being achieved by means of negative spherical lenses. The lenses were mounted in a wheel which was placed behind the semi-silvered mirror of the optometer. The accommodation stimulus was varied by rotating the wheel so that the subject binocularly viewed the~~ir~~ respective targets through the appropriate lens. The experimental apparatus is illustrated in Fig. 6.1. Values of accommodation stimulus were calculated with reference to the anterior corneal surface. Following the introduction of an accommodative stimulus, subjects were required to perform a counting task which consisted of the addition of a line of four two digit numbers (black on white, contrast≈90%), placed at 33 cms from the eye. The size of the numbers was approximately equivalent to N6. Normal room lighting was maintained during the task to provide a target luminance of approximately 30 cd m^{-2}.

Following completion of the counting task the near heterophoria was measured for a given accommodation stimulus level using a Maddox rod. The rod was placed before the right eye and the subject viewed a small spotlight located just above the numbers used for the counting task. Changes in vergence were measured using a tangent scale placed above the spotlight. This allowed subjective assessment of heterophoria to ±0.5 prism dioptres.

Accommodation response was measured from the left eye using a modified Canon

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* This study has been published in Ophthalmic & Physiological Optics 1987 ; 7: 225-233. (see Appendix B) and was presented at the meeting of the American Academy of Optometry, Toronto, Canada. December, 1986.

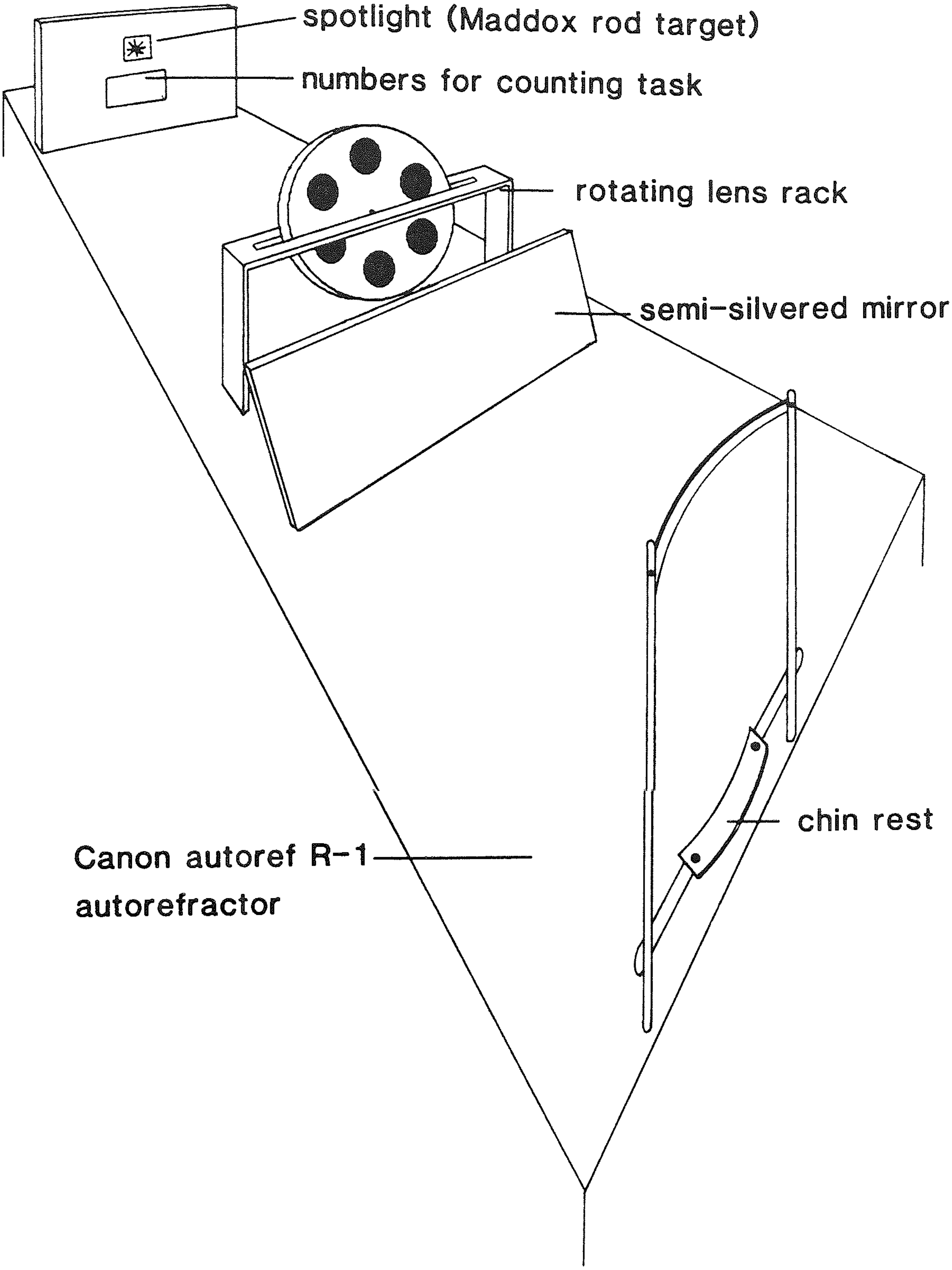

Fig. 6.1 Illustration of the experimental apparatus

Autoref R-1 objective infra-red optometer. This instrument is capable of measuring the refractive state at approximately one second intervals and allows unrestricted viewing of the target through a semi-silvered mirror. Further discussion of this optometer appeared in Section 2.6A. The mean of three readings was taken for each value of accommodation response.

The time-course of the experiment is illustrated in Fig. 6.2. Following the introduction of an accommodative stimulus the counting task was performed. After the subject had completed the arithmetic task, accommodation and heterophoria were measured. The three accommodation stimuli were presented in random order and each individual cycle of the experiment took approximately 20 seconds, therefore the subject completed the near-vision task at all three accommodation stimulus levels in approximately one minute. These experimental observations were recorded continuously for a period of 14 minutes.

Prior to commencement of the counting task, dark focus (DF) was measured for the left eye using the method described by Gilmartin and Bullimore (1987). The subject sat in total darkness for ten minutes and following this period ten readings of the refractive error were taken each minute for a period of five minutes. This gave a total of fifty readings which were then averaged. Immediately following completion of the experiment, the room lights were extinguished and post-task DF was measured at one minute intervals (ten readings each minute) for five minutes.

A total of 51 subjects were used, all of whom were students in the Department of Vision Sciences, Aston University. These consisted of 17 emmetropes, 17 late-onset myopes (LOMs) and 17 early-onset myopes (EOMs). The emmetropic subjects all had an unaided distance visual acuity of at least 6/6 with either eye and a mean sphere refractive error not greater than ±0.50D (and astigmatism not exceeding 0.50D). No subject had any major oculomotor imbalance (i.e. heterotropia, uncompensated heterophoria),

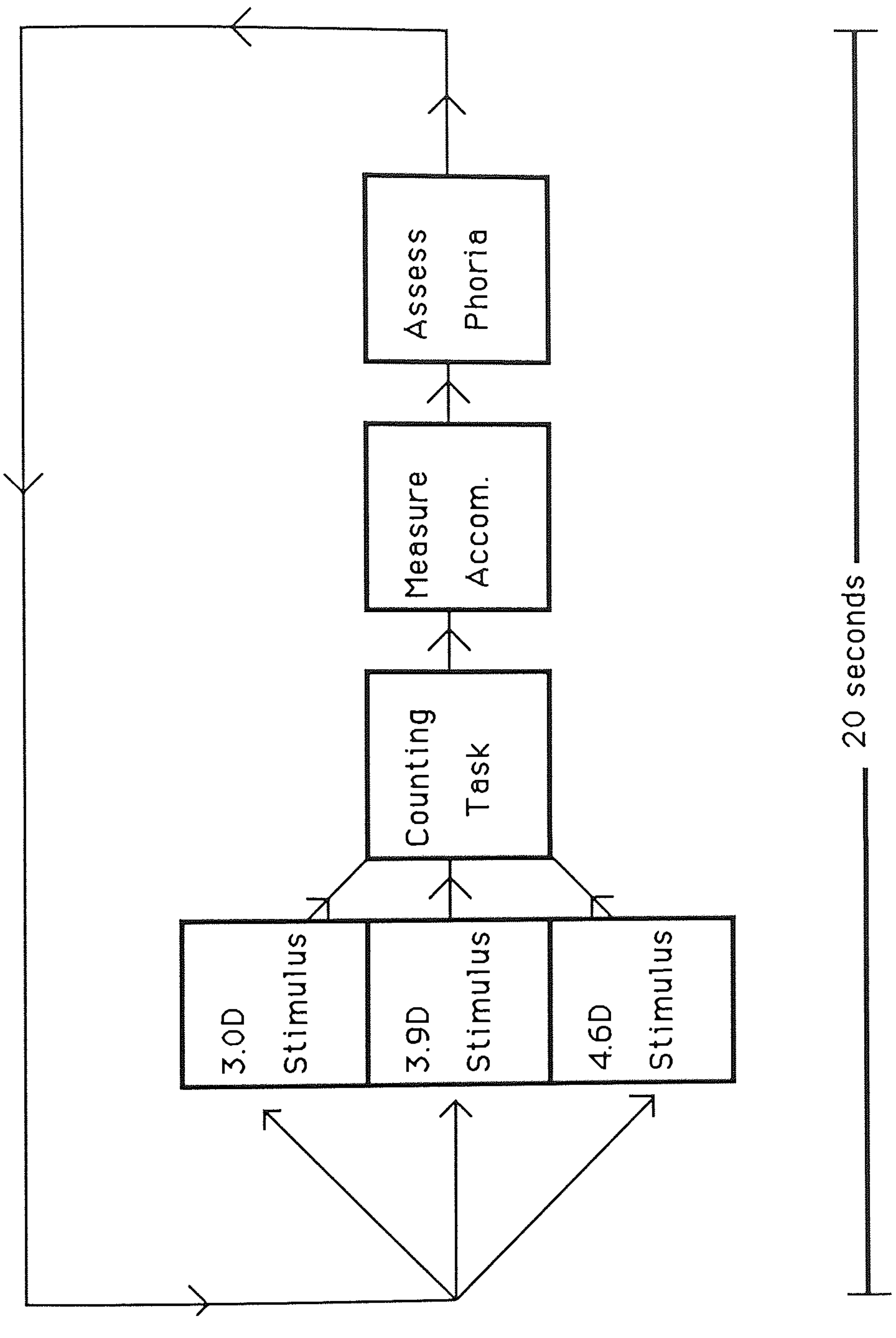

Fig. 6.2 Example of the experimental cycle.

asthenopic symptoms or ocular pathology. Details of the mean age, refractive error and age of myopia onset for each refractive group are shown in Table 6.1.

Myopic subjects were corrected with ultra-thin soft contact lenses (Hydron 06), in order to facilitate operation of the infra-red optometer, and an adaptation period of at least 20 minutes was allowed before commencing the experiment. All myopes could attain a visual acuity of at least 6/6 when corrected by the contact lenses.

In order to determine whether the presence of the contact lenses would induce a change in either heterophoria or accommodative response, and thereby alter the response AC/A ratio, a preliminary study was performed on 5 emmetropic subjects who were fitted with plano soft contact lenses (Hydron 06). Subjects were required to perform the near-vision counting task at an accommodation stimulus level of 3.9D. The task was performed continuously for a 15min period. Heterophoria and accommodative response were assessed at 1min intervals during this period. The results of this preliminary study are illustrated in Figs. 6.3 and 6.4. It is clearly indicated that the presence of the soft contact lenses did not produce any significant changes in accommodation or vergence in emmetropic subjects. However in myopic subjects, there will be a difference in both accommodation and vergence stimuli when corrected by contact lenses in comparison with a spectacle correction. This is discussed further in Section 6.4.

Additionally all subjects were asked to complete a questionnaire giving details of their refractive history and any family history of myopia.

6.3 RESULTS

Data received from the questionnaire issued to all subjects is shown in Table 6.1. It is of interest to note that there was a higher incidence of myopia amongst the siblings of LOMs than in the siblings of EOMs.

Table 6.1 Details of subjects used and data received from questionnaire issued to myopic subjects

	LOMs	EOMs	Emmetropes
Number of subjects	17	17	17
Mean age (years)	21.8 (sd = 3.96)	21.7 (sd=3.96)	20.7 (sd = 1.50)
Mean refractive error (D)	-2.18 (sd = 1.04)	-3.59 (sd = 1.64)	+0.08 (sd = 0.28)
Age of myopia onset (years)	15.7 (sd = 1.10)	10.2 (sd = 2.57)	—
Correction worn:			
i) constantly	65%	94%	
ii)occasionally	35%	6%	
History of myopia in:			
i) one or both parents	29%	50%	41%
ii)one or more siblings	53%	31%	17%

Siblings of LOMs; 12 subjects : 5 LOMs (mean age of myopia onset 16.2 years, sd = 0.84, range 15-17 years); 7 EOMs (mean age of myopia onset 9.14 years, sd = 4.00, range 1.5-13 years).

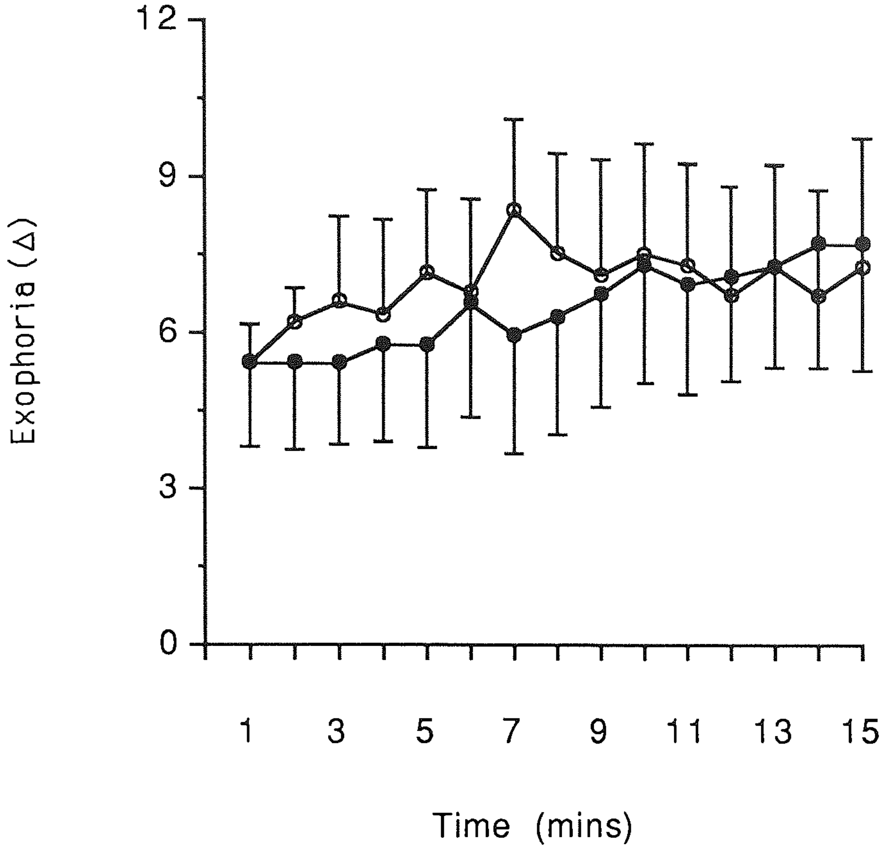

Fig. 6.3. Mean values of heterophoria measured for 3.9D accommodative stimulus in 5 emmetropic subjects. Closed circles indicate measures of heterophoria when fitted with plano soft contact lenses. Open circles indicate values of heterophoria without contact lenses. Error bars indicate ±1 sd.

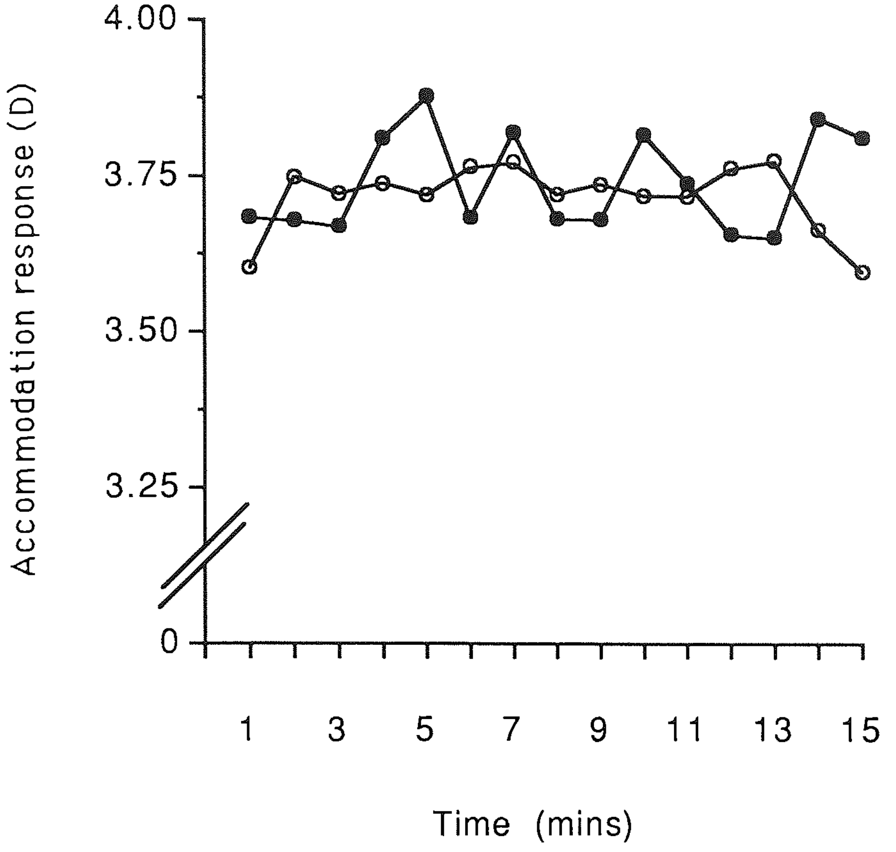

Fig. 6.4. Mean values of accommodative response measured for 3.9D accommodative stimulus in 5 emmetropic subjects. Closed circles indicate measures of accommodation when fitted with plano soft contact lenses. Open circles indicate values of accommodation without contact lenses. Error bars have been omitted for clarity but standard deviations were of the order of ±0.22.

Mean values of response AC/A were calculated for each two minute period of the near-vision task for the 3.0-3.9D accommodation stimulus range and these are illustrated in Fig. 6.5. EOMs show a higher response AC/A than the other two refractive groups. The mean values of AC/A for the 3.0-3.9D and 3.0-4.6D accommodation stimulus ranges are shown in Table 6.2. It can be seen that both stimulus ranges show very similar trends and hereafter only data relating to the 3.0-3.9D stimulus range will be referred to for brevity. The values of AC and accommodative response for the 3.0-3.9D accommodation stimulus range, together with a summary of the data for the 3.0-4.6 and 3.9-4.6D accommodation stimulus ranges are shown in Appendix I.

These observed values of AC/A are somewhat higher than those reported in previous

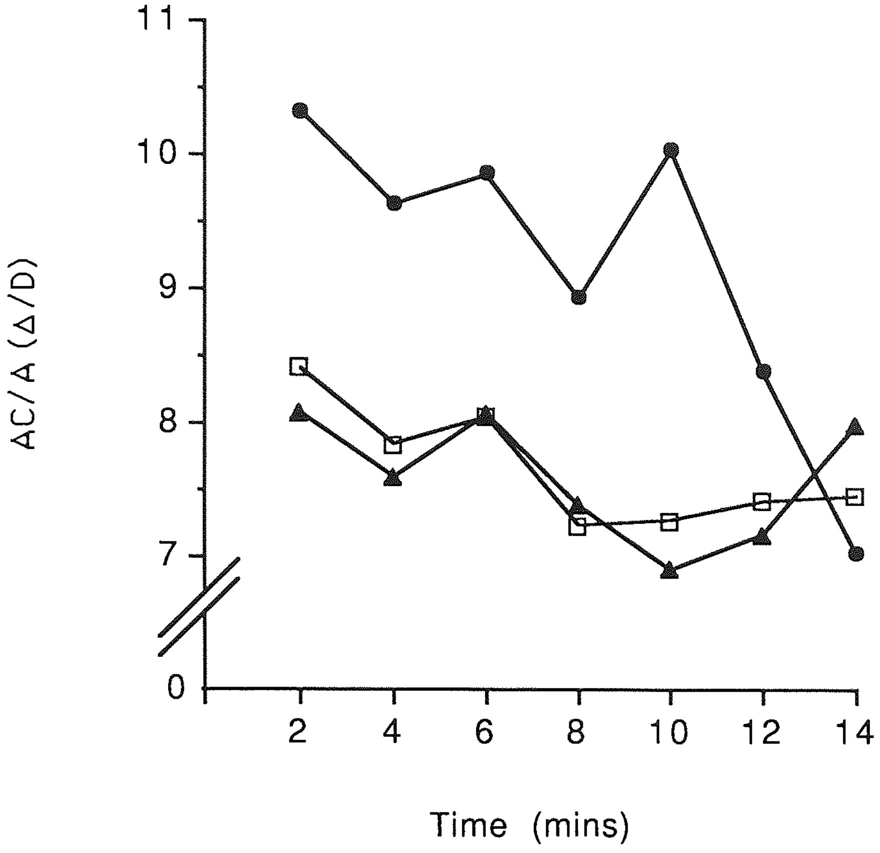

Fig. 6.5. Response AC/A ratio for three refractive groups. Circles = EOMs (N = 17); Triangles = LOMs (N =17) ; Open squares = emmetropes (N = 17). Ratio measured for the 3.0-3.9D accommodation stimulus range. Error bars have been omitted for clarity but SEMs were of the order of ±1.64.

Table 6.2 Mean value of response AC/A (Δ/D) over the course of a 14 minute counting task for the two accommodation stimulus ranges (figures in parentheses represent ± 1 sd).

Accommodation stimulus range	**3.0-3.9D**	**3.0-4.6D**
Early-onset myopes	9.55 (0.73)	10.14 (0.33)
Late-onset myopes	7.61 (0.47)	8.67 (0.37)
Emmetropes	7.69 (0.41)	8.91 (0.31)

studies (e.g. Breinin and Chin, 1973) although Manas (1955) reported a higher AC/A ratio in myopes and Flom and Takahashi (1962) found a mean stimulus AC/A ratio of 6.29Δ/D for 28 undercorrected (mean degree of undercorrection =0.91D) myopes. However it is the relative values between the refractive groups which are of interest in the present study rather than the absolute values of AC/A.

It will be noted from Table 6.1 that the mean refractive error of the EOM group was higher than for LOMs (-3.59D compared with -2.18D). In order to compare the two refractive groups more accurately and to ensure that any observed variations were not caused by differences in the degree of myopia, 10 subjects were selected from each myopic group in order to equate the mean refractive error (LOM subgroup, mean refractive error -2.49D, sd =1.00; EOM subgroup , mean -2.47D, sd =0.65). For these two subgroups, the deviation of each individual refractive error from the mean was computed. A t-test indicated that the distribution of the deviations from the mean for the two subgroups was not significantly different ($t = 0.02$; df = 18; $p = 0.98$). A comparison of these two subgroups can be made with reference to the data illustrated in Figs. 6.6 and 6.7. The values of AC for emmetropic subjects are included in Fig. 6.8 which shows that they are similar to the LOM data. Two factor analysis of variance (time, refractive group) indicated that the difference in AC between LOMs and EOMs was significant (F=15.39; df=1,15 ; $p<0.01$) whereas the difference in accommodative response was not significant. The time factor was not significant in any of the analyses. The difference in AC between LOMs and emmetropes was not significant.

It can be seen in Table 6.1 that 35% of LOMs reported occasional wear of their refractive correction. It is likely that these subjects will normally perform near-vision tasks unaided and may develop a "habitual" AC/A ratio which is higher than their "corrected" AC/A due to the reduced accommodation response when uncorrected. This lower corrected AC/A may then account for the differences between LOMs and EOMs shown in Fig. 6.6. To examine this hypothesis 14 subjects were selected (7 LOMs and 7 EOMs) who all

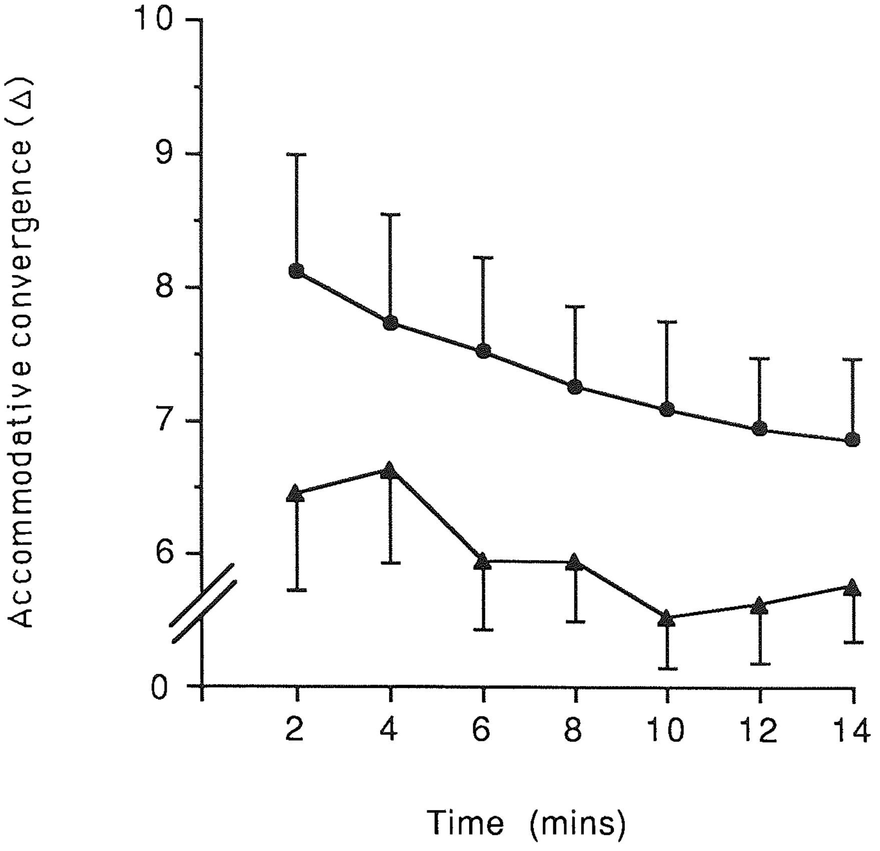

Fig. 6.6. Accommodative convergence (AC) measured for 10 EOMs (circles) and 10 LOMs (triangles) for the 3.0-3.9D accommodation stimulus range. The subjects were selected so that the two subgroups had similar refractive errors (EOMs : mean Rx = -2.47D, sd = 0.65; LOMs : mean Rx = -2.49D, sd =1.00). Error bars indicate ±1 SEM. Thus differences in AC between LOMs and EOMs cannot be accounted for by variations in refractive error.

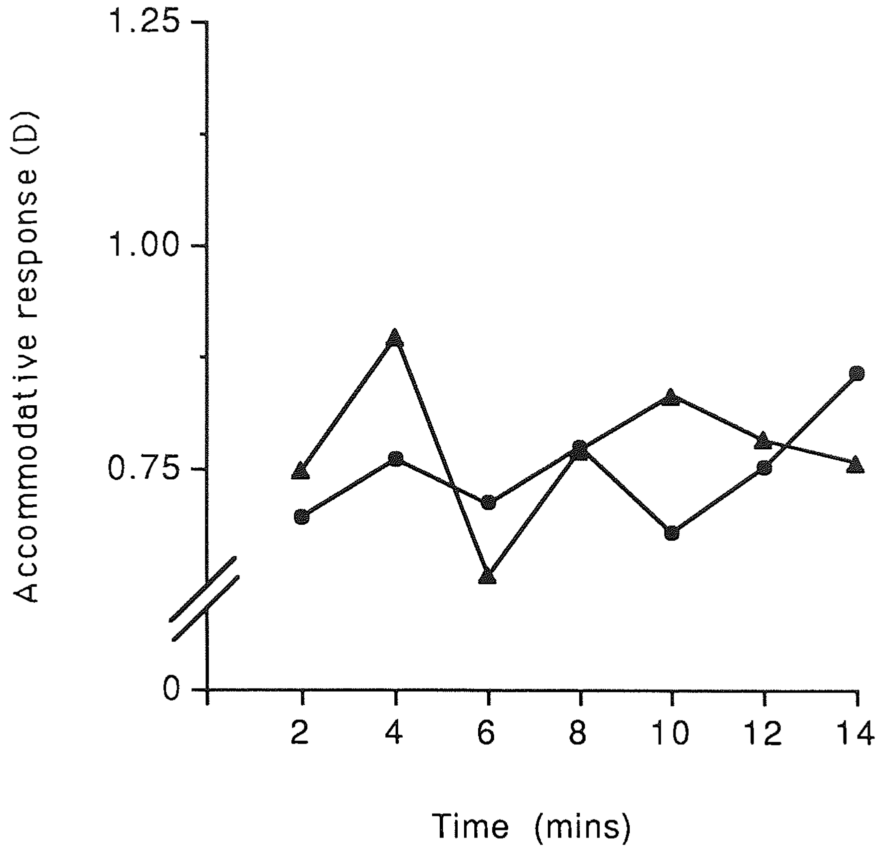

Fig. 6.7. Accommodative response (AR) measured for 10 EOMs (circles) and 10 LOMs (triangles) for the 3.0-3.9D accommodation stimulus range. The subjects were selected so that the two subgroups had similar refractive errors (EOMs : mean Rx = -2.47D, sd = 0.65; LOMs : mean Rx = -2.49D, sd =1.00). Error bars have been omitted for clarity but SEMs were of the order of ±0.07

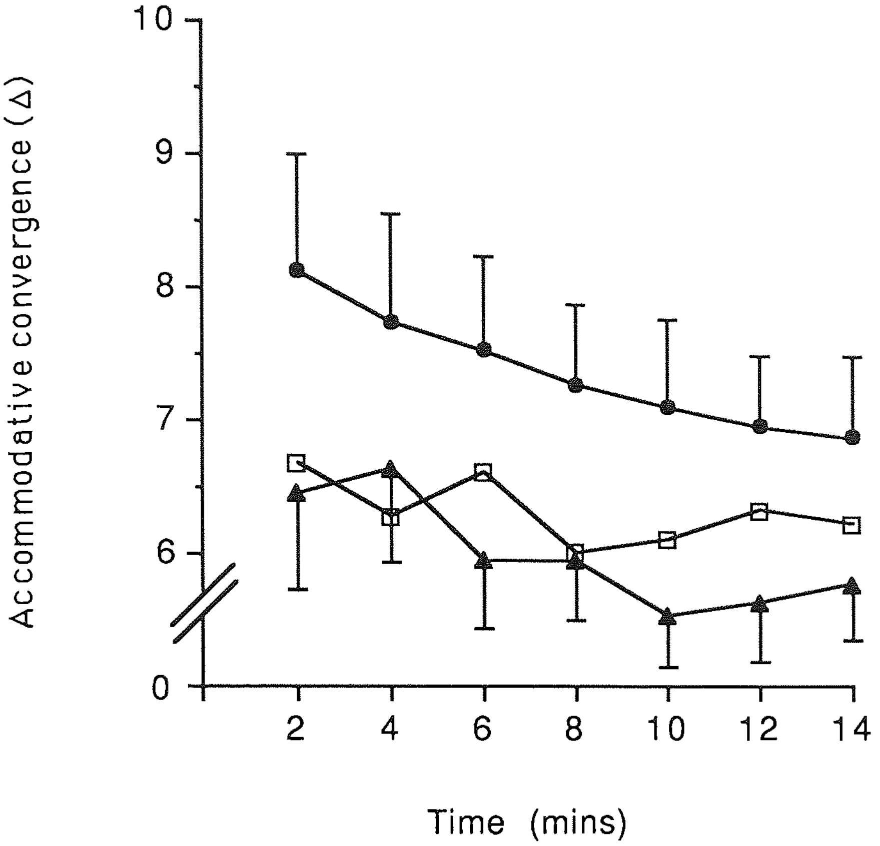

Fig. 6.8. Mean AC data (3.0-3.9D accommodation stimulus range) for 17 emmetropic subjects (open squares) superimposed upon data from 10 LOMs (triangles) and 10 EOMs (circles) from Fig. 6.6. Error bars indicate ±1 SEM.

reported constant wear of their refractive correction. The two subgroups had similar mean refractive errors. Again the distribution of these subgroups about their mean was computed and a t-test indicated that the distributions of refractive error for the two subgroups were not significantly different (t = 0; df =12; p = 1). The difference in AC between the LOM and EOM subgroups is shown in Fig. 6.9 and is statistically significant (F=9.71; df=1,12; p<0.01). Thus the differences in AC between LOMs and EOMs (see Fig. 6.6) were not significantly affected by differences between habitual AC/A and corrected AC/A.

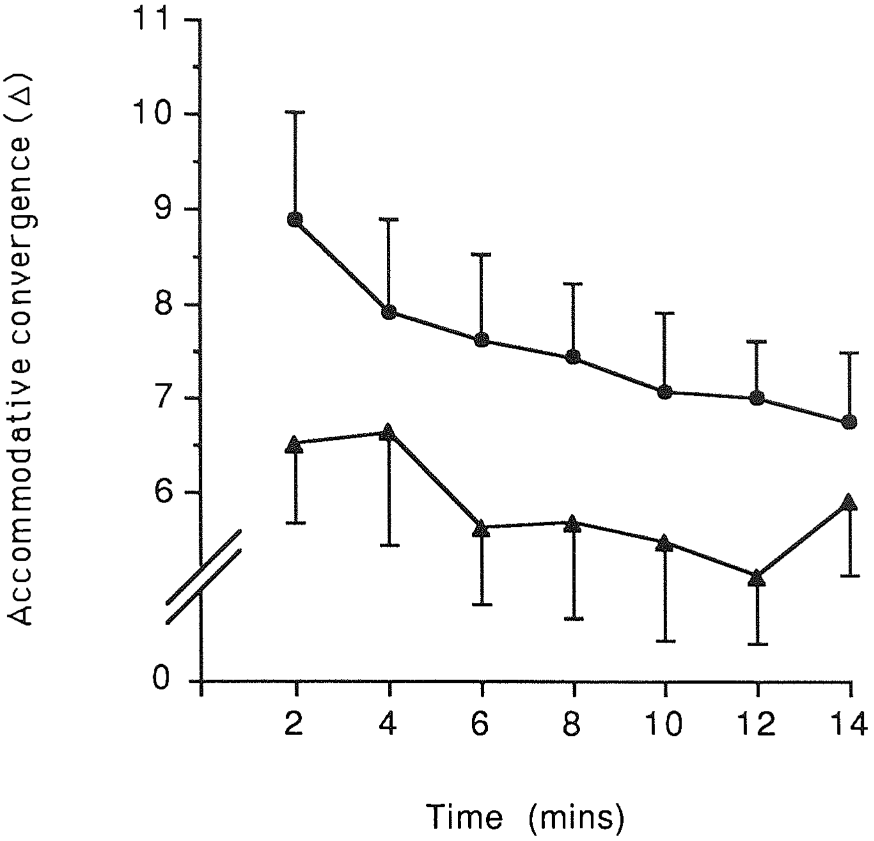

Fig. 6.9. Accommodative convergence (3.0-3.9D accommodation stimulus range) for 7 EOMs (circles) and 7 LOMs (triangles) all of whom reported constant wear of their refractive correction, the two groups having similar refractive error (EOMs : mean Rx = -2.71D, sd = 0.42; LOMs : mean Rx = -2.66, sd = 1.05). Error bars indicate ±1 SEM. Thus the difference in AC between LOMs and EOMs (Fig. 6.6) is not significantly affected by differences between the subjects habitual AC/A and the value of AC/A obtained when corrected for refractive error.

The pre-task levels of DF for the three refractive groups are shown in Fig. 6.10. One-factor analysis of variance indicated that the difference between the three refractive groups was significant (F = 4.02; df = 2, 50; p = 0.02). The mean values for emmetropes and LOMs were significantly different (t=2.81, df=48, p<0.05) but the differences between EOMs and LOMs or between EOMs and emmetropes were not significant. The task-induced shifts in DF for the three refractive groups are shown in Table 6.3. There was no significant difference in the task-induced changes in DF between the three refractive groups.

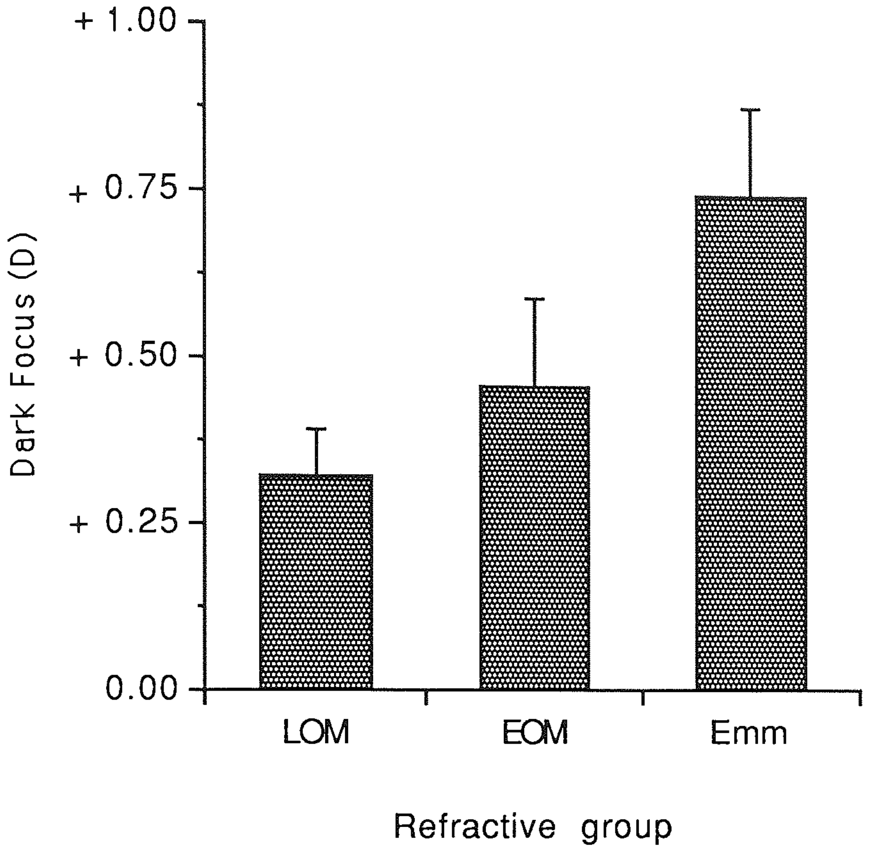

Fig. 6.10. Pre- task values of dark-focus (DF) for the three refractive groups (each comprising N = 17). No correction factor has been added to the optometer reading. Error bars indicate 1 SEM.

Table 6.3 Post-task shift in dark-focus (DF), in dioptres, measured with respect to the pre-task level at 1 min intervals immediately following completion of the near-vision task. Values in brackets represent ±1sd.

Minutes post-task	**LOMs (N=17)**	**EOMs (n=17)**	**Emm (N=17)**
1	+0.15 (0.45)	+0.19 (0.51)	+0.07 (0.60)
2	+0.03 (0.35)	+0.07 (0.38)	+0.28 (0.71)
3	+0.19 (0.44)	+0.06 (0.38)	+0.40 (0.82)
4	+0.09 (0.46)	+0.07 (0.31)	+0.29 (0.71)
5	+0.09 (0.32)	0 (0.33)	+0.25 (0.60)

6.4 DISCUSSION

It has been suggested that the aetiology of late-onset myopia is more likely to relate to environmental factors when compared with early-onset myopia (Goldschmidt, 1968). The data relating to family history of myopia (Table 6.1) shows no significant trends although the high incidence of myopia amongst siblings of LOMs is of interest. Bear and Richler (1981) and Sorsby et al. (1963) have reported that there is often a higher resemblance in ocular refraction between siblings than between parents and offspring. It remains unclear whether this similarity in refractive error amongst siblings relates to shared environmental experiences (Young et al., 1969), genetic factors (Hegmann et al., 1974) or a combination of the two (Alsbirk, 1979).

It was noted that the correction of myopia with contact lenses will alter both the accommodation and vergence stimulus when compared with a spectacle correction. However in this study comparison was made between two myopic groups exhibiting equal degrees of refractive error and each being corrected in the same manner. Therefore any observed differences in AC/A cannot be accounted for by changes in the effective accommodation or vergence stimulus.

Post-task changes in DF one minute following completion of the near-vision task (Table 6.3) are in accordance with the work of Gilmartin and Bullimore (1987). They demonstrated that subjects with a pre-task DF level greater than +0.55D showed a more rapid regression of post-task DF to the pre-task level when compared with those subjects having a pre-task DF less than +0.55D. It would therefore be predicted from Fig. 6.10 that emmetropic subjects (mean pre-task DF =+0.75D) would show a faster post-task regression during the first minute following completion of the task, when compared with the two myopic groups (EOMs, mean pre-task DF = +0.46D; LOMs, mean pre-task DF =+0.32D). This prediction is verified by the data tabulated in Table 6.3.

Gilmartin and Bullimore (1987) also showed that those subjects having pre-task DF levels greater than +0.55D were vulnerable to beta-adrenoceptor antagonism during the 50 seconds following the near-vision task. They deduced that inhibitory sympathetic innervation to the ciliary muscle was occurring during the task in these subjects and it has been proposed that this inhibitory facility may be involved in adaptational mechanisms of DF to sustained near-vision. It may be that LOMs, having a lower pre-task DF than the other two refractive groups, have a reduced adrenergic inhibitory facility to the ciliary muscle during sustained near-vision, and that this reduced facility may be a contributing factor in the aetiology of their late-onset myopia.

In order to examine sympathetic innervation to the ciliary muscle during the course of a near-vision task, the effect of timolol maleate (0.5%), a non-selective beta-adrenergic antagonist, on AC was investigated. The experiment was performed on a population consisting of emmetropes, LOMs and EOMs. The findings of this study are reported in Chapter 7.

The Hung-Semmlow model of accommodation-vergence interaction is shown in Fig. 6.11 (see also Section 4.9). It has been demonstrated that the accommodative response (AR) in LOMs and EOMs does not differ significantly (see Fig. 6.7). Thus the difference in AC must be due to differences in the dead-space* of accommodation (which relates to the lag of accommodation) or to the accommodative controller gain† (ACG). In this model the ACG describes the relationship between the effective accommodative stimulus (after consideration of the dead-space) and the output to the accommodation and accommodative convergence effector plant.

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* dead-space: That portion of the operating range of a control element over which there is no change in output for a given input.

† gain : The ratio of output magnitude to input magnitude

(both definitions from Hung and Ciuffreda, 1983)

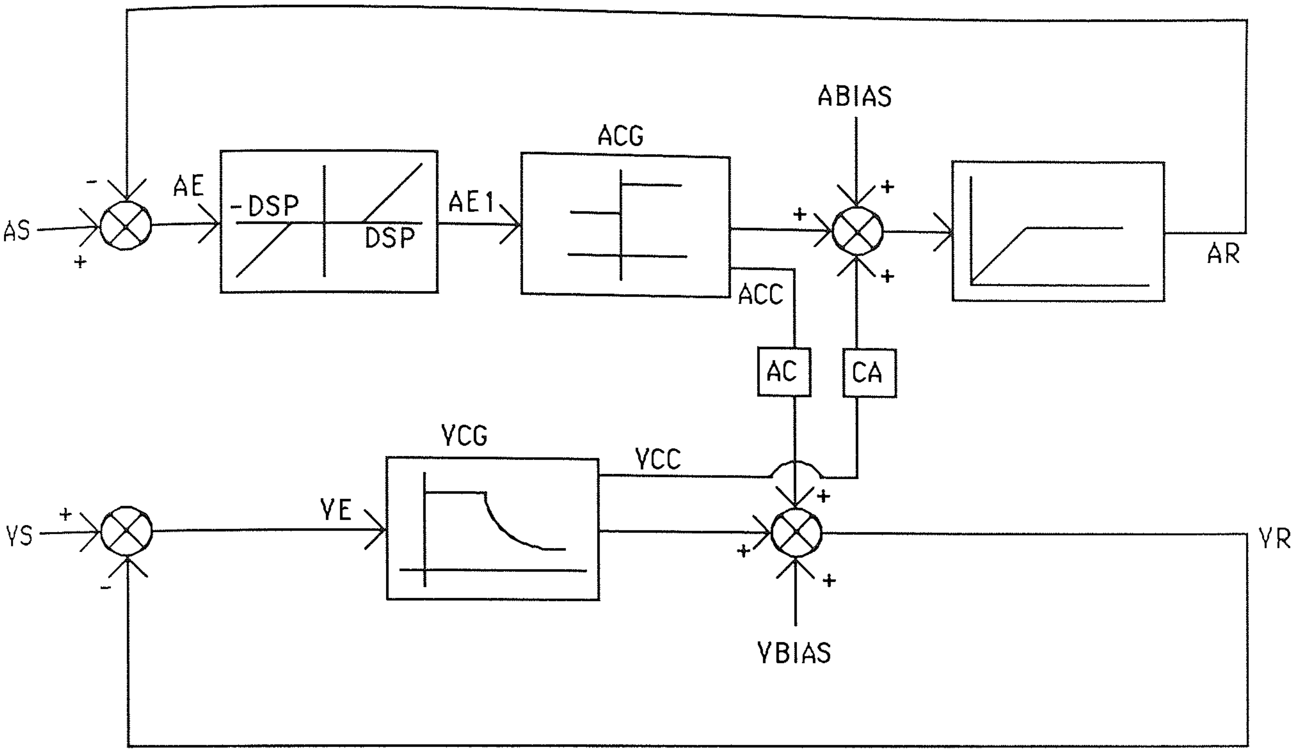

Fig. 6.11 Hung-Semmlow (1980) model of accommodation-vergence interaction.

Key:

AS: accommodation stimulus
AE: accommodative error
AR: accommodation response
DSP: dead space of accommodation
AE1: accommodation error after consideration of dead space
ACG: accommodative controller gain
ABIAS: tonic accommodation
ACC: stimulus for accommodative convergence
AC: accommodative convergence
CA: convergent accommodation
VBIAS: tonic vergence
VCG: vergence controller gain
VCC: stimulus for convergent accommodation
VS: vergence stimulus
VE: vergence error
VR: vergence response

The schematic figures are explained in Fig. 4.10b.

McBrien and Millodot (1986a) examined the accommodation stimulus-response curve in a population consisting of 10 hypermetropes, 10 emmetropes, 10 EOMs and 10 LOMs. They observed no significant difference in accommodative response gradient between the two myopic groups. As this relationship will reflect the dead-space of accommodation (DSP), it would appear that the variation in AC between LOMs and EOMs is produced by differences in the ACG. Thus EOMs would have a higher gain factor with respect to LOMs. Since the lower ACG in LOMs does not result in a reduced accommodation response (AR) (Fig. 6.7) the balance of accommodation must be made up from another source, presumably convergent accommodation (CA). The question arises therefore whether the differences in ACG are directly induced by a change in accommodation, or indirectly via increased convergence. Increased convergence will produce a rise in CA with an associated reduced requirement for blur-induced accommodation. McBrien and Millodot (1986b) showed that LOMs have a significantly higher amplitude of accommodation than EOMs. This would suggest that there are primary differences in the accommodation systems of LOMs and EOMs. However it is unclear whether these differences in amplitude of accommodation are simply due to the lower degree of refractive error found in LOMs or whether they relate to differences between the myopic subgroups. Late-onset myopia may itself be a means of reducing accommodative load (see Chapter 8) and Birnbaum (1985a) stated that myopia should not be viewed as a primary problem but as an adaptive change that occurs secondary to nearpoint stress.

Whilst differences in AC between LOMs and EOMs have been demonstrated, it should be noted that the values of AC obtained for LOMs were similar to those shown for emmetropes (see Fig. 6.8). Thus it is only the EOM group which shows variations in AC. These findings would imply that the onset of late-onset myopia does not result from a change in AC, nor does it produce any alteration in the response AC/A ratio. However the observed differences between LOMs and EOMs would confirm the presence of two distinct subgroups within the myopic population. The fact that attempts to slow the progression of myopia (e.g. bifocals, cycloplegic drugs and prisms) have had mixed success may relate to this lack of homogenity within the myopic population (see Goss, 1982 for a review).

6.5 CONCLUSIONS

Differences in response AC/A ratio have been demonstrated between LOMs and EOMs, the higher AC/A in EOMs resulting from increased AC while no significant difference in accommodative response was observed. It has been suggested that the variations between the two myopic groups may relate to differences in the sympathetic innervation to the ciliary muscle. Therefore in Chapter 7, two studies will be reported which attempt to examine adrenergic innervation to the ciliary muscle during the course of a sustained near-vision task, firstly in a group of emmetropes and then in a population consisting of emmetropes, LOMs and EOMs.

CHAPTER 7

THE RELATIONSHIP BETWEEN SYMPATHETIC INNERVATION TO THE CILIARY MUSCLE AND THE ACCOMMODATIVE CONVERGENCE/ACCOMMODATION (AC/A) RATIO

7.1 INTRODUCTION

The proposal that the ciliary muscle receives a dual autonomic innervational supply i.e. from both parasympathetic and sympathetic nervous systems was discussed in Section 2.4. However Gilmartin and Bullimore (1987) observed that investigating the nature of autonomic control while a task is in progress presents considerable methodological difficulty. They attempted to monitor sympathetic innervation to the ciliary muscle by examining the effect of a non-selective beta-adrenergic receptor antagonist (timolol maleate, 0.5%) on the shift in dark-focus (DF) immediately following a sustained near-vision task (see section 2.5Aiii). Subjects with pre-task values of DF greater than +0.75D were shown to be vulnerable to beta-adrenoceptor antagonism during the 50s immediately following the near-vision task. It was deduced that inhibitory sympathetic innervation to the ciliary muscle was occurring during the task in these subjects. In an earlier paper Gilmartin and Hogan (1985) proposed that a possible role for adrenergic innervation to the ciliary muscle may be to attenuate the accommodative hysteresis (see Section 2.5A iii) which follows periods of sustained near-vision.

Details are presented in this chapter of two studies which attempt to assess sympathetic activity during the course of a near-vision task rather than following its completion. The first study will give an account of the proposal that the role of adrenergic innervation to the ciliary muscle may be monitored via the accommodative convergence /accommodation (AC/A) ratio*.

Stephens (1985) examined the effect of alpha and beta adrenergic agonists on the response AC/A ratio and showed that hydroxyamphetamine hydrobromide (1%), a predominantly indirect acting alpha and beta agonist, produced a significant increase in AC/A whereas phenylephrine hydrochloride (10%), a direct acting alpha adrenergic agonist with very little beta-receptor activity, produced a small but insignificant rise in AC/A. He concluded that the inhibitory effects associated with beta-adrenergic agonism were responsible for this increase in AC/A. It should be noted that Stephens did not employ a near-vision task when measuring the response AC/A ratio but assessed AC/A using a phoro-accommodometer based on the design of Allen (1960) following the instillation of the adrenergic agonists. The efficacy of the alpha-agonist effects of phenylephrine and hydroxyamphetamine on the ciliary body vasculature does however vary due to their different pharmacological modes of action. Direct subtraction of respective AC/A ratios may not therefore reflect solely beta-receptor responses.

In this study the role of beta-adrenergic innervation to the ciliary muscle is investigated directly by the use of a non-selective beta-adrenergic antagonist timolol maleate (0.5%). The effect of timolol on the response AC/A ratio was examined during the course of a sustained near-vision task.

7.2 METHOD

Response AC/A, vergence changes and accommodation response were measured for three accommodation stimulus levels, 3.0D, 3.9D and 4.6D respectively. As timolol maleate is widely used as an ocular hypotensive, intra-ocular pressure was measured at

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* This study has been published in Ophthalmic & Physiological Optics 1987; 7,127-130 (see Appendix A) and was presented at the Local Optical Organisation Conference, London, May 1986.

the beginning and end of each session using a "Digilab" pneuma-tonometer following instillation of one drop of the topical anaesthetic Benoxinate 0.4%.

Seventeen emmetropic subjects (8 male, 9 female) were used, all of whom were staff or students in the Department of Vision Sciences, Aston University. The mean age of the group was 20.7 years (sd = 1.50). All subjects had unaided distance visual acuity of at least 6/6 with either eye and a mean sphere refractive error not greater than ±0.50D (with astigmatism not exceeding 0.50D). No subject had any major oculomotor imbalance (heterotropia, uncompensated heterophoria), asthenopic symptoms or ocular pathology. Each subject signed a consent form prior to taking part in this study and following a full explanation of all experimental procedures.

A double blind protocol was adopted between timolol maleate (0.5%)† and a saline control. Instillations of timolol or saline were made using a precision micropipette delivering 25µl of drug. Each subject was given two instillations separated by a period of five minutes i.e. 50µl. of drug per eye. The saline and timolol trials were separated by at least one week.

Subjects were required to perform the counting task described in Section 6.2, at a viewing distance of 33cms. This task was undertaken continuously for a period of sixteen minutes. Measures of response AC/A were taken during the course of the task using the method previously described (see Section 6.2). Thus vergence changes were assessed by means of a Maddox rod placed before the right eye while the accommodative response of the left eye was measured objectively using the Canon Autoref R-1 infra-red optometer.

Before and after the counting task dark-focus (DF) was measured using the method

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† Timolol maleate 0.5% : Merck,Sharp & Dohme 5ml.dropper bottle
Saline : Smith & Nephew single dose applicators ("Minims")of normal saline
Benoxinate 0.4% : Smith & Nephew single dose applicator ("Minims").

described by Gilmartin and Bullimore (1987). The subject sat in total darkness for ten minutes and following this period ten readings of the refractive error were taken each minute for a period of five minutes. This gave a total of fifty readings which were then averaged. Post-task DF was measured at one minute intervals (10 readings) for four minutes following completion of the near-vision task.

7.3 RESULTS

Values of response AC/A determined for the 3.0-3.9D accommodation stimulus range are shown in Fig. 7.1. The difference in AC/A between the timolol and saline trials is illustrated in Fig. 7.2. The 3.0-4.6D stimulus range showed similar changes and has been excluded for brevity. The values of AC/A, AC and accommodative response for the 3.0-3.9D accommodation stimulus range, together with a summary of the data for the 3.0-4.6D accommodation stimulus range may be found in Appendix 2.

The effect of timolol on the components of the AC/A ratio namely AC and accommodative response are shown in Figs. 7.3 and 7.4. It would appear that in the initial 4 minutes the effect of the beta-adrenergic antagonist is to produce a fall in AC/A via a change in AC, with minimal effect on the net accommodation response.

The pre- to post-task change in dark-focus (DF) was compared for the two trials and Fig. 7.5 shows the timolol-induced shift in DF . There is a relative myopic shift of 0.33D (sd=0.44) with respect to saline one minute following completion of the task. The mean value of pre-task DF was +0.80D (sd =0.69).

Timolol produced a significant reduction in IOP (-2.41mm Hg; sd=1.28) which did not correlate with the changes in AC or accommodative response. The mean change in IOP recorded in the saline trial was +0.17mm Hg (sd =1.13).

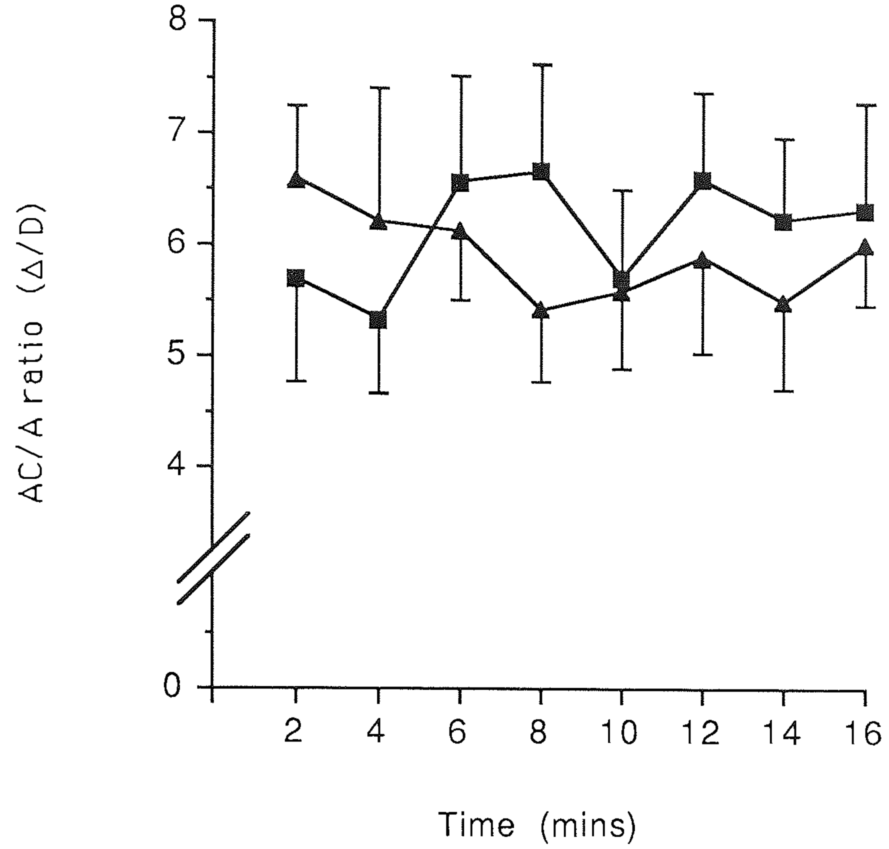

Fig. 7.1 Values of response AC/A ratio for the saline (triangles) and timolol (squares) trials measured for the 3.0-3.9D accommodation stimulus range over the course of the near-vision task. Error bars indicate ±1 SEM.

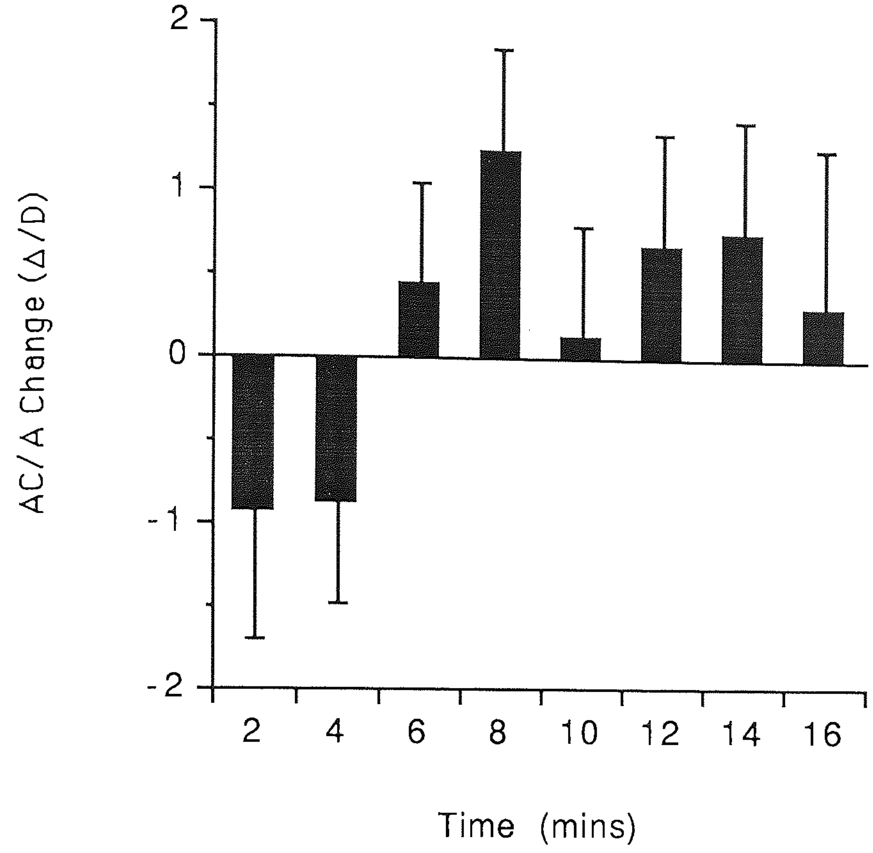

Fig. 7.2. Mean difference in response AC/A between timolol and saline trials over the course of the near-vision task. This illustrates the division of the experiment into two portions, the initial 4 mins and the remaining 12 mins. Error bars indicate ±1 SEM.

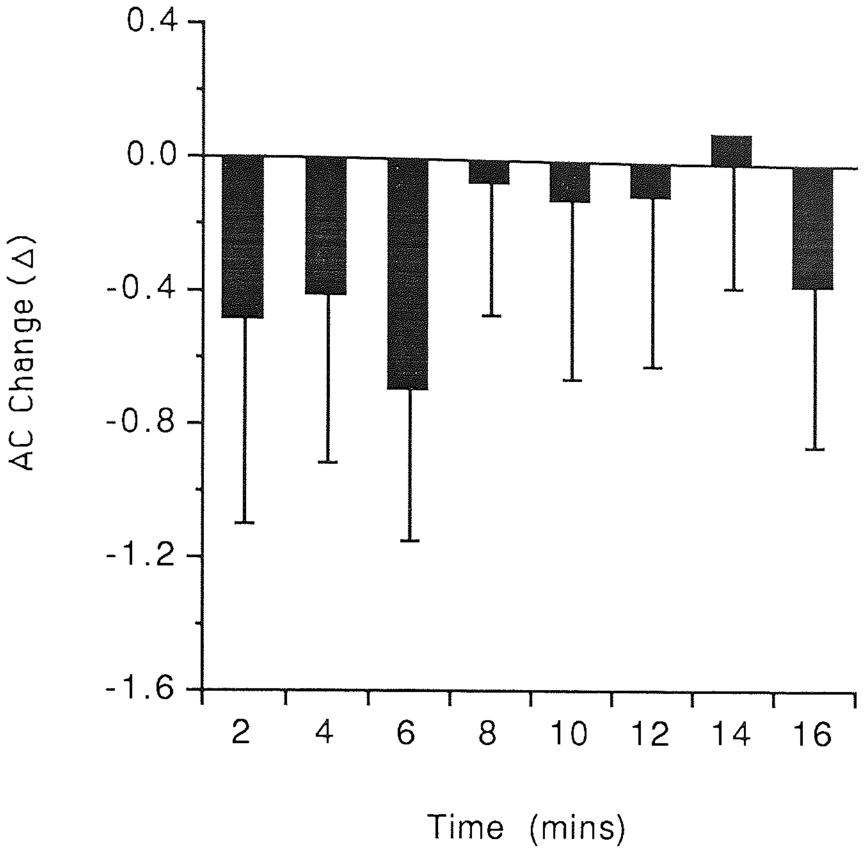

Fig. 7.3. Mean difference in accommodative convergence (AC) for 3.0-3.9D accommodation stimulus range between timolol and saline trials over the course of the task. Error bars represent 1 SEM.

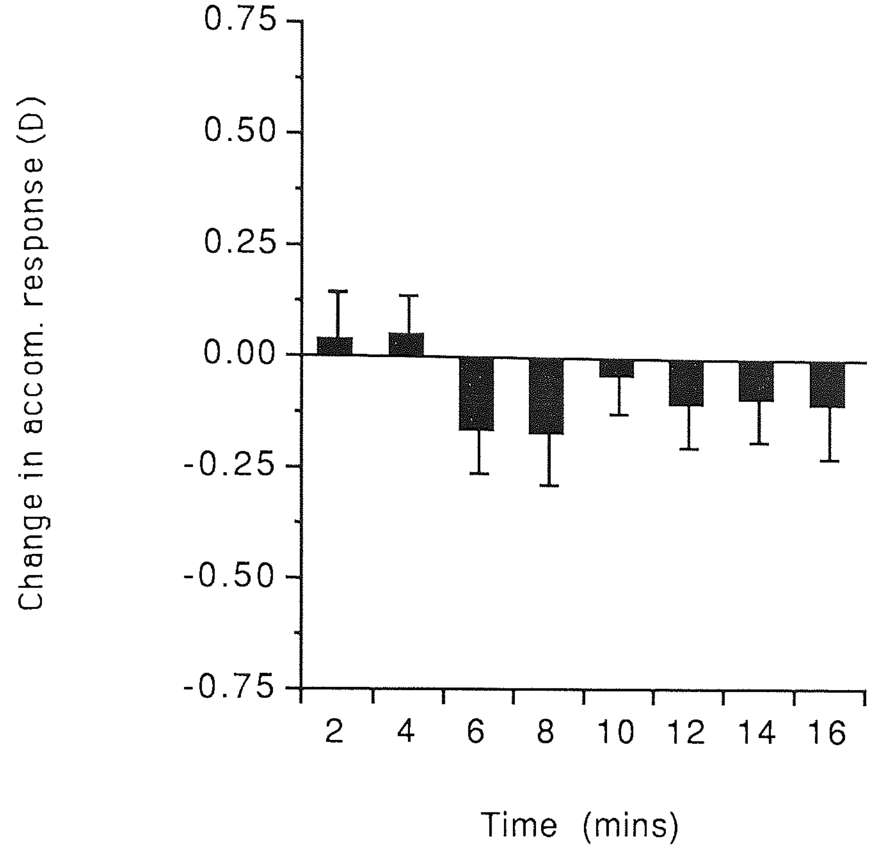

Fig. 7.4 Mean difference in accommodative response for 3.0-3.9D accommodation stimulus range between saline and timolol trials over the course of the task. The change in accommodative response was significant after the initial 4 min period. Error bars represent ±1 SEM.

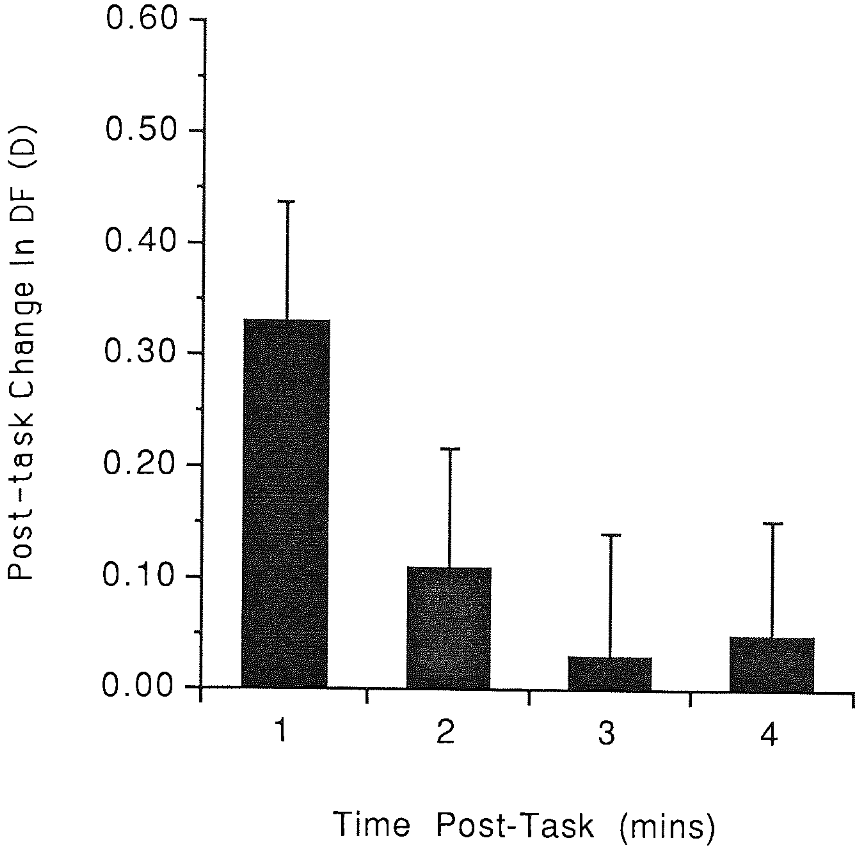

Fig. 7.5 Mean post-task dioptric shift in dark-focus (DF) for timolol with respect to post-task DF shift in saline trial at 1 min intervals following completion of the near-vision task. Error bars indicate 1 SEM.

Two-factor analysis of variance (drug, time) was carried out on the timolol-induced changes illustrated in Figs. 7.3 and 7.4. This indicated that the timolol effect on accommodative convergence was significant (F=3.65; df=1,30; p=0.05). Analysis of the accommodative response data indicated that the drug effect was significant (F=6.40; df=1,30; p<0.05). However it may be observed from Fig. 7.4 that the accommodation response differs in the initial four minute period from the remainder of the experiment. Partial analysis on this initial four minute period indicated that this change in accommodative response was not significant (F=0.09; df=1,15 p=0.76) whereas the changes after the first four minutes were significant (F=10.93; df=1,30; p<0.01).

7.4 DISCUSSION

The timolol-induced reduction in AC/A during the first four minutes of the task provides evidence for an active role of beta-adrenergic innervation to the ciliary muscle during this period. The change in AC/A is mediated via a reduction in accommodative convergence (AC) with a small but insignificant increase in accommodative response (Figs. 7.3 and 7.4) . The observed timolol-induced reduction in AC/A would support the observations of Stephens (1985) who showed that beta-agonism produced a significant rise in AC/A .

It is proposed that the timolol-induced fall in AC during the initial 4 minutes is a consequence of reduced sympathetic innervation to the ciliary muscle. The absence of an inhibitory component will produce a lower parasympathetic requirement in order to obtain the same net accommodation response. It would appear that the level of AC is related to parasympathetic outflow and is independent of sympathetic innervation as timolol produced a reduction in AC with no change in accommodation response. Thus reduced parasympathetic innervation is reflected as a fall in AC.

The direction and magnitude of the post-task changes in DF illustrated in Fig. 7.5 are consistent with the earlier report of Gilmartin and Bullimore (1987) and provides further evidence for sympathetic control during sustained near-vision.

It appears that after the initial 4 minutes, adaptation processes are occurring to attenuate the reduction in AC/A. This adaptation is mediated via a reduced accommodative response, thus producing the rise in AC/A seen after the initial period and this may serve to restore the previous synkinetic link between accommodation and vergence. The relative myopic shift in DF seen one minute following completion of the task indicated that sympathetic antagonism is active through the entire task period and hence this adaptation is not mediated via attenuation of sympathetic function. The exact mechanism behind this adaptation remains unclear as Fig. 7.3 indicated that there was a concurrent restoration of AC to the saline level. It is of interest to note that the time scale of the adaptation, i.e. around 4 minutes, is of a similar value to the adaptation to prism- and lens-induced heterophorias (Henson and North, 1980; North and Henson, 1985) and it may be that similar processes are occurring. Further discussion on the adaptation of accommodation and vergence during sustained near-vision appears in Chapters 8-10.

7.5.BETA-ADRENERGIC RECEPTOR ANTAGONISM IN MYOPIA

The previous investigation demonstrated that sympathetic innervation to the ciliary muscle may be monitored via accommodative convergence (AC). The aim of this second study was to compare the effects of blocking beta-adrenergic innervation to the ciliary muscle during the course of a near-vision task in a population consisting of myopic and emmetropic subjects. Previous studies have demonstrated that myopic subjects have a lower level of dark-focus (DF) when compared with emmetropes (McBrien and Millodot, 1987b; Bullimore and Gilmartin, 1987d; Rosenfield and Gilmartin, 1987a). In view of the observations of Gilmartin and Bullimore (1987) who noted that subjects with pre-task levels of DF greater than +0.75D were more vulnerable to beta-adrenoceptor antagonism when compared with those subjects having pre-task values of DF less than +0.75D, one might infer a lower level of sympathetic innervation to the ciliary muscle in myopes. A reduced adrenergic inhibitory facility to the ciliary muscle may result in increased demand on the near-response and alternative adaptational mechanisms may therefore be required in order to avoid near-point stress (Birnbaum, 1984 and 1985a).

Van Buskirk (1980) noted in an analysis of 547 adverse effects reported with topical timolol therapy that 52 of the reports indicated visual disturbance and 7 noted myopia of between 1.5 and 3D. The myopia reversed on discontinuation of the drug. Lutjen-Drecoll et al. (1986a, 1986b) in studies on cynomolgus monkeys reported that the monkeys treated with timolol (N=6) for around 6 months were significantly more myopic by approximately 2.0D compared with monkeys treated with epinephrine (N=2) or the control monkeys (N=6) who did not receive any drug treatment. They concluded that this increase in myopia could either be solely due to ciliary muscle beta-antagonism or could be due to pathophysiological changes in the ciliary muscle and trabecular meshwork.

The aim of this study was to demonstrate whether there is less adrenergic innervation to the ciliary muscle during a sustained near-vision task in myopic subjects when compared with emmetropes. If this is the case then it would be predicted that timolol would have a reduced effect on the AC of myopes. It was not possible to measure the accommodation response during the course of this experiment due to the possible adverse consequences of instilling drugs into subjects fitted with soft contact lenses. The Canon Autoref R-1 optometer is unable to provide reliable estimates of the accommodative response in a subject corrected by spectacle lenses (see section 2.6A). However it was demonstrated in Fig. 7.4 that timolol did not produce any significant change in accommodative response.

In order to ascertain whether there are variations in adrenergic innervation between environmentally-induced and inherited myopia, myopic subjects were subdivided into late-onset myopes (LOMs) i.e. myopia onset at fifteen years of age or later, and early-onset myopes (EOMs) i.e. myopia onset prior to fifteen years of age (see section 5.2G).

Timolol maleate (0.5%) is widely used as an ocular hypotensive in the treatment of open-angle glaucoma and probably lowers intra-ocular pressure (IOP) by decreasing the rate of aqueous humour formation (Yablonski et al. 1978; Coakes and Brubaker, 1978). In order to examine whether the reduction in IOP produces a significant change in anterior corneal curvature (and thus induce refractive changes that are independent of accommodative variations) keratometry measurements were recorded for each subject before and after each experimental trial.

7.6 METHOD **

Changes in accommodative convergence (AC) were measured for accommodative stimuli of 3.3, 4.1 and 4.8D, the latter two stimuli being created by means of negative spherical lenses. These lenses were placed into a trial frame which was fitted at a vertex distance of 10mm. Values of accommodation stimulus were calculated with respect to the anterior corneal surface. Following the introduction of an accommodative stimulus, subjects were required to perform a counting task which consisted of the addition of a line of four two digit numbers (black on white, contrast ≈90%) placed at 30 cms from the eye. The size of the numbers was approximately equivalent to N6. Normal room lighting was maintained during the task to provide a target luminance of approximately 50 cd m^{-2}.

Following completion of the counting task the near heterophoria was measured for a given accommodation stimulus using a Maddox rod. The rod was placed before the right eye and the subject viewed a small spotlight located just above the numbers used for the counting task. Changes in vergence were measured using a tangent scale placed above the spotlight. This allowed subjective assessment of heterophoria to an accuracy of $\pm 0.5\Delta$.

A double-blind protocol was adopted between timolol maleate (0.5%) and a saline control. Instillations of timolol or saline were made using a precision micropipette delivering 25μl of drug. Each subject was given two instillations separated by a period of 5 mins., i.e. 50 μl of drug per eye. The near-vision task was commenced ten minutes after the second instillation. The saline and timolol trials were separated by at least one week.

At the beginning and end of each session, measurement of the central anterior corneal curvature of both eyes was made using a two-position keratometer (Haag-Streit, Bern).

** This study has been published in Ophthalmic & Physiological Optics 1987; 7, 359-364 (see Appendix C) and was presented at the 60th Anniversary Conference at the School of Optometry, University of Bradford. April 1987.

This keratometer measures the central 3.4mm of the cornea for average values of anterior corneal curvature (Lehmann, 1967). As timolol maleate is widely used as an ocular hypotensive, intra-ocular pressure (IOP) was measured at the start and finish of each experimental session using a Goldmann applanation tonometer mounted on a table slit-lamp following instillation of one drop of the topical anaesthetic benoxinate 0.4%. Assessment of IOP took place immediately following keratometry measurement.

The time course of the experiment is illustrated in Fig. 7.6. Following the introduction of an accommodative stimulus the counting task was performed. After the subject had completed the arithmetic addition, accommodation and heterophoria were measured. A new accommodation stimulus was then introduced, stimuli being presented in random order, and the cycle repeated. Each individual experimental cycle took approximately 20 seconds and therefore all three accommodative stimuli were completed in around one minute. The experiment was performed continuously for a period of fifteen minutes.

A total of 60 subjects were used (25 men, 35 women), all of whom were students in the Department of Vision Sciences, Aston University. The group consisted of 20 emmetropes, 20 late-onset myopes (LOMs) and 20 early-onset myopes (EOMs). The emmetropic subjects all had an unaided distance visual acuity of at least 6/6 with either eye and a mean sphere refractive error not greater than ±0.50D (or astigmatism exceeding 0.50D.) No subject had any major oculomotor imbalance or ocular pathology. Myopic subjects wore their distance spectacle prescription before both eyes. All subjects signed a consent form prior to taking part in the study and following a full explanation of all experimental procedures. Subjects were asked to complete a questionnaire giving details of their refractive history and any family history of myopia. Details of mean age, refractive error and age of myopia onset for the subjects used for this study is shown in Table 7.1.

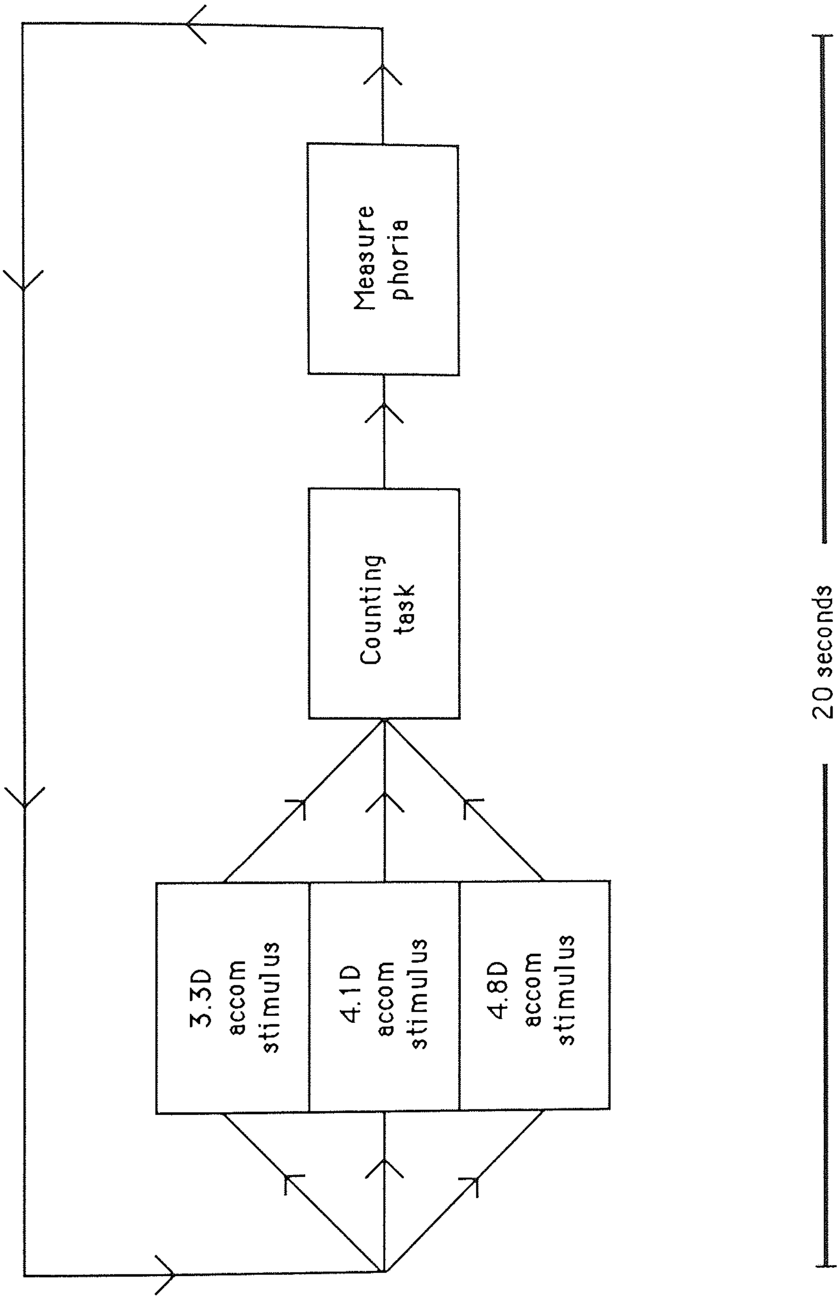

Fig. 7.6 Example of the experimental cycle.

Table 7.1. Details of subjects used

	Mean age (years)	Mean refractive error (D)	Mean age of myopia onset (years)
Early-onset myopes (N=20)	22.52 (sd=3.34)	-4.02 (sd=1.92)	9.71 (sd=2.33)
Late-onset myopes(N=20)	21.70 (sd=3.09)	-1.74 (sd=0.94)	16.85 (sd=2.43)
Emmetropes (N=20)	21.75 (sd=2.05)	—	—

7.7 RESULTS

Pre- and post-task values of intra-ocular pressure (IOP) are shown in Fig. 7.7 for the saline and timolol trials. There was no significant difference in the pre-task levels of IOP for the three refractive groups. However timolol produced a marked reduction in IOP. Two factor (drug, refractive group) analysis of variance indicated that the timolol induced reduction in IOP was significant ($F=140.4$; $df=1,4$;$p<0.01$) and consistent for each refractive group.

Pre- and post-task keratometry readings for the saline and timolol trials are shown in Table 7.2. No significant difference in central corneal curvature was observed between the three refractive groups, nor did timolol produce any significant change in central anterior corneal curvature.

Table 7.2 Values of central anterior corneal curvature (mm radius) for three refractive groups for the saline and timolol trials. F refers to the keratometry reading for the flatter principal meridian and S refers to the steeper principal meridian. Numbers in parentheses represent ±1 sd.

	SALINE				TIMOLOL			
	PRE-		POST-		PRE-		POST-	
	F	S	F	S	F	S	F	S
LOMs	7.89	7.76	7.86	7.73	7.86	7.74	7.86	7.75
	(0.26)	(0.29)	(0.24)	(0.25)	(0.19)	(0.23)	(0.22)	(0.24)
EOMs	7.90	7.71	7.90	7.71	7.89	7.70	7.89	7.72
	(0.23)	(0.24)	(0.24)	(0.24)	(0.25)	(0.25)	(0.26)	(0.27)
EMMs	7.92	7.78	7.93	7.78	7.90	7.78	7.91	7.76
	(0.30)	(0.27)	(0.28)	(0.25)	(0.27)	(0.25)	(0.28)	(0.28)

The incidence of family history of myopia within the three refractive groups is shown in Table 7.3. This shows a high incidence of myopia in both parents and siblings of LOMs, which may suggest the presence of genetic factors in late-onset myopia. However 67% of the myopic parents and 69% of the myopic siblings were also LOMs which may indicate a predisposition to late-onset myopia which is inherited. Consequently although late-onset myopia may be primarily induced by envionmental factors e.g prolonged near-work, its onset may be facilitated by the presence of genetic factors.

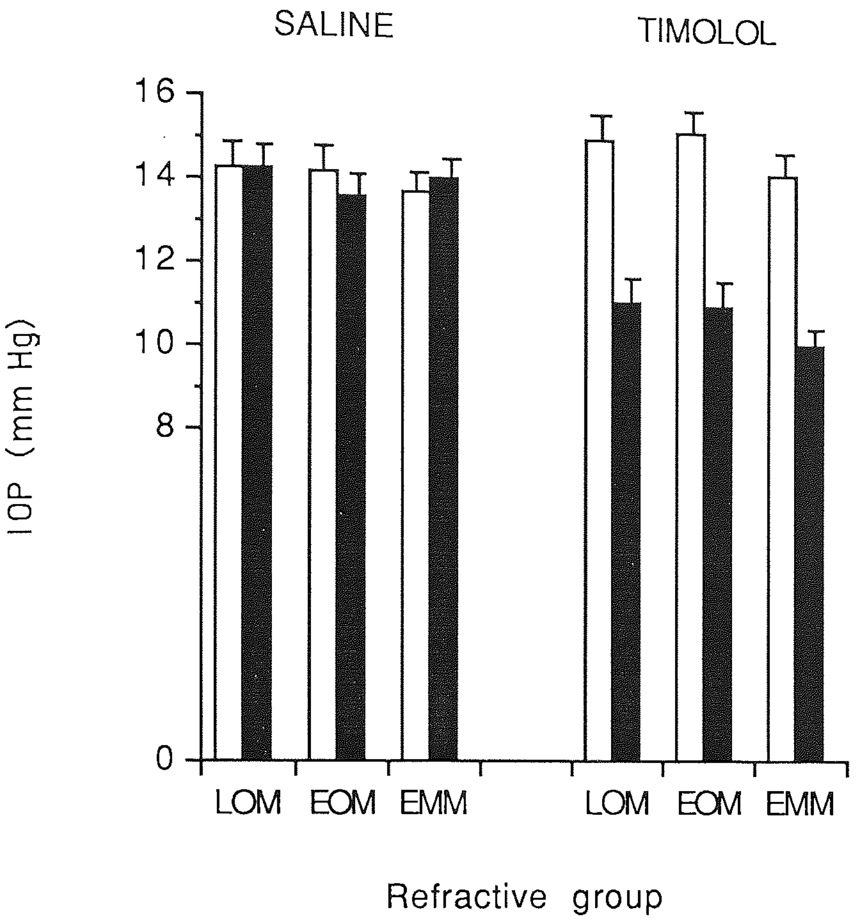

Fig.7.7. Pre-task (open bars) and post-task (shaded bars) values of intra-ocular pressure (IOP) measured by applanation tonometry for the saline and timolol trials. Timolol produced a significant reduction in IOP which was consistent for each of the three refractive groups. Error bars indicate 1 SEM.

Table 7.3. Incidence of family history of myopia amongst subjects

	History of myopia in:	
	one or both parents	one or more siblings
LOMs (N=20)	**35%** (N=9)	**55%** (N=13)
Breakdown of myopic relatives	6 LOMs 2 EOMs 1 unknown	9 LOMs 3 EOMs 1 unknown
EOMs (N=20)	**50%** (N=10)	**40%** (N=11)
Breakdown of myopic relatives	2 LOMs 6 EOMs 2 unknown	3 LOMs 8 EOMs
Emm (N=20)	**25%** (N=8)	**15%** (N=3)
Breakdown of myopic relatives	8 LOMs	2 LOMs 1 EOMs

Values of accommodative convergence (AC) for the 3.3-4.8D accommodation stimulus range are shown in Fig. 7.8. Data from the 3.3-4.1D accommodation stimulus range showed very similar trends and are omitted for brevity. Both myopic groups show a higher level of AC compared with emmetropes but there was no significant difference between LOMs and EOMs. In Fig. 7.9 the mean data for all myopic subjects is illustrated and analysis of variance indicated that the difference between emmetropes and all myopes was significant (F=23.75; df=1,16; p<0.01).

Data indicating the timolol-induced shift in AC for the three refractive groups may be found in Appendix 3. The effect of timolol on AC in emmetropes is illustrated in Fig. 7.10. There was a reduction in AC during the initial four minutes of the task. Partial analysis of variance indicated that the timolol-induced reduction in AC shown in

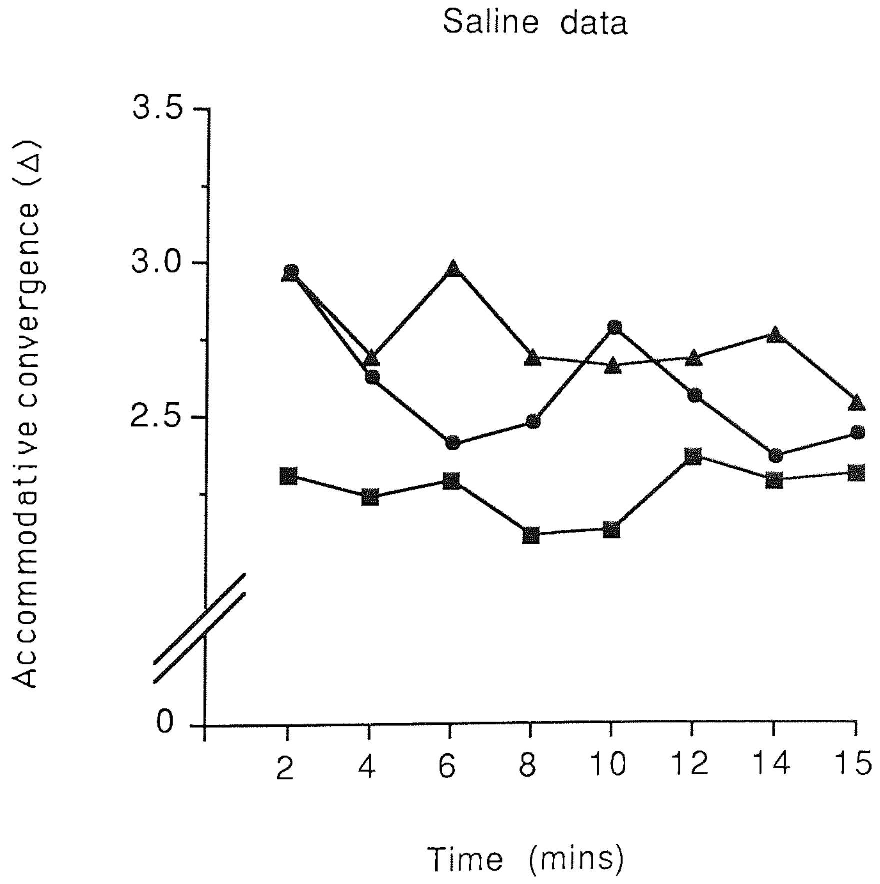

Fig. 7.8. Mean values of accommodative convergence for the saline trial over the course of the near-vision task (3.3-4.8D accommodation stimulus range). Triangles: late-onset myopes(N=20); Circles: early-onset myopes (N=20); Squares: emmetropes (N=20). Error bars have been omitted for clarity but SEMs were of the order of ±0.25.

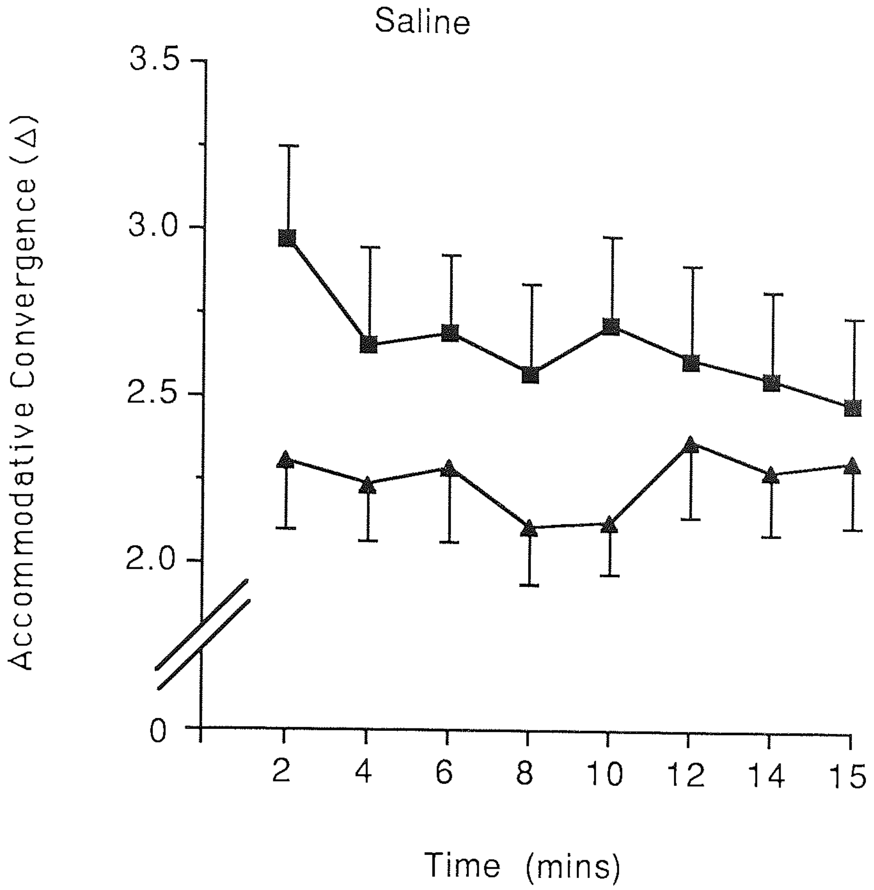

Fig. 7.9. Mean values of accommodative convergence for the saline trial over the course of the near-vision task (3.3-4.8D accommodation stimulus range). Triangles: emmetropes (N=20); Squares: all myopic subjects i.e. mean of LOMs and EOMs (N=40). Error bars indicate ±1 SEM.

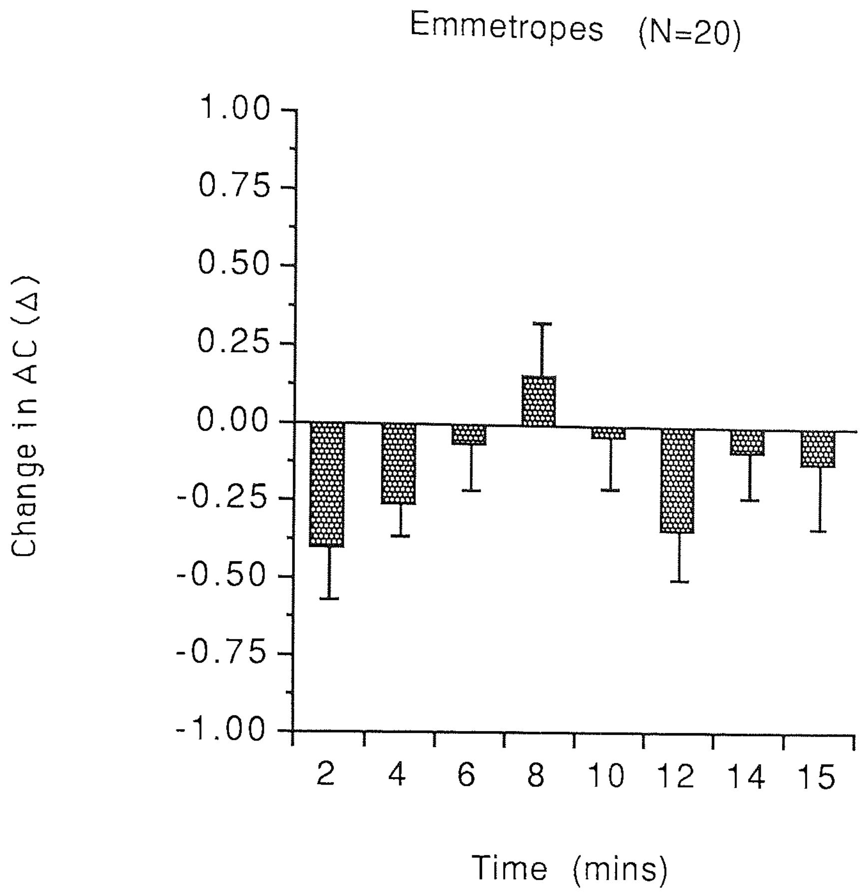

Fig. 7.10. Mean difference in accommodative convergence for 3.3-4.8D accommodation stimulus range between timolol and saline trials over the course of the near-vision task for 20 emmetropic subjects. Error bars indicate ±1 SEM.

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emmetropes during the initial four minutes was significant (F=7.87; df=1,24; $p<0.05$) when compared with the subsequent 11 minutes. However timolol does not have any significant effect on the AC of LOMs (Fig. 7.11) or EOMs (Fig. 7.12).

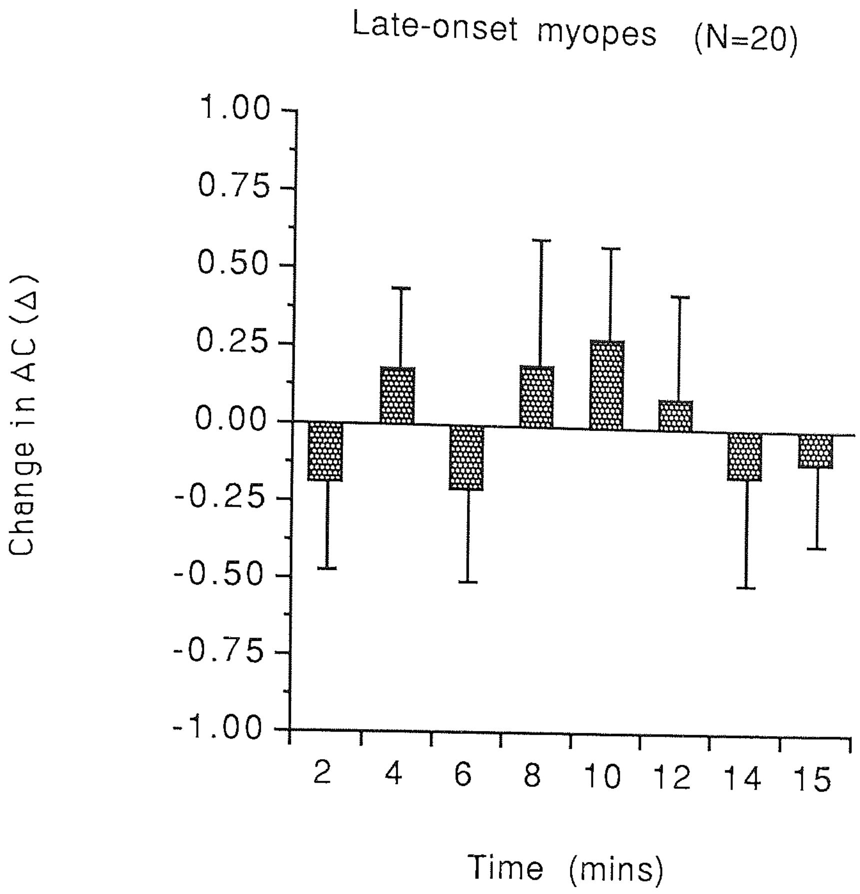


Fig. 7.11. Mean difference in accommodative convergence for 3.3-4.8D accommodation stimulus range between timolol and saline trials over the course of the near-vision task for 20 late-onset myopes. Error bars indicate ±1 SEM.

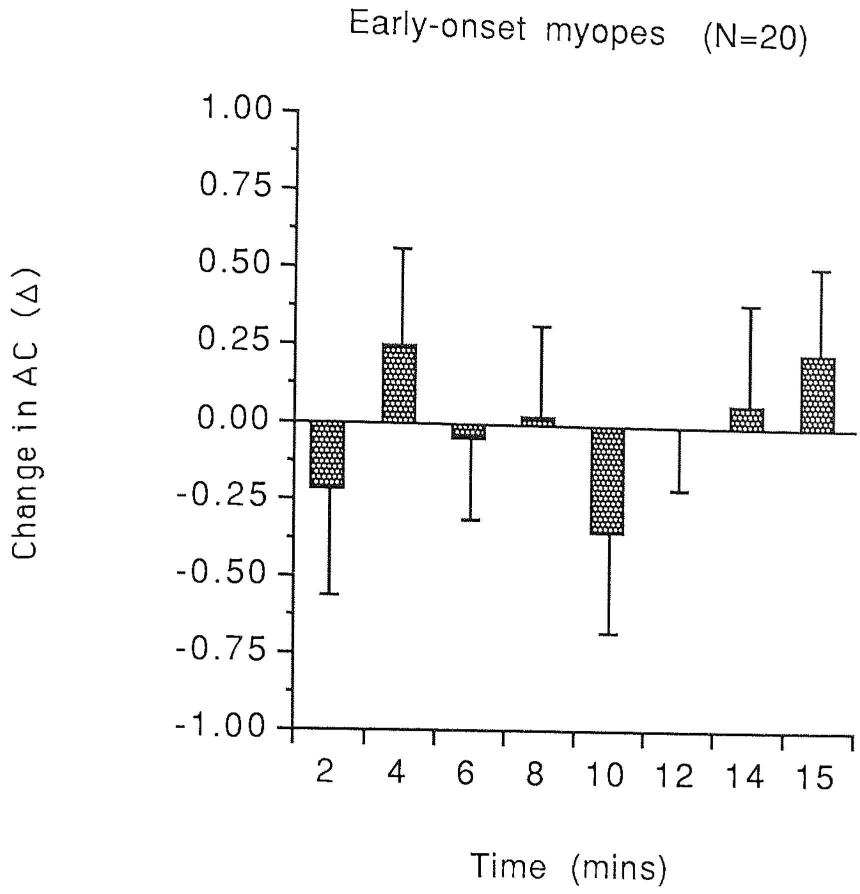


Fig. 7.12. Mean difference in accommodative convergence for 3.3-4.8D accommodation stimulus range between timolol and saline trials over the course of the near-vision task for 20 early-onset myopes. Error bars indicate ±1 SEM.

7.8 DISCUSSION

It was demonstrated in Table 7.2 and Fig. 7.7 that the reduction in IOP induced by timolol does not result in any significant change in anterior corneal curvature. Thus the changes in AC demonstrated both here and in the previous study (Section 7.2) cannot be accounted for by changes in corneal power producing variations in the refractive state of the eye.The apparent adaptation of emmetropic subjects to the effect of beta-adrenergic antagonism after the initial four minutes supports the findings of the previous experiment (Rosenfield and Gilmartin, 1987b). The fall in AC is attenuated after this initial period and it has been suggested that the adaptation occurs via a reduction in accommodation response in order to restore the previous synkinetic link between accommodation and vergence.

It was illustrated in Figs. 7.8 and 7.9 that myopes exhibit higher levels of AC compared with emmetropes and thus have higher stimulus AC/A ratios. It was demonstrated in the previous study (see Section 6.3) that EOMs have significantly higher levels of AC compared with LOMs, a finding which has not been reproduced here. Clearly the definition of late-onset myopia is of an arbitrary nature and it is likely that variations of myopia aetiology exist even within a population of LOMs. It is perhaps not surprising therefore to discover that two groups of LOMs should show differing near-response characteristics. Whilst comparison of family histories from the two studies shows very similar findings there may still be aetiological differences between the two sample groups. This does not exclude the possibility that variability of the accommodation-vergence synkinesis may be associated in some cases with the aetiology of late-onset myopia. However no clear evidence has been found in this study for the presence of reduced adrenergic inhibitory facility to the ciliary muscle in late-onset myopia.

7.9 CONCLUSIONS

It has been demonstrated that sympathetic innervation to the ciliary muscle may be monitored via accommodative convergence (AC). Timolol maleate (0.5%), a non-selective beta-adrenergic receptor antagonist, produced a significant reduction in AC during the first 4 mins of a near-vision task in an emmetropic population. However timolol produced no significant change in AC in LOMs or EOMs.

In this chapter accommodation-vergence interaction has been examined with the vergence system open-loop and the accommodation system closed-loop. In Chapter 8 the synkinesis between accommodation and vergence will be examined with both accommodation and vergence in closed-loop state i.e. with the normal negative feedback mechanisms allowed to operate.

CHAPTER 8

ASSESSMENT OF CLOSED-LOOP ACCOMMODATION-VERGENCE SYNKINESIS DURING SUSTAINED NEAR-VISION

8.1 INTRODUCTION

In Chapters 6 and 7, the interaction between accommodation and vergence was examined with the vergence system under open-loop conditions. However it was stated in Section 4.8 that opening one of the oculomotor loops will alter the synkinetic link between accommodation and vergence: removing negative feedback is likely to produce a change in the relative proportions of individual components of the near-response. Two studies will be described in this chapter which examined accommodation-vergence synkinesis with both oculomotor systems closed-loop. Whilst examination of accommodation-vergence interaction under closed-loop conditions will not provide absolute values of the AC/A or CA/C ratios, it may still demonstrate variations in the near-response between LOMs and EOMs.

The first study which will be discussed examined the accommodative response to differing forms of accommodation stimuli. Two forms of accommodative stimulus (AS) were used; i) blur-driven accommodation, i.e. where AS resulted from a change in retinal blur and ii) disparity-induced accommodation i.e. accommodation resulting from vergence stimulated by retinal disparity.

The difference between disparity-induced accommodation and convergent accommodation should be emphasized. Convergent accommodation can only be examined while the accommodative system is open-loop i.e. where a change in vergence provides the only stimulus to a change in accommodation. In this study the accommodation system was in a closed-loop state, with normal negative feedback mechanisms allowed to operate. Thus both blur and vergence provided a stimulus to accommodation.

Accommodation-vergence synkinesis was examined in a population consisting of early-onset myopes (EOMs) i.e myopia onset prior to fifteen years of age, late-onset myopes (LOMs) i.e. myopia onset at fifteen years of age or later and emmetropes. Two effects were investigated: a change in vergence stimulus (VS) with no concomitant change in the blur-driven accommodative stimulus (BS) and a change in BS with no change in VS.

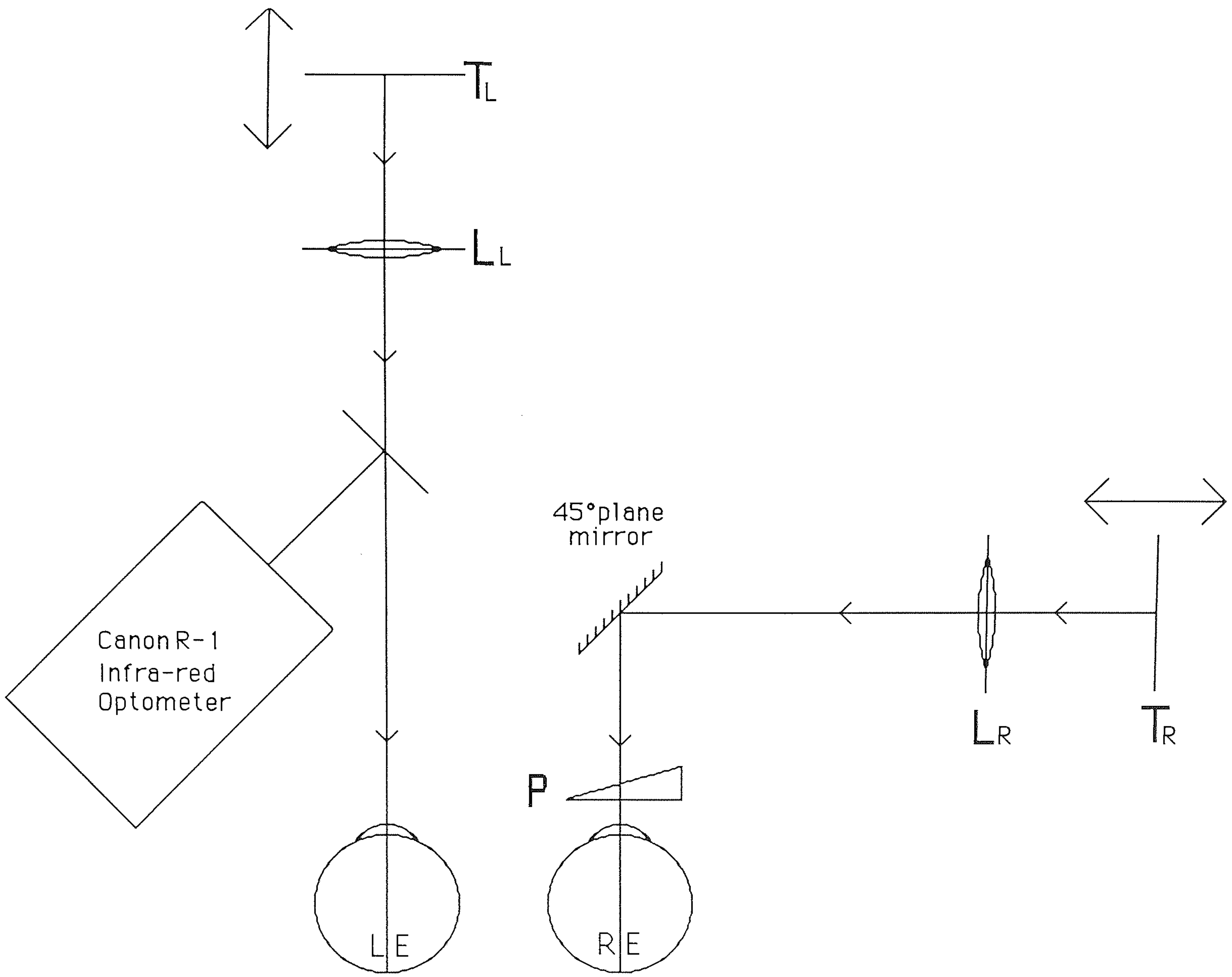
8.2 METHOD

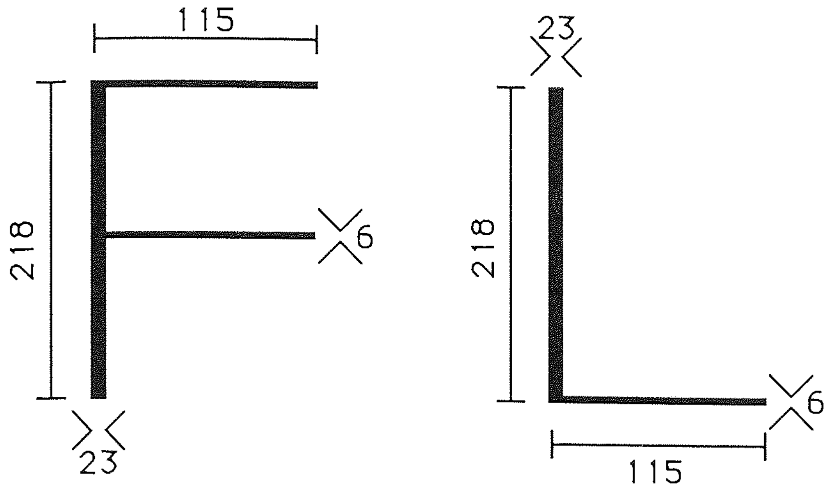
A schematic diagram of the experimental apparatus is illustrated in Fig. 8.1. The subject viewed the targets T_L and T_R via a single mirror haploscope and Badal optometer (+5.00DS lenses placed at 20cms from the anterior cornea). The Badal optometer avoids a change in proximal stimulation of accommodation by maintaining a nearly constant retinal image size as the blur stimulus is varied (Schor and Kotulak, 1986). The subject viewed the targets through a semi-silvered mirror which allowed objective assessment of the accommodative response to be made using the Canon Autoref R-1 infra-red optometer. All measures of accommodative response were taken from the left eye and readings were calculated as mean spherical power (i.e. sphere + half cylinder power). No correction factors have been added to the optometer readings.

8.2A TARGET DETAILS

High contrast (≈90%) targets as illustrated in Fig. 8.2 were presented to the subject via the haploscope and Badal optometer. The targets were printed on opaque white card. Subjects were instructed to keep the targets,"single and clear" and to report if they were unable to do so. All the subjects were able to maintain a single, clear image throughout the experiment. A target luminance of 45cd m^{-2} was provided by a source located 2 metres above the target.

Fig. 8.1. Diagram of the experimental apparatus. The subject viewed targets T_L and T_R with the left and right eyes respectively via a single mirror haploscope and Badal optometer [L_L and L_R represent the Badal (+5.00DS) lenses]. The subject viewed target T_L through a semi-silvered mirror allowing objective measurement of the accommodative response to be made using the infra-red optometer. Disparity-induced accommodation was stimulated by the introduction of the 4Δ base-out prism at P (10mm from the anterior cornea) whereas blur-induced accommodation was stimulated by movements of the targets T_L and T_R as shown by the arrows.


T_L
L_L
Canon R-1
Infra-red
Optometer
LE
45°plane
mirror
L_R
T_R
P
RE



Dimensions shown in minutes of arc

Fig. 8.2. Form and dimensions of the targets presented to the subject via the haploscope and Badal optometer.

8.2B DISPARITY-STIMULUS

This was induced by the addition of a 4 Δ base-out prism placed before the right eye at position "P" (Fig. 8.1). The introduction of the prism will induce retinal disparity and hence produce a convergence response. This convergence response will induce convergent accommodation and may require a relaxation of blur-driven accommodation (BA) in order to keep the target clear. The relaxation of BA however will cause a reduction of accommodative convergence thus increasing the demand on disparity-vergence if the target is to be kept single.

8.2C BLUR-STIMULUS

This was induced by movement of both targets along the line of sight of the optometer as shown by the arrows in Fig. 8.1. Thus the blur-stimulus was altered with no concomitant change in vergence stimulus. The increased BA response will induce accommodative convergence and therefore require a reduction in disparity-vergence in order to maintain single-vision. The reduction in disparity-vergence will produce a fall in convergent accommodation and thereby increase the stimulus to BA.

The accommodative response (AR) was measured for accommodative stimulus levels of 2.50 and 3.25D (measured with respect to the anterior corneal plane). Following introduction of the accommodative stimulus (AS), AR was measured from the left eye at approximately 1 second intervals for a period of 50 seconds. In all stimulus conditions recording of AR commenced within 10 secs of the introduction of AS in order to minimize prism adaptation.

The accommodative response was measured for four accommodation-vergence stimuli. Stimulus values of 2.50D/0Δ and 2.50/4Δ were denoted as AS1 and AS2 respectively. Similarly the 3.25D/0Δ and 3.25/4Δ stimuli were designated AS3 and AS4 respectively. These four accommodation-vergence stimuli were introduced in random order.

The response to disparity-induced accommodation was calculated as the difference between the accommodation responses at AS1 and AS2 and between AS3 and AS4. The accommodative response to blur-induced accommodation was calculated by the change in response AR3-AR1 and AR4-AR2.

A total of 45 subjects were used (17 men, 28 women), all of whom were optometry students at Aston University. These consisted of 15 emmetropes, 15 LOMs and 15 EOMs. The mean age and refractive error of each group is shown in Table 8.1. Myopic subjects were corrected with ultra-thin soft contact lenses (Hydron 06) and an adaptation period of at least 20 mins was allowed before commencing the experiment. Visual acuity was checked at the beginning and end of the experimental session. All myopic subjects could achieve visual acuity of at least 6/6 when corrected by the contact lenses. All subjects were asked to complete a questionnaire giving details of their refractive history and any family history of myopia*.

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* This study has been published in the American Journal of Optometry & Physiological Optics (1987) 64, 929-937 (see Appendix D) and was presented at ARVO, Sarasota, Florida,U.S.A. May 1987.

8.3 RESULTS

Data received from the questionnaire issued to all subjects is shown in Table 8.2. This shows a high incidence of myopia in both parents and siblings of LOMs which may suggest the presence of genetic or cultural factors in the aetiology of late-onset myopia. However 57% of the myopic parents and 70% of the myopic siblings were also LOMs which may indicate a predisposition to late-onset myopia which is inherited. Consequently while late-onset myopia may be primarily induced by environmental factors e.g. prolonged near-work, its onset may be facilitated by the presence of genetic factors. The mean accommodative response (AR) was calculated for each 10 second period of near fixation (i.e. mean of 9 readings). These values are shown in Appendix 4. The mean change in accommodative response induced by the introduction of the 4Δ base-out prism at the 2.50 D accommodative stimulus level (i.e. AR2-AR1) is shown in Fig. 8.3. LOMs exhibit significantly higher disparity-induced accommodation when compared with EOMs whereas emmetropes showed a similar response to EOMs. Two-factor analysis of variance (refractive group, time) indicated that the difference in accommodative response between the three refractive groups was significant (F=3.97; df=2, 42; $p<0.05$).

The blur-induced change in accommodative response following the change of accommodative stimulus from 2.50-3.25D (i.e. AR3-AR1) is illustrated in Fig. 8.4. LOMs show a greater blur-induced accommodative response when compared with EOMs while the response of emmetropes lies between the two myopic groups. Two-factor (refractive group, time) analysis of variance indicated that the difference between the three refractive groups was statistically significant (F=7.44 ; df=2, 42 ; $p<0.01$).

It was shown in Table 8.2 that 53% of LOMs (8 subjects) reported constant wear of their refractive correction while 47% (7 subjects) of LOMs reported only occasional wear of their correction. The level of disparity-induced accommodation at the 2.50D accommodative stimulus level is shown in Fig. 8.5 for these two groups. Analysis of

Table 8.1. Details of subjects used in each refractive group. Figures in parentheses represent +1sd.

	Mean age (years)	Mean refractive Error (D)	Mean age of myopia onset(yrs)
LOMs (N=15)	22.6 (4.60)	-1.71 (0.68)	16.5 (2.07)
EOMs (N=15)	21.9 (2.74)	-3.92 (1.82)	9.63 (2.12)
Emmetropes (N=15)	21.9 (2.23)	+0.10 (0.25)	

Table 8.2 Data received from questionnaire issued to all subjects regarding refractive history and any family history of myopia.

	Refractive correction worn;		History of myopia in;	
	constantly	occasionally	one or both parents	one or more siblings
LOMs (N=15)	**53%**	**47%**	**40%**(N=7)	**53%**(N=10)
Division of myopic relatives			4 LOMs 2 EOMs 1 unknown	7 LOMs 3 EOMs
EOMs (N=15)	**93%**	**7%**	**48%** (N=7)	**40%** (N=7)
Division of myopic relatives			4 EOMs 3 unknown	3 LOMs 4 EOMs
Emm (N=15)			**20%** (N=4)	**13%** (N=2)
Division of myopic relatives			3 LOMs 1 EOM	2 EOMs

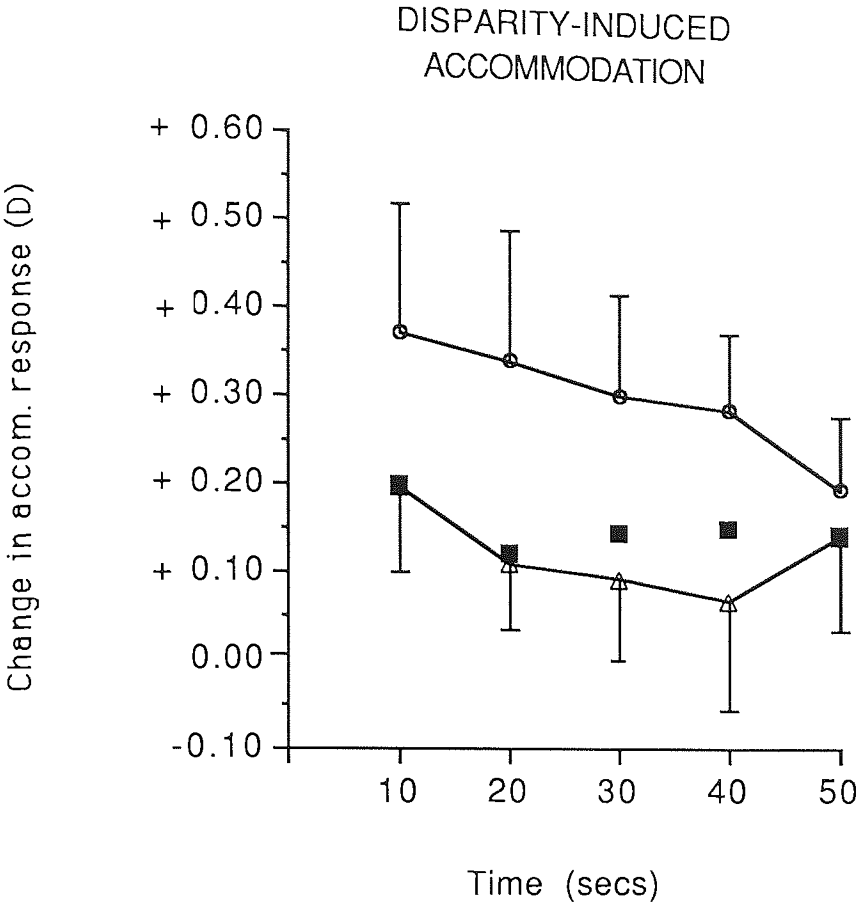

Fig.8.3 Mean values of disparity-induced accommodation at the 2.50D accommodation stimulus level. Open circles: late-onset myopes (N=15); Open triangles: early-onset myopes (N=15); Squares: emmetropes (N=15). Error bars indicate ±1 SEM. Error bars have been omitted from the emmetropic data for clarity but SEMs were of the order of ±0.09.

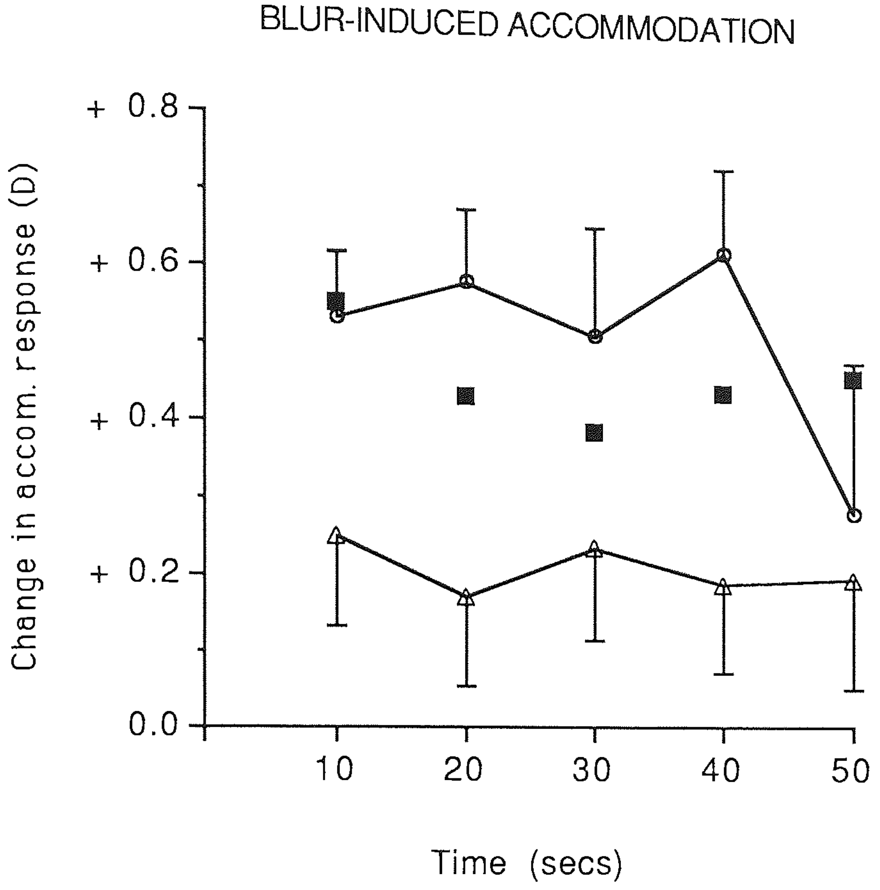

Fig. 8.4. Mean values of blur-induced accommodation (2.50-3.25D accommodation stimulus range). Circles: LOMs (N=15); Triangles: EOMs (N=15); Squares: Emmetropes (N=15). Error bars represent ±1 SEM. Error bars have been omitted from the emmetropic data for clarity but SEMs were of the order of ±0.12.

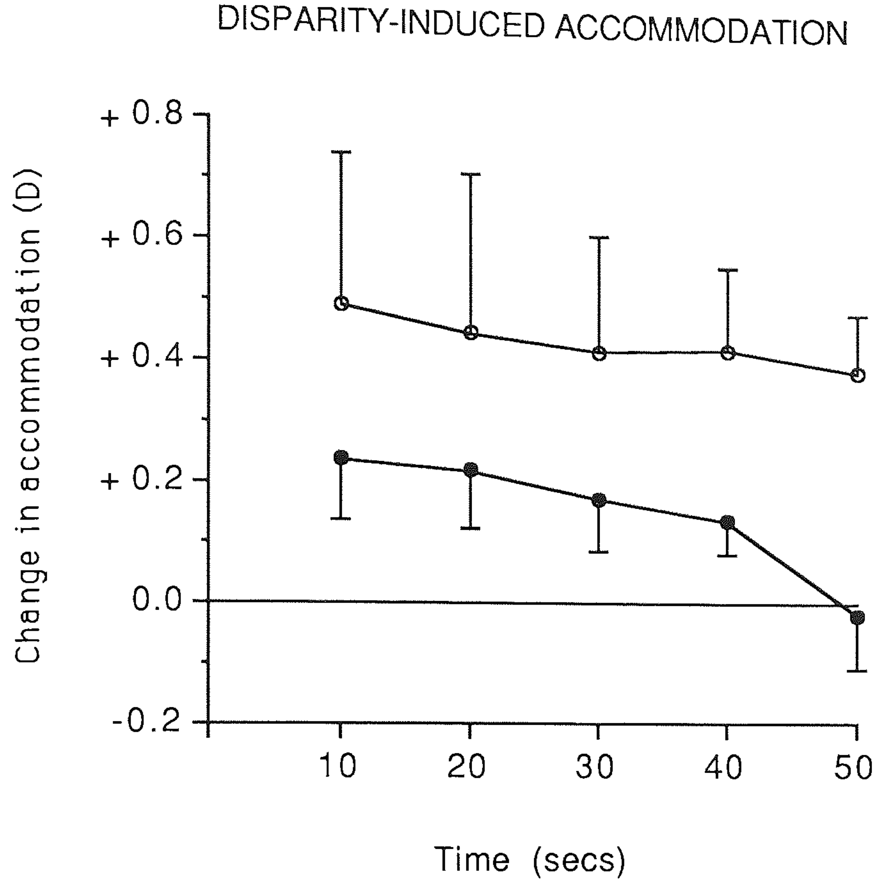

Fig. 8.5 Mean value of disparity-induced accommodation (2.50D accommodation stimulus) for 8 LOMs who reported constant wear of their refractive correction(open circles) and 7 LOMs who reported occasional wear of their refractive correction (closed circles). Error bars represent ±1 SEM.

variance indicated that the difference in disparity-induced accommodation was significant (F=7.82; df=1,14; $p<0.01$). However there was no significant difference in blur-induced accommodation between these two groups (Fig. 8.6).

It should also be noted that not all of the myopic subjects were habitual contact lens wearers and therefore the vergence demand would be increased in the habitual spectacle wearers when they were fitted with soft contact lenses. To examine whether the differences in accommodative response between LOMs and EOMs could be accounted for by this variation in vergence demand, disparity and blur-induced accommodation was examined in 7 LOMs and 8 EOMs, all of whom were habitual contact lens wearers. These findings are shown in Figs. 8.7 and 8.8. Analysis of variance indicated that the differences between the LOM and EOM contact lens wearers were

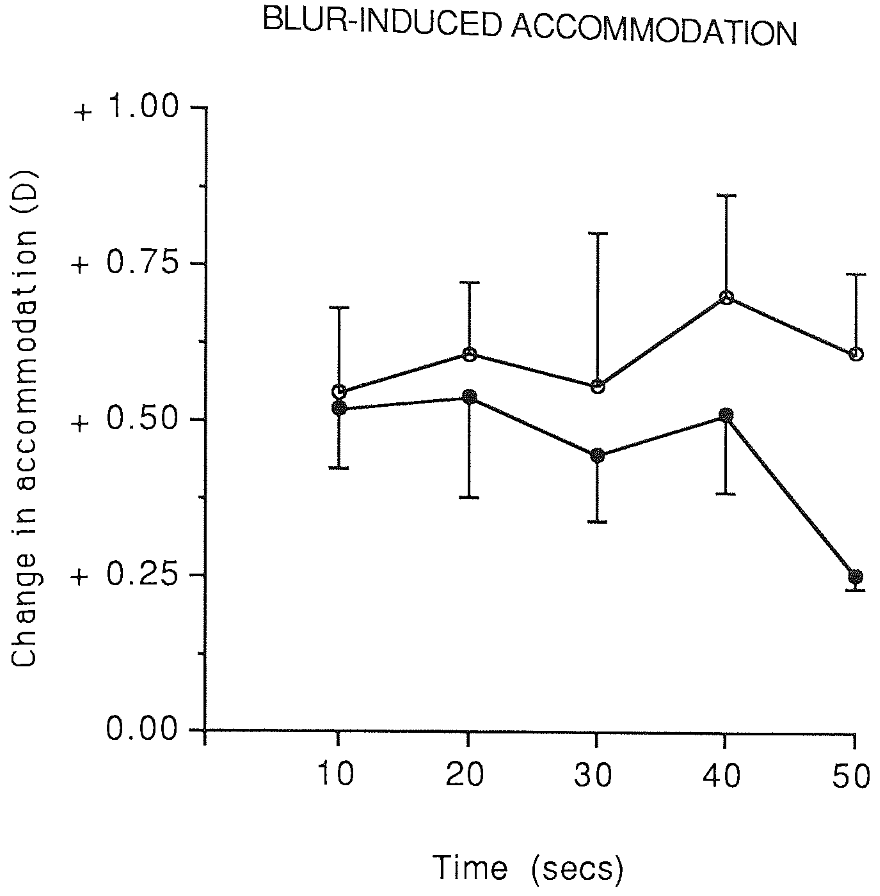

Fig. 8.6 Mean value of blur-induced accommodation (2.50-3.25D accommodation stimulus range) for 8 LOMs who reported constant wear of their refractive correction(open circles) and 7 LOMs who reported occasional wear of their refractive correction (closed circles). Error bars represent ±1 SEM.

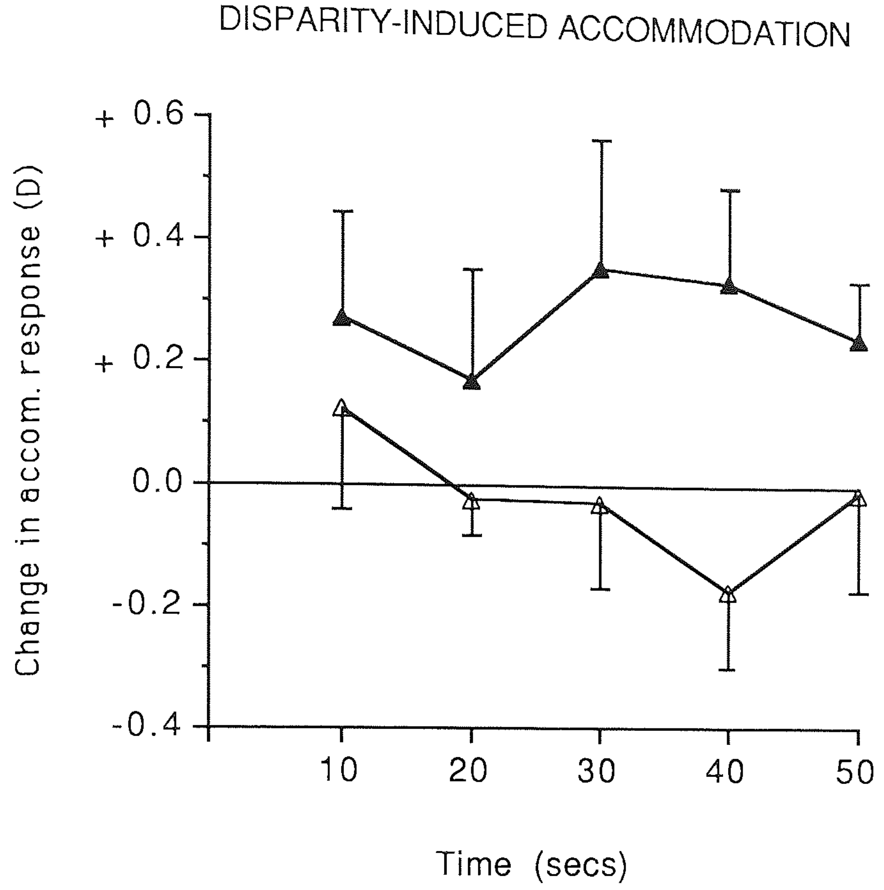

Fig. 8.7 Mean value of disparity-induced accommodation (2.50D accommodation stimulus) for 7 LOMs(closed triangles) and 8 EOMs (open triangles) who were all habitual contact lens wearers. Error bars represent ±1SEM.

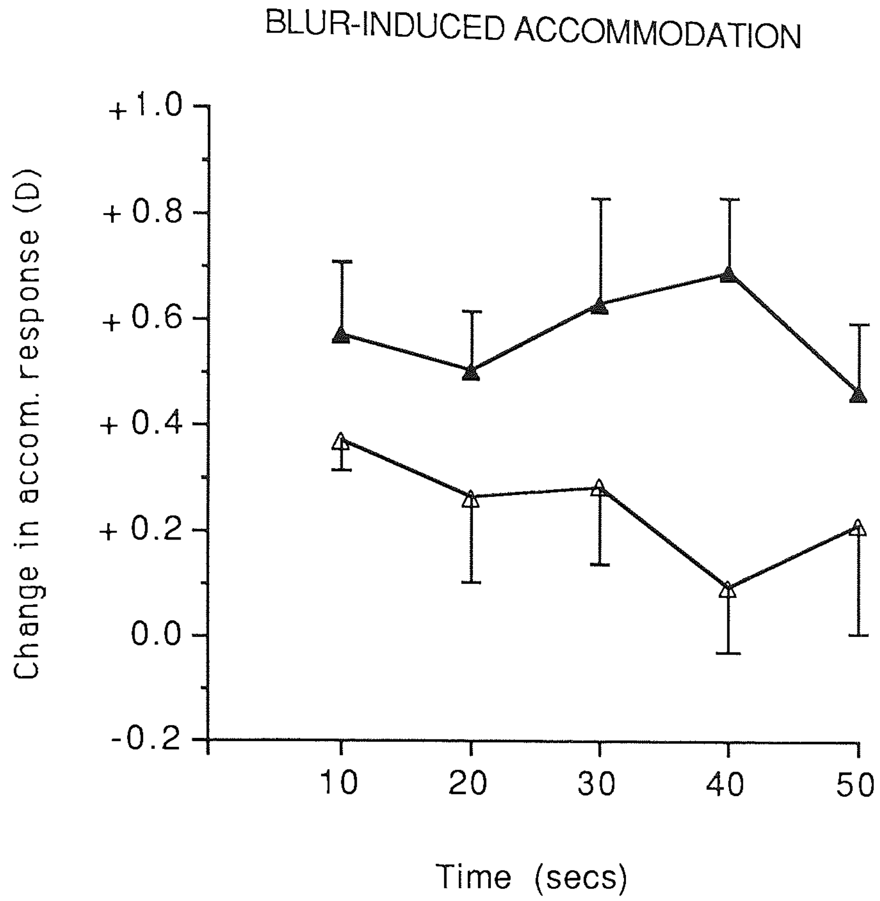

Fig. 8.8 Mean value of blur-induced accommodation (2.50-3.25D accommodation stimulus range) for 7 LOMs(closed triangles) and 8 EOMs (open triangles) who were all habitual contact lens wearers. Error bars represent ±1SEM.

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significant (disparity-induced accommodation F=8.48; df=1,60; p<0.01; blur-induced accommodation F=14.22; df=1,12; p<0.01).

8.4 DISCUSSION

It has been shown in Fig. 8.3 that LOMs exhibit a greater level of disparity-induced accommodation when compared with EOMs and emmetropes. The implication is that LOMs have a higher CA/C ratio than EOMs. This result might have been predicted from the data presented in Section 6.3 (Rosenfield and Gilmartin, 1987a) which indicated that LOMs have a lower response AC/A ratio when compared with EOMs. Alternatively, under the closed loop conditions of the present experiment, increased disparity-induced accommodation may also result from an altered interaction between elements of the combined accommodative response. If the increase in disparity-induced accommodation following the introduction of the prism is not accompanied by a concomitant reduction in blur-driven accommodation then there will be an increase in the aggregate accommodative response. Thus the increased disparity-induced accommodation in LOMs (see Fig. 8.3) may result from failure to relax blur-driven accommodation and may not be derived from an altered CA/C ratio. The absence of attenuation of blur-induced accommodation may relate to a reduced sympathetic inhibitory input to the ciliary muscle during sustained near-vision. It has been suggested that LOMs may have reduced sympathetic innervation to the ciliary muscle (Gilmartin and Bullimore, 1987) which might also be associated with lower levels of dark-focus (Rosenfield and Gilmartin,1987a; McBrien and Millodot, 1987b; Bullimore and Gilmartin, 1987d).

Increased disparity-induced accommodation might produce an excessive accommodative response during near-work. The onset of myopia could then be an adaptation in order to reduce the accommodative demand. Birnbaum (1985) stated that myopia should not be viewed as a primary problem but as an adaptive change that occurs secondary to nearpoint stress.

There was a significant difference (Fig. 8.5) in disparity-induced accommodation between those LOMs reporting constant wear of their refractive correction (constant wearers) and LOMs who only wore their correction occasionally (occasional wearers). It is likely that occasional wearers would perform near-vision tasks unaided, thereby reducing the accommodative demand. If the original increase in disparity-induced accommodation resulted from excessive near-vision stress, perhaps due to an increased requirement for accommodative convergence, then a reduction in accommodative demand would allow this function to return to normal values. The value of disparity-induced accommodation shown in Fig. 8.5 for occasional wearers is similar to that of emmetropes (Fig.8.3), suggesting this may be the case. This would indicate that myopes should be encouraged, where practical, to perform sustained near-vision tasks unaided.

It was shown in Fig. 8.3 that LOMs show a gradual reduction in disparity-induced accommodation over the course of the task. It would appear that adaptation to the introduction of the 4Δ prism is taking place. Schor (1979) described the fusion response as consisting of fast fusional vergence which acts within one second to reduce retinal disparity (Rashbass and Westheimer, 1961) and slow fusional vergence which maintains the net vergence response. The terms reflex or phasic vergence and adaptive or tonic vergence may also be used to describe the output of the fast and slow neural intergrators respectively. The stimulus initiating adaptive vergence is the output of reflex vergence (Schor, 1983a). The reduction of disparity-induced accommodation in LOMs after 30-50 seconds (see Fig. 8.3) may relate to the onset of adaptive vergence. Schor and Tsuetaki (1987) stated that subjects having increased CA/C and reduced AC/A ratios would have good accommodation adaptation and poor vergence adaptation. It would be predicted therefore that LOMs would show increased accommodative hysteresis on removal of a sustained accommodative stimulus; this point is discussed further in Section 8.5.

It can be seen in Fig. 8.4 that EOMs show less blur-induced accommodation when compared with LOMs. This finding together with the reduced level of disparity-induced accommodation (Fig. 8.3) may reflect a "reluctance to accommodate" in EOMs . Analysis of variance showed no significant difference in disparity-induced accommodation between EOMs and emmetropes whilst the difference in blur-induced accommodation between these two refractive groups was significant(F=9.53; df=1,8; $p<0.01$). This variation may indicate that EOMs are less sensitive to blur or may reflect differences in the relative effectivity of the components of the near-response mechanism; disparity-drive being a greater stimulus to accommodation than blur in EOMs. McBrien and Millodot (1986a) showed no significant difference between the accommodation stimulus-response curves of LOMs and EOMs suggesting that the variation in blur-induced accommodation cannot be accounted for by differences in accommodative lag.

Differences in disparity-induced accommodation have been demonstrated between LOMs and emmetropes. In an attempt to gain a greater understanding of these variations, a second investigation of disparity-induced accommodation in LOMs was performed. In this second study the effect of disparity-induced accommodation on accommodative adaptation was investigated.

8.5 ACCOMMODATIVE ADAPTATION INDUCED BY SUSTAINED DISPARITY-VERGENCE.

A number of investigations have demonstrated that adaptive changes in dark-focus (DF) and dark-vergence (DV) may be induced by periods of sustained near-vision (see Section 2.5Aiii and 3.7A). Immediately following removal of a sustained near-vision stimulus, it is likely that the output of the reflex components of accommodation and vergence will dissipate rapidly whilst the adaptive components, due to their slower time course, will exhibit a reduced rate of decay. The increase in DF following a near-vision task will therefore relate to the output of adaptive accommodation. Thus if the regression of DF back to the pre-task value is examined following a period of sustained near-vision, this will give information relating to the amplitude and rate of decay of adaptive accommodation.

The aim of this experiment was to determine the relative influences of individual elements of the near-response on accommodative adaptation by examining the effect of within-task disparity-induced accommodation (DA) on the post- to pre-task shift in DF. The accommodation system was maintained in a closed-loop state during the course of the near-vision task, with normal negative feedback mechanisms allowed to operate.

Schor and Kotulak (1986) examined the effect of convergent accommodation on DF. The vergence system was adapted to a step stimulus (8Δ base-out) for two separate periods of 5 seconds and 2 minutes while the accommodation system remained open-loop throughout. The aftereffects of the stimulus were examined immediately following the task with both accommodation and vergence open-loop. The vergence loop was opened by occluding the left eye and the accommodation loop was opened using a pinhole. Schor and Kotulak observed that following the 5 second stimulus there was a rapid decay in both the vergence and accommodation responses. However following a two minute period of vergence adaptation, there was an increase in DV and DF of +8Δ and 0.75D respectively. These aftereffects decayed over a 60-90s period. Schor and Kotulak noted that the regression of DF and DV towards pre-task levels were independent, indicating that the post-task increase in DF is not produced by increased DV stimulating accommodation.

A similar finding was also observed by Wolfe and O'Connell (1987) who examined DF before and after a 5 min period fixating small (8 minutes of arc) light-emitting diodes (LEDs) at a viewing distance of 14 cms (7.1 metre-angles) in 21 subjects. They noted that the small LEDs did not constitute a stimulus to accommodation directly (accommodation being measured using a vernier optometer)but did act as a stimulus to vergence. This period of vergence adaptation produced a mean increase in DF of +0.22D with respect to pre-task levels in the 90s period immediately following the task. It should be noted that the subjects used in the Wolfe and O'Connell study were not all emmetropic although all wore their refractive correction during the course of the near-vision task.

In this study the effect of DA on accommodative adaptation was investigated by examining DF before and after a near-vision task performed under differing levels of vergence stimuli. These effects were examined in a population consisting of emmetropes and LOMs i.e. myopia onset at fifteen years of age or later. In addition two different task durations were used in order to examine temporal aspects of accommodative adaptation.

8.6 METHOD

A total of twenty subjects were used, all of whom were students in the Department of Vision Sciences, Aston University. These consisted of 10 emmetropes and 10 LOMs. The mean age of the emmetropic group was 21.13 years (sd=2.25) and of the myopic group 21.83 years (sd=2.33). Mean refractive error for the LOMs was -1.75D (sd=0.94; range -0.75 to -4.00D). The mean age of myopia onset was 16.2 years (sd=0.71). Emmetropic subjects all had unaided distance visual acuity of at least 6/6 with either eye and a mean sphere refractive error not greater than one half dioptre of myopia or hypermetropia (with astigmatism not exceeding 0.50D). No subject had any major oculomotor imbalance (i.e. heterotropia or uncompensated heterophoria), asthenopia or ocular pathology. Myopic subjects were corrected with ultra-thin soft contact lenses (Hydron 06) and an adaptation period of at least 20 mins was allowed before commencing the experiment. All LOMs could achieve visual acuity of at least 6/6 when corrected by the contact lenses. Each subject signed a consent form prior to taking part in this study and following a full explanation of all experimental procedures.

The accommodation response was measured objectively using the Canon Autoref R-1 infra-red optometer. All measures of accommodation response were taken from the left eye and readings were calculated as mean spheres (i.e. sphere + half cylinder power). No calibration factor has been added to the optometer reading.

Pre-task values of dark-focus (DF) were measured according to the method described by Gilmartin and Bullimore (1987) . The subject sat in total darkness for 10 minutes and following this period 10 readings of the refractive error were taken each minute for a period of 5 minutes. This gave a total of 50 readings which were then averaged.

Following measurement of pre-task DF, subjects were required to perform a counting task which consisted of the addition of a line of high contrast (≈90%) two digit numbers, size equivalent to N6, which were placed at 33 cms from the eyes. Normal room lighting was maintained during the task to provide a target luminance of 45cd m^{-2}. Disparity-induced accommodation (DA) was stimulated by the introduction of 3 and 6Δ base-out prisms before the right eye. In a third (control) condition the subject performed the task whilst viewing through a plano lens (0Δ). The near-vision task commenced within 10 seconds of the introduction of the prism in order to minimize prism adaptation. The accommodation response (mean of five readings) of the left eye was measured at 1 min intervals during the course of the near-vision task.

Immediately following completion of the near-vision task the room lights were extinguished and the regression of accommodation towards the pre-task DF position was measured over a 90sec period. Subjects were randomly allocated to six trials comprising two task durations; a 3 or 10 minute task combined with three levels of disparity stimulus i.e. 0, 3 or 6Δ. The experimental sessions were separated by a period of at least two days †.

8.7 RESULTS

The mean value of pre-task DF for emmetropes and LOMs was +0.61D (sd=0.35) and +0.49D (sd=0.36) respectively. This difference was not significant (F=1.78; df= 1,118; p=0.18) although other studies have also reported lower levels of DF in LOMs compared with emmetropes (McBrien and Millodot, 1987b; Bullimore and Gilmartin, 1987d; Rosenfield and Gilmartin, 1987a).

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† The findings of this study will be published in the February 1988 edition of the American Journal of Optometry & Physiological Optics, see Appendix E and the July 1988 edition of Ophthalmic and Physiological Optics, see Appendix F. They have also been presented at the Society of Experimental Optometry, Birmingham, July 1987 and the meeting of the American Academy of Optometry, Denver, Colorado, U.S.A. December 1987.

The values of accommodation response (AR) measured during the course of the near-vision task are illustrated in Fig. 8.9 (emmetropes) and Fig. 8.10 (LOMs) and are tabulated in Appendix 5. Under closed-loop conditions, disparity-vergence did not produce a significant change in AR for emmetropic subjects. However LOMs show significant increases in AR following stimulation of disparity-vergence. Two-factor (time, disparity) analysis of variance indicated that the difference in disparity-induced accommodation (DA) in LOMs (Fig. 8.10) was significant (F=9.59; df=2, 30; p<0.01).

The levels of AR for the two refractive groups in the zero prism condition during the course of the task is shown in Fig. 8.11. LOMs show a significantly lower AR when compared with emmetropes. Two-factor (time, refractive group) analysis of variance indicated that the difference in AR between the 2 refractive groups was significant (F=22.49; df=1, 20; p<0.01). There was no significant difference in AR between LOMs and emmetropes for the 3Δ or 6Δ conditions.

Mean values of pre-task DF together with the post- to pre-task change in DF are shown in Appendix 6. The post-task regression pattern (TRP) following the 3min task (0Δ condition) for the two refractive groups is illustrated in Fig. 8.12. It is shown that whilst emmetropes initially show a larger shift in DF, they also exhibit a steeper TRP gradient, and DF becomes negative with respect to the pre-task value. LOMs however fail to show this negative response and furthermore exhibit a reduced TRP gradient.

The TRPs following the 3 minute task for the different disparity-stimuli are shown in Fig. 8.13 (emmetropes) and Fig. 8.14 (LOMs). In emmetropes, an increase in disparity-stimulus produced a reduction in the initial post-task shift in DF. In LOMs the result was less clear as the 3Δ stimulus produced a larger shift in DF than 0Δ . Three-factor analysis of variance (time, refractive group, disparity-stimulus) indicated that all three of these factors were significant (time, F=4.36; df=8,54; p<0.01: refractive

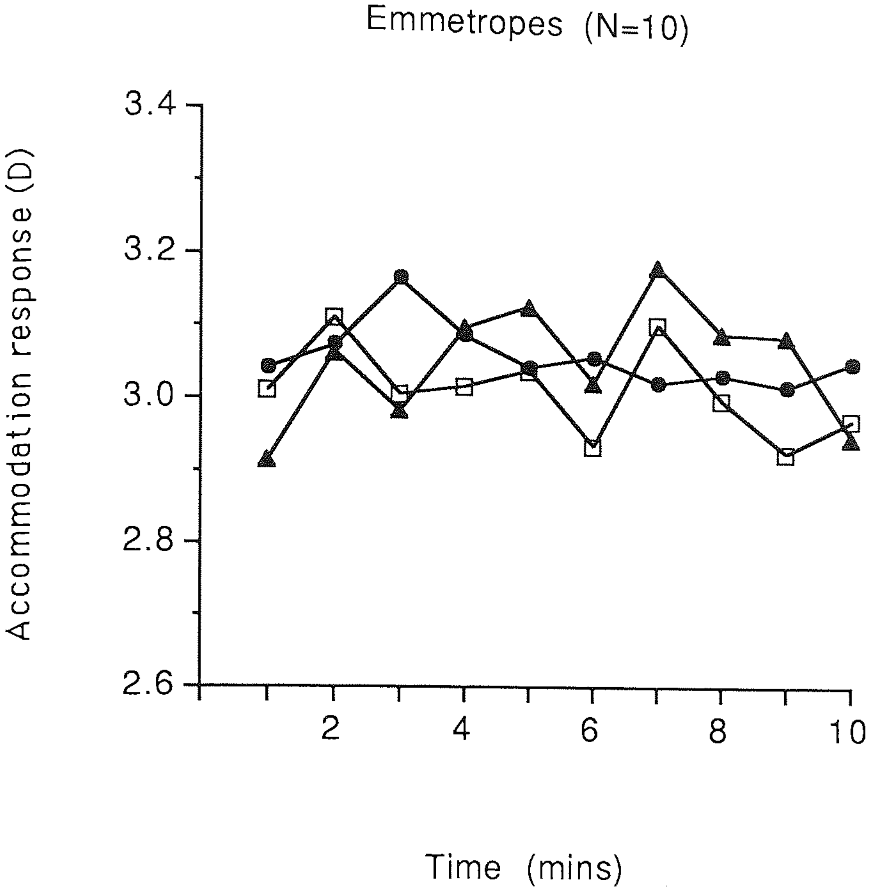

Fig. 8.9. Effect of disparity-vergence on the accommodation response (AR) for 10 emmetropic subjects over the course of a 10 min near-vision task. AR was measured for three vergence stimulus levels induced by the introduction of 0Δ (triangles), 3Δ (open squares) and 6Δ(circles) base-out prisms before the right eye. Emmetropes show no significant change in AR following introduction of the prism. Error bars have been omitted for clarity but SEMs were of the order of ±0.09.

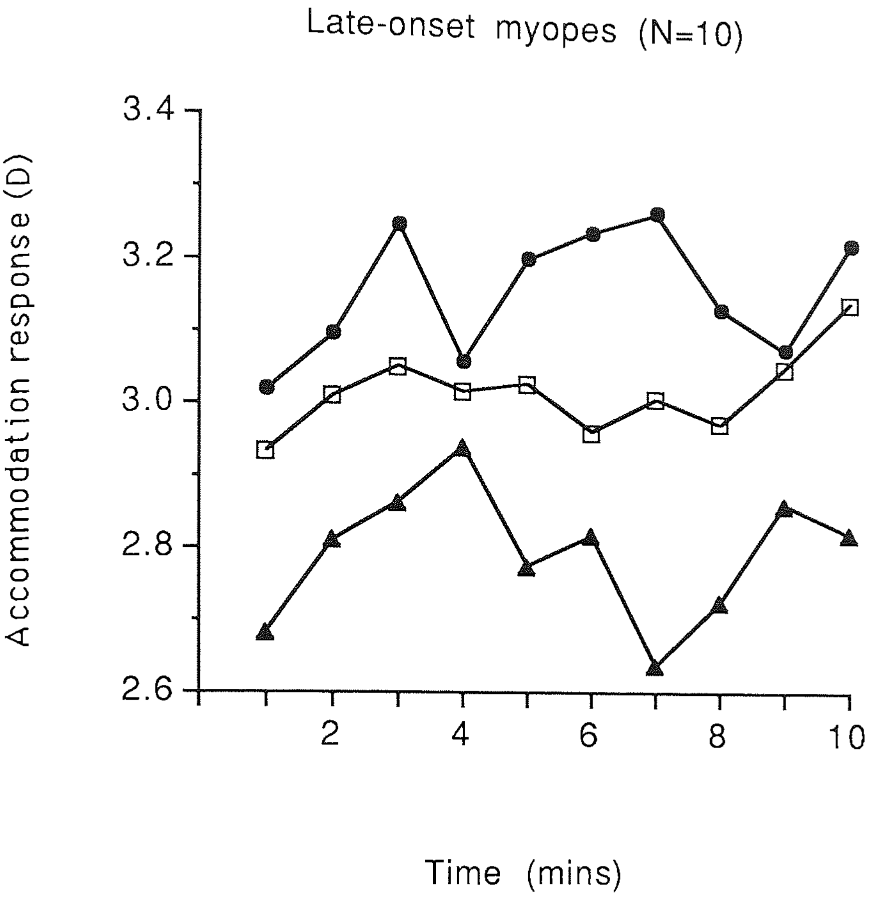

Fig. 8.10. Effect of disparity-vergence on the accommodation response (AR) for 10 LOMs over the course of a 10 min near-vision task. AR was measured for three vergence stimulus levels induced by the introduction of 0Δ (triangles), 3Δ(open squares) and 6Δ(circles) base-out prisms before the right eye. Disparity-vergence produced significant changes in AR under closed-loop conditions. Error bars have been omitted for clarity but SEMs were of the order of ±0.17.

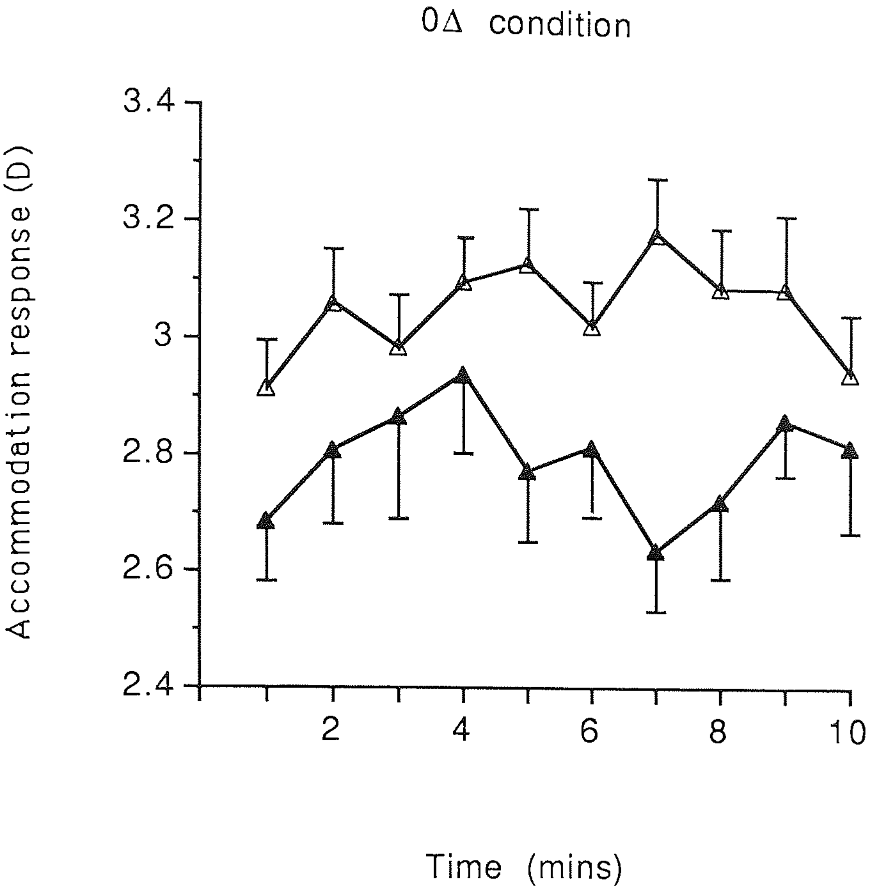

Fig. 8.11. Mean accommodation response for 10 emmetropes (open triangles) and 10 LOMs (closed triangles) during the course of the near-vision task in the absence of a disparity-stimulus. LOMs show a significantly lower AR than emmetropes. Error bars represent ±1 SEM.

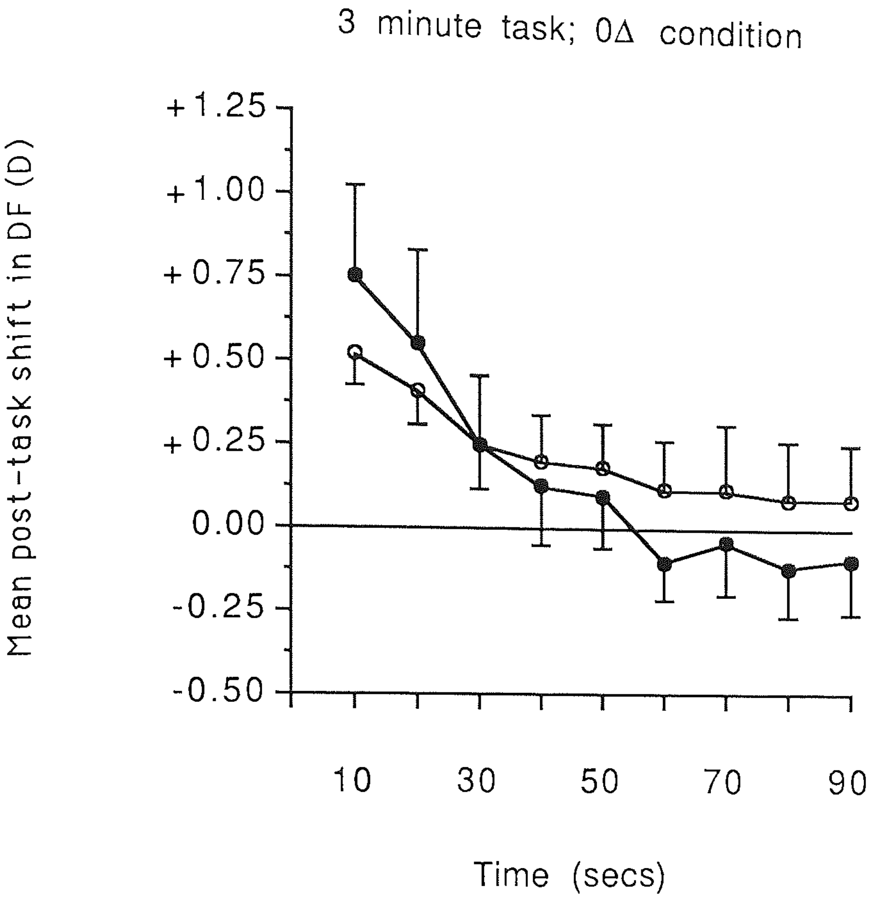

Fig. 8.12 Mean post-task dioptric shift in dark-focus (DF) against time for 10 emmetropes (filled circles) and 10 LOMs (open circles) for the 90s period immediately following completion of a 3min task (3D) in the absence of any supplementary disparity-stimulus (0Δ). Error bars indicate ±1 SEM.

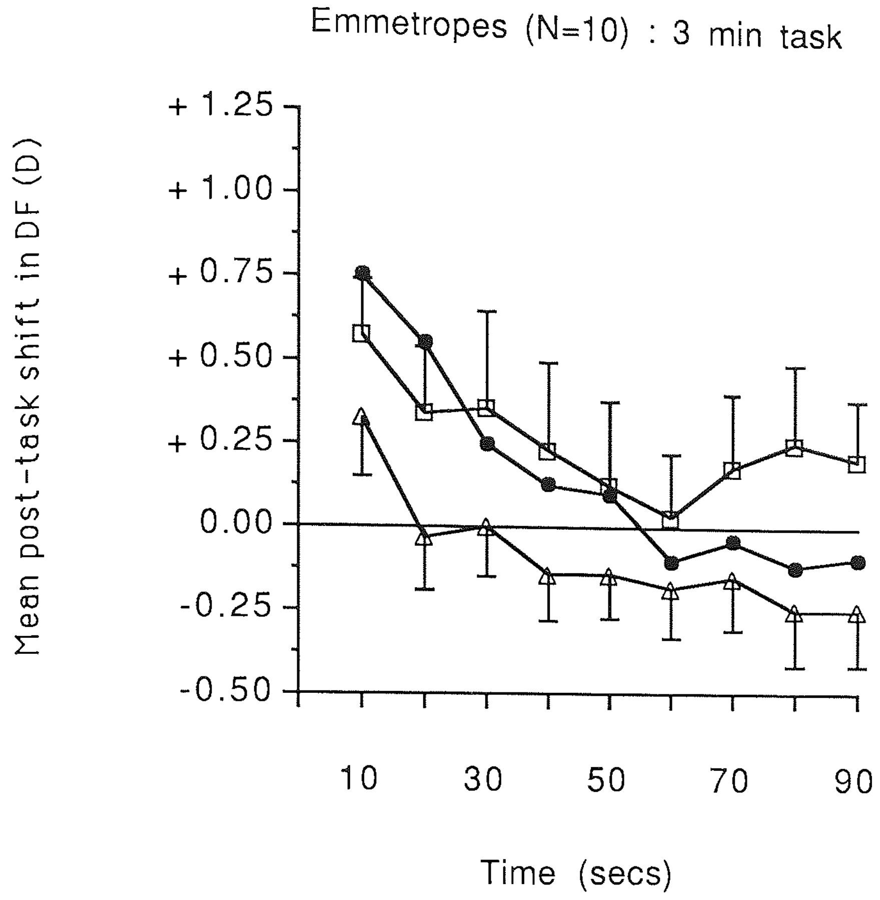

Fig. 8.13. Mean post-task dioptric shift in DF against time for the three disparity-stimuli (0Δ: filled circles; 3Δ: open squares; 6Δ: open triangles) following the 3min near-vision task in 10 emmetropic subjects. Error bars indicate ±1 SEM.

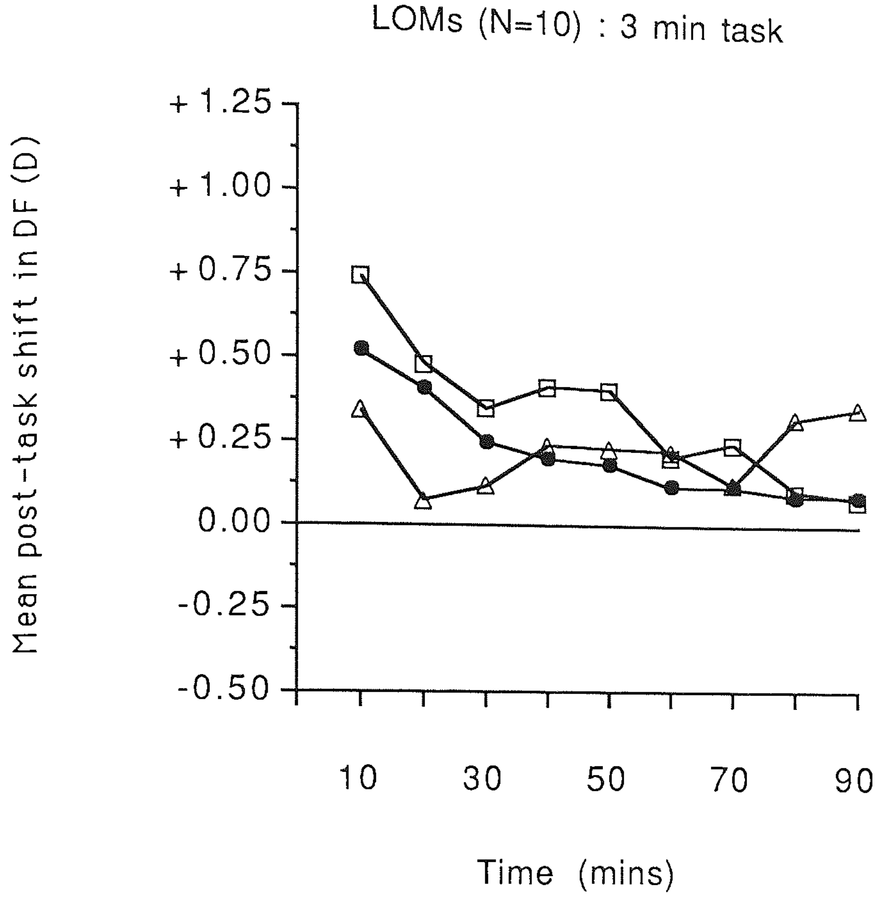

Fig. 8.14. Mean post-task dioptric shift in DF against time for the three disparity-stimuli (0Δ: filled circles; 3Δ: open squares; 6Δ: open triangles) following the 3min near-vision task in 10 LOMs. Error bars have been omitted for clarity but SEMs were of the order of ±0.16.

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group, F=10.45; df=1,54; p<0.01: disparity stimulus, F=7.60; df=2,54; p<0.01). The second order interactions were not significant.

The effect of task duration on the TRP of emmetropes under the 0Δ disparity condition is shown in Fig. 8.15. There was no significant difference in accommodative adaptation for the two task durations. TRPs following the 10 minute task are illustrated in Fig. 8.16 (emmetropes) and Fig. 8.17 (LOMs). In emmetropes, increasing disparity ceased to produce a significant change in DF adaptation suggesting that prism adaptation had taken place. In LOMs however disparity continued to induce changes in TRP although again the variable response for the 6Δ stimulus should be noted. Analysis of variance indicated that the effect of disparity on the TRP of LOMs after the 10 minute task (Fig. 8.17) was significant (F= 4.84; df=2,27; p<0.01). In emmetropes, only the time factor

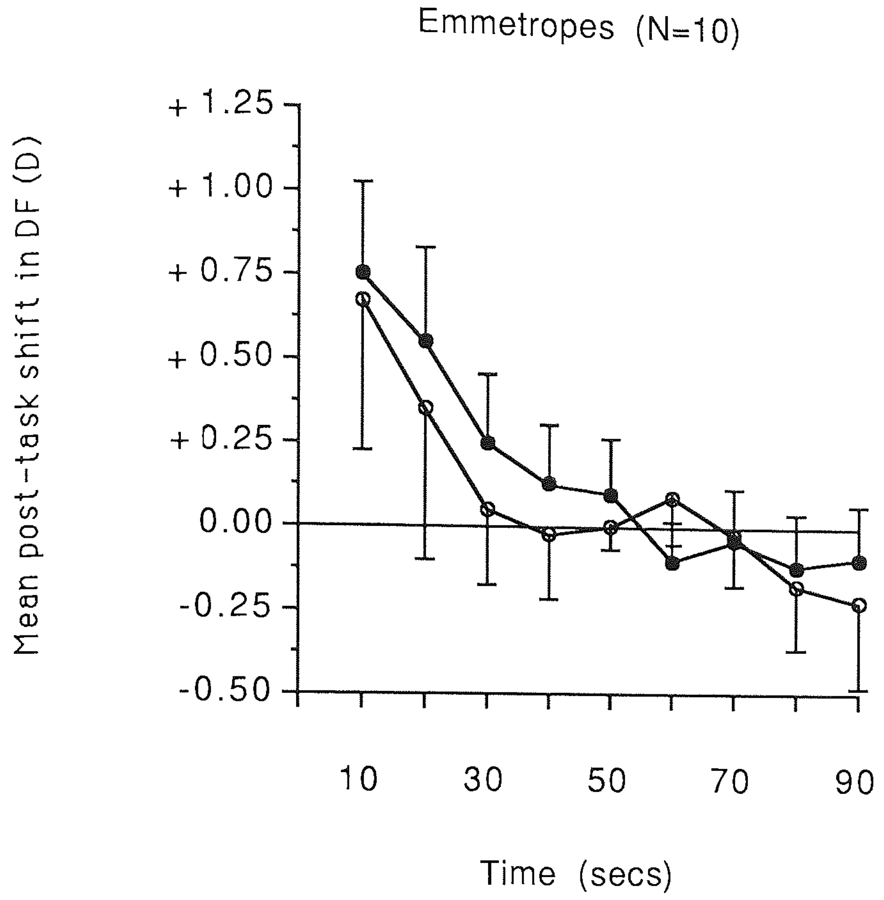

Fig 8.15. Mean post-task dioptric shift in DF against time following the 3min (closed circles) and 10 min (open circles) near-vision tasks in the absence of supplementary disparity-stimulus (0Δ). Error bars indicate ±1SEM.

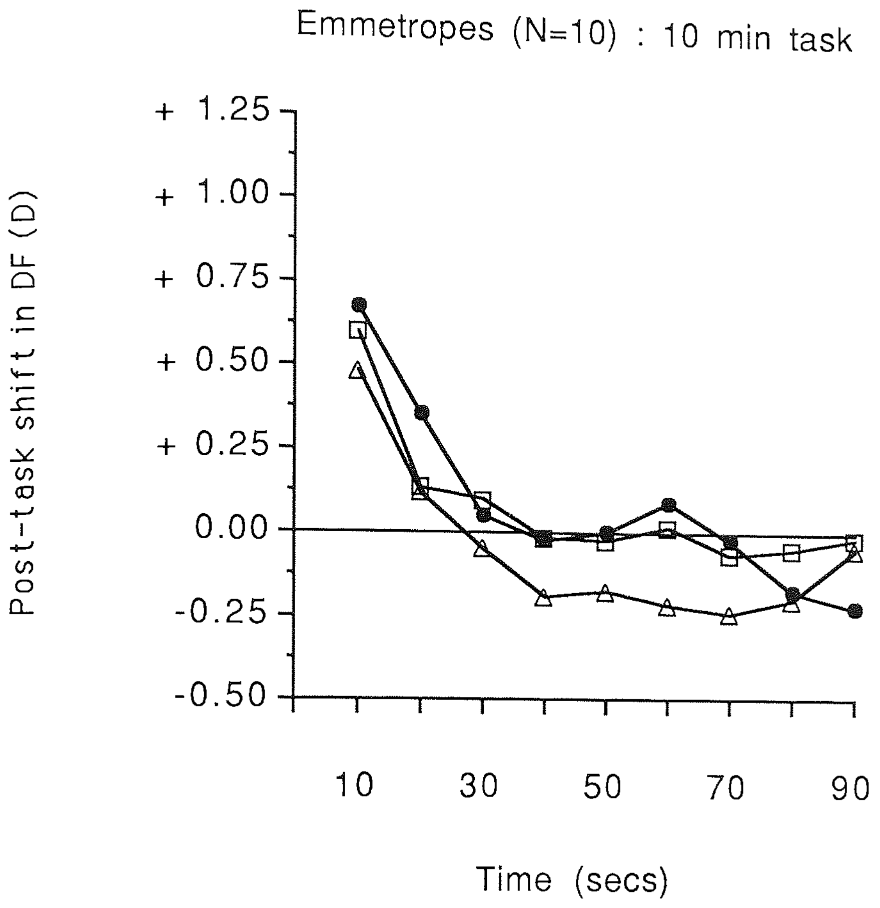

Fig. 8.16 Mean post-task dioptric shift in DF against time for the three disparity-stimuli (0Δ: closed circles; 3Δ: open squares; 6Δ: open triangles) following the 10min near-vision task for 10 emmetropic subjects. Error bars have been omitted for clarity but SEMs were of the order of ±0.15.

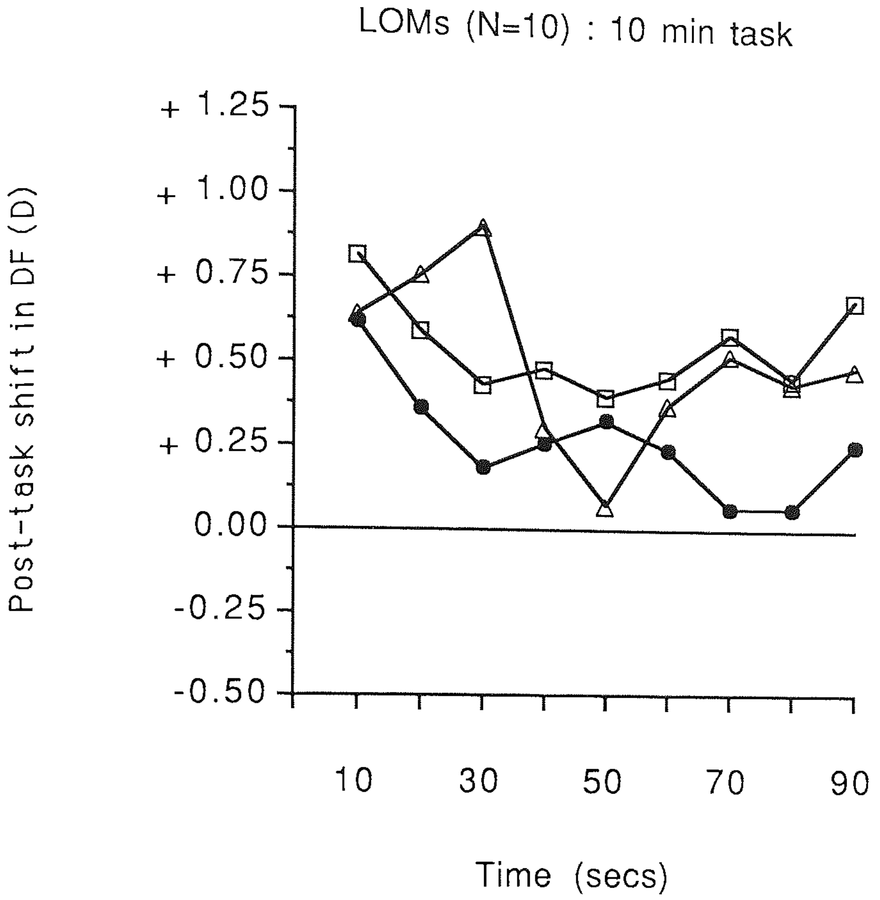

Fig. 8.17 Mean post-task dioptric shift in DF against time for the three disparity-stimuli (0Δ: closed circles; 3Δ: open squares; 6Δ: open triangles) following the 10min near-vision task for 10 LOMs. Error bars have been omitted for clarity but SEMs were of the order of ±0.21.

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was significant in analysis of the TRP following the ten minute task (F=4.49; df=8,27 ; p<0.01).

8.8 DISCUSSION

It has been demonstrated that LOMs exhibit higher levels of disparity-induced accommodation (DA) compared with emmetropes. This supports the findings of the previous study (see Fig. 8.3) which demonstrated higher levels of DA in LOMs over a 50 second period. This increased DA may result from either the presence of an increased CA/C ratio in LOMs or from an altered interaction between DA and blur-induced accommodation (see section 8.4). Further discussion on the assessment of the CA/C ratio in a myopic population appears in Chapter 9.

It is perhaps surprising to note that the difference in DA observed in LOMs is maintained during the course of the task (see Fig. 8.10). It might have been predicted that subjects would adapt to the presence of the prism and thereby attenuate the differences in DA. Henson and North (1980) noted that following the introduction of a 6Δ base-out prism, the induced change in heterophoria was reduced by approximately 50% after about 1 minute of binocular viewing. However only one of the subjects used in that study was myopic and it may be that LOMs show poorer prism adaptation when compared with emmetropes. In the model of accommodation-vergence interaction proposed by Schor and Tsuetaki (1987), subjects having reduced AC/A and increased CA/C ratios would be predicted to have good accommodative adaptation and poor vergence adaptation. It might therefore be expected that LOMs would have poorer prism adaptation and this study would appear to support that prediction. Recent work by North (personal communication) provides evidence for differences in vergence adaptation between LOMs, EOMs and emmetropic subjects.

The observation of a reduced accommodative response for LOMs in the 0Δ condition (Fig. 8.11) supports the work of both McBrien and Millodot (1986a) and Bullimore and Gilmartin (1987d). The reduced response may indicate a greater proportion of disparity-driven accommodation in the normal accommodative response of LOMs when compared with emmetropes. The case for an enhanced disparity-drive is supported by the finding that there was no significant difference in AR between LOMs and emmetropes following stimulation of retinal disparity i.e. in the 3Δ and 6Δ conditions.

It has been observed that an increase in disparity-induced accommodation (DA) produced a reduction in the post-task shift in dark-focus (DF) in emmetropic subjects (see Fig. 8.13). This result would not have been predicted from the previously reported effect of convergent accommodation (CA) on DF adaptation (Schor and Kotulak, 1986; Wolfe and O'Connell, 1987): these studies demonstrated that CA produced an increase in accommodative adaptation. The difference between DA and CA should again be noted: DA is induced with both accommodation and vergence closed-loop. Additionally the subjects used by Wolfe and O'Connell (1987) were not all emmetropic and this study has demonstrated that differences in accommodative adaptation can occur between LOMs and emmetropes. Therefore an averaged response for subjects of mixed ametropia may well show differences in adaptation when compared with emmetropes alone. Furthermore Wolfe and O'Connell recorded the post-task accommodative response at an unspecified time within the 90s post-task period and Figs. 8.12-8.17 demonstrate considerable variation in accommodative adaptation during this post-task period.

The introduction of a vergence stimulus will induce retinal disparity and hence produce a vergence response in order to eliminate this disparity. The vergence response will induce convergent accommodation and may require a relaxation of blur-driven accommodation in order to keep the target clear i.e. to maintain the aggregate accommodative response constant. The data illustrated in Fig. 8.9 indicated that the introduction of 3 or 6Δ base-out prisms under closed-loop conditions did not produce any significant change in the net accommodation response during the course of the 10 minute near-vision task in emmetropic subjects.

The reduction in post- to pre-task shift in DF with increasing disparity-vergence (Fig. 8.13) indicated a reduced output of adaptive accommodation with increasing DA . The increase in DA is likely to be accompanied by a reduction of blur-driven accommodation in order to maintain the net accommodative response. As this decrease in blur-driven accommodation results in a reduction in post-task accommodative adaptation; this suggests that under closed-loop conditions, within-task changes in adaptive accommodation are stimulated by the action of the blur (or non-vergence) reflex components of the accommodation response only i.e. reflex accommodation not induced by the near-response cross-link. This suggestion is consistent with the model of accommodation-vergence interaction proposed by Ebenholtz and Fisher (1982) which indicated that the innervation to the adaptive components of accommodation and vergence occurs prior to stimulation of the near-response cross-links i.e. accommodative convergence (AC) and convergent accommodation (CA).

If it is indeed the case that the accommodation-vergence cross-links occur after innervation to adaptive accommodation and vergence, then one would predict that the output of CA and AC would not be affected by the onset of adaptive accommodation and vergence respectively. However Schor (1986) proposed that the near-response cross-links receive input from the reflex elements only i.e. reflex accommodation driving AC and reflex vergence driving CA. Further discussion on the position of the near-response cross-links within a model of accommodation-vergence interaction appears in Chapter 9.

If the adaptation of DF (i.e. onset of adaptive accommodation) is directly stimulated by the output of blur-driven accommodation only, then this may explain the lower level of accommodative adaptation seen in LOMs in the absence of supplementary vergence drive (Fig. 8.12). It has been demonstrated that LOMs exhibit greater levels of DA during the course of a near-vision task when compared with emmetropes. It has also been observed that LOMs have a reduced aggregate accommodation response (Fig. 8.11). Thus the normal net accommodation response of LOMs may contain a greater proportion of disparity-induced accommodation and less blur-driven accommodation.

The observation of reduced accommodative adaptation in LOMs supports the finding of Fisher et al (1987b) who reported a smaller change in DF in low myopes compared with emmetropes. It is also consistent with the study of Gilmartin and Bullimore (1987) who noted that the post-task regression pattern (TRP) of DF following a 10 minute near-vision task (5D) varied with respect to pre-task DF. In subjects with pre-task DF greater than +0.55D (N=8), TRP reached the pre-task level within 30-40 seconds post-task whereupon DF became negative with respect to pre-task values. However in those subjects having pre-task DF less than +0.55D (N=7), the TRP did not attain negative values at any point. Whilst all the subjects used in that particular study were emmetropic, it has been shown that LOMs tend to have a lower level of pre-task DF with respect to emmetropes; hence it might be predicted that the TRP in LOMs would be similar to those emmetropes having a reduced pre-task DF.

It is shown in Fig. 8.15 that there was no significant difference between the TRPs in emmetropes following the 3 and 10 minute tasks in the absence of supplementary disparity-stimuli. This would indicate that adaptation is complete within 3 minutes of the commencement of the task. Schor et al. (1984) examined the effect of two durations of accommodative adaptation on DF: a short-term period of less than 2 minutes and a long-term period of 30 minutes. They reported that the short adaptation period did not produce any consistent after-effects in 3 subjects whilst the 30 min. adaptation did produce an increase in DF for 9 subjects. It should be noted that Schor's study was performed monocularly and therefore the crosslink inputs to accommodation were removed. Further discussion on temporal aspects of accommodative adaptation appears in Chapter 10.

It would appear from Fig. 8.16 that after a 10 min period the emmetropic subjects have fully adapted to the base-out prism and hence there was no significant difference in the three TRPs obtained for differing levels of disparity. LOMs however continued to show a significant effect of disparity on TRP (Fig. 8.17) suggesting that they have not fully adapted to the prisms. The suggestion of a reduced level of vergence adapatation in LOMs is consistent with the observation of sustained differences in disparity-induced accommodation over the course of the ten minute task in LOMs (Fig. 8.10).

The sustained post- to pre-task shift in DF for LOMs together with a reduced TRP gradient (see Fig. 8.11) may indicate differences in temporal aspects of accommodative adaptation in LOMs and emmetropes: sustained TRPs in LOMs resulting from a failure to relax adaptive accommodation. The increased demand for reflex accommodation during periods of sustained near-vision may, over a period of time, induce near-point stress. The onset of myopia could then be an adaptation in order to reduce this accommodative demand. Fisher et al. (1987a) investigated adaptation of DF in 32 subjects, 16 subjects reporting near-vision symptoms and 16 asymptomatic subjects. They noted that the asymptomatic group showed rapid adaptation of DF during the course of a 45 minute near-vision task (working distance=5D); accommodative adaptation being completed within 5 minutes of the commencement of the task. The symptomatic group however continued to show an increase in DF adaptation throughout the 45 minute task. Fisher et al. suggested that subjects having slow onset of adaptive accommodation would require a higher level of active (reflex) accommodation and vergence during near-vision and this may relate to the onset of asthenopic symptoms.

8.9 CONCLUSIONS

Differences have been demonstrated in accommodative adaptation between emmetropes and LOMs following stimulation of disparity-induced accommodation. However it remains unclear exactly how these changes relate to the aetiology of late-onset myopia. It has also been observed that the differences in disparity-induced accommodation may relate either to variation in the convergent accommodation / convergence (CA/C) ratio or to an altered interaction between the individual components of the combined accommodative response. In an attempt to clarify this issue, the CA/C ratio was directly measured by opening the accommodation loop. This study will be discussed in Chapter 9.

CHAPTER 9

ASSESSMENT OF THE CONVERGENT ACCOMMODATION/CONVERGENCE (CA/C) RATIO IN A MYOPIC POPULATION

9.1 INTRODUCTION

In Chapter 8 two studies were described which examined accommodation- vergence synkinesis with both oculomotor systems closed-loop. Differences in disparity-induced accommodation, i.e. accommodation driven by vergence under closed-loop conditions, were observed between LOMs and emmetropes during task durations of 50 secs and 10 mins respectively (Rosenfield and Gilmartin, 1987d and 1988b). However it remains unclear whether the observation of increased disparity-induced accommodation in LOMs relates to an increased convergent accommodation/convergence (CA/C) ratio or to variation in the interaction between individual elements of the combined accommodative response (see Section 8.4). In order to clarify this issue, the CA/C ratio was directly measured by placing the accommodation system into an open-loop state.

The CA/C ratio has not received the same degree of attention as other oculomotor parameters due to the difficulties in its clinical assessment. For a review of previous techniques of measurement see Kent (1958) and Kersten and Legge (1983). Recent studies have used laser (Kersten and Legge, 1983) and infra-red (Schor and Kotulak, 1986; Tsuetaki and Schor, 1987) objective optometers to assess the accommodative response while maintaining accommodation under open-loop conditions i.e. with negative feedback mechanisms removed.

The CA/C ratio may be examined clinically by using dynamic retinoscopy to assess the accommodative response. The accommodation loop was "quasi opened" (Schor, 1983a) by viewing a target at a working distance of 40 cm through a +3.50DS lens. Thus the subject was effectively blurred by 1D. Using the monocular estimate method

(Weisz,1980) minus lenses of increasing power are introduced until a neutral reflex is observed. This method of dynamic retinoscopy is performed at different vergence stimulus levels in order to determine the CA/C ratio.

An alternative method of opening the accommodation loop under clinical conditions utilizes the binocular cross cylinder test. Owens (1979) noted that when two differing accommodative stimuli are presented simultaneously, the accommodative response brings into focus that stimulus which is dioptrically closer to the position of dark-focus (DF). If the position of the cross cylinder foci are arranged to fall equidistant from DF by means of spherical lenses, then the accommodative response will not be biased towards either of the cylinderical foci. Thus on viewing a grid pattern, both the horizontal and vertical lines would appear to be equally blurred and hence the grid would not act as a stimulus to blur-driven accommodation. The CA/C ratio can then be determined by measuring the accommodative response while viewing the grid at differing vergence stimulus levels. However the repeatability of both the monocular estimate method and cross-cylinder techniques in the assessment of the CA/C ratio has recently been questioned (Waugh, 1986).

Tsuetaki and Schor (1987) demonstrated that a low spatial frequency (0.2 cpd) difference of Gaussian (DOG) target did not constitute a stimulus to blur-driven accommodation. They used a DOG target to open the accommodation loop and measured the CA/C ratio by recording the accommodative response while viewing the target at different vergence stimulus levels. The accommodation response was measured using both dynamic retinoscopy and an objective infra-red optometer and they observed a high correlation (r=0.92) between the CA/C values obtained using these two methods.

The present study has examined the CA/C ratio in a population of myopic and emmetropic subjects. The myopic subjects were subdivided into late-onset myopes

(LOMs) i.e. onset of myopia at fifteen years of age or later, and early-onset myopes (EOMs) i.e. myopia onset prior to fifteen years of age* .

9.2 METHOD

Two methods were used to open the accommodation loop. In the first method the subject viewed a 0.1mm diameter white spotlight at distances of 33 cms and 1m in an otherwise dark room. The spotlight was created by mounting a laser drilled precision pinhole (Ealing Optical, Watford, U.K.; Catalogue no. 29-7127) in front of a tungsten filament source contained within a light-proof box. A sheet of 3mm thick ground glass (transmission ≈90%) was placed in front of the pinhole in order to blur the edges of the spotlight . This arrangement is similar to that described by Miller (1980). Miller used a 0.08mm diameter spotlight and demonstrated that this served as a stimulus to convergence but did not act as a stimulus to accommodation. Miller reported that the use of a larger spotlight (0.29mm diameter) failed to open the accommodation loop at viewing distances closer than 0.5m.

In a preliminary study on 10 emmetropic subjects, the 0.1mm spotlight was placed at viewing distances of 0.5, 1.0 and 2.0m in an otherwise dark room and the accommodative response of the left eye was measured objectively using the Canon Autoref R-1 infra-red optometer. Subjects viewed the target both monocularly and binocularly; target luminance being maintained at a constant level by the use of neutral density filters. The findings of this preliminary study are illustrated in Fig. 9.1. One-factor analysis of variance indicated that the binocular accommodative response varied significantly with stimulus distance (F=7.46; df= 2,29; $p < 0.01$). However there was no significant difference in the monocular accommodative response (F= 0.29; df=2,29; p=0.29). It should be noted that due to the low luminance of the stimulus, two of the subjects were unable to see the target at 2m. These findings indicate that the

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* This study will be published in the April 1988 edition of the American Journal of Optometry & Physiological Optics (see Appendix G) and was presented at the meeting of the American Academy of Optometry, Denver, Colorado, U.S.A. December 1987.

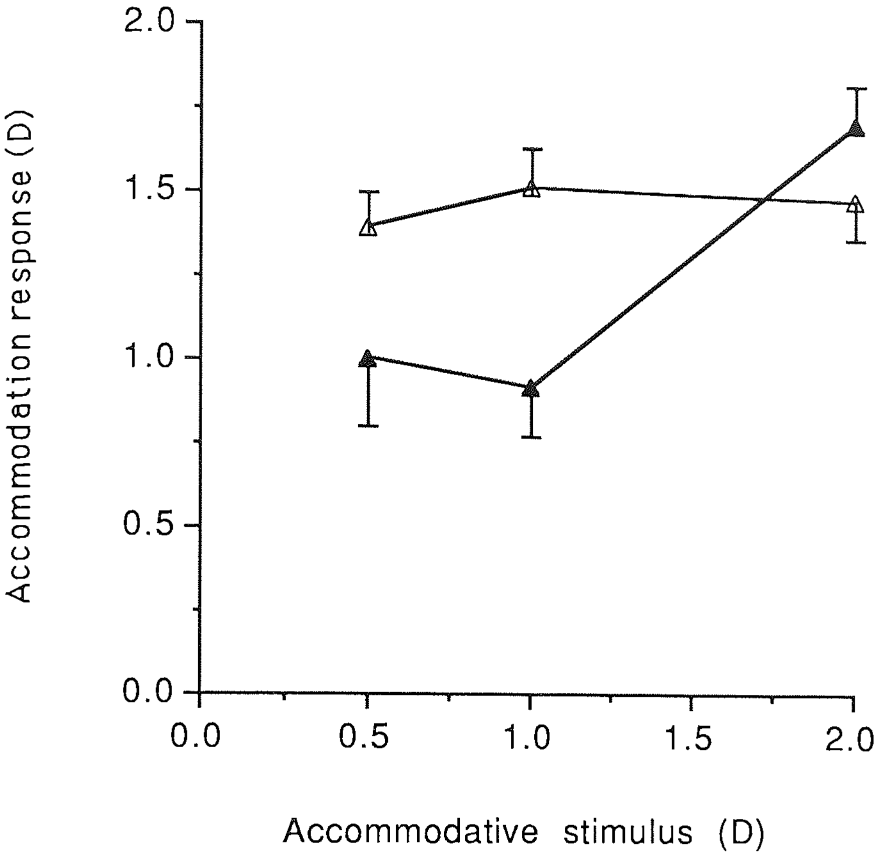

Fig. 9.1 Mean accommodative response for 10 emmetropic subjects viewing a 0.1mm diameter spotlight. Target luminance was maintained at a constant level for the three viewing distances by the use of neutral density filters. Open triangles indicate monocular viewing, closed triangles indicate binocular viewing. Accommodation was shown to be open-loop as there was no significant change in the accommodative response when the target was viewed monocularly. Under binocular viewing the accommodative response varied with stimulus distance, indicating that the target provided an adequate stimulus to vergence. Error bars indicate ±1 SEM.

monocular accommodative response was indeed open-loop whilst the changes in accommodative response under binocular viewing would suggest that the spotlight provided an adequate stimulus to vergence, the observed changes in accommodation being produced by convergent accommodation.

In the second method a technique was used to open the accommodation loop as described and evaluated by Ward and Charman (1987). The subject viewed near-type through 0.5mm pinholes at a viewing distance of 33cms. The target was back-illuminated by tungsten light through a green gelatine filter having a peak wavelength transmission of 490 nm and a halfwidth of approximately 30 nm. The pinholes were cut with a rotary drill into a Kodak Wratten 87 gelatine filter. The transmission of the Wratten filter was virtually zero for the 490nm stimulus but allowed transmission of an infra-red beam, thus allowing measurement of the refractive state to be made through the natural pupil using the infra-red optometer.

CA/C ratios were examined in thirty subjects (10 male, 20 female), all of whom were staff or students in the Department of Vision Sciences, Aston University. These consisted of 10 LOMs, 10 EOMs and 10 emmetropic subjects. The mean ages of each refractive group were for emmetropes 22.4 years (sd=3.07); for LOMs 22.7 years (sd=2.68); for EOMs 24.3 years(sd=3.65). One-factor analysis of variance indicated that the mean ages of the three refractive groups were not significantly different (F = 0.15; df= 2,29; p=0.86). The mean refractive error for the two myopic groups was LOMs -2.15D (sd=0.83) and EOMs -3.50D (sd=1.68). Emmetropic subjects all had unaided distance visual acuity of at least 6/6 with either eye and a mean sphere refractive error not greater than ±0.50D (with astigmatism not exceeding 0.50D). No subject had any major oculomotor imbalance (e.g. heterotropia, uncompensated heterophoria), asthenopic symptoms associated with near-vision or ocular pathology. Myopic subjects were corrected with ultra-thin soft contact lenses (Hydron 06) and an adaptation period of at least twenty minutes was allowed between lens insertion and the commencement of the experimental session. All myopic subjects could achieve visual acuity of at least 6/6 when corrected by the contact lenses.

For both techniques, convergence was induced by the introduction of 3 and 6Δ base-out prisms before the right eye. In a third condition (the control) the subject viewed the target through a plano lens (0Δ). The accommodative response of the left eye was measured objectively using the Canon Autoref R-1 infra-red optometer. Measures of accommodative response were calculated as mean spheres (i.e. sphere + half cylinder power). No correction factor has been added to the optometer reading.

9.2A SPOTLIGHT METHOD

At the beginning of the experimental session all subjects spent a period of ten minutes in total darkness in order to remove the effects of any visual activity prior to the experiment. The 0.1mm spotlight was then illuminated and prisms introduced in random order for the two working distances. The order of presentation of the two distances was also randomized. Ten readings of the accommodative response were taken over an eleven second period after which the vergence stimulus was changed in order to minimize prism adaptation. Measurement of the accommodative response commenced within five seconds of the introduction of the prism. Two periods of measurement were taken for each vergence stimulus (i.e. twenty readings) and the mean accommodative response calculated. The cycle was then repeated for the other working distance. Subjects were instructed to close their eyes while the prism or spotlight viewing distance was changed. There was an interstimulus period of approximately 15 seconds during which the subjects kept their eyes closed. This also served to minimize adaptational effects.

9.2B PINHOLE METHOD

Subjects were required to perform a counting task which consisted of the addition of a line of four high contrast (≈80%) two digit numbers, size equivalent to N6, which were placed at 33cms from the eyes. The numbers were printed onto a clear transparency and were illuminated as previously described. A 0.5mm diameter pinhole was placed before each eye and subjectively aligned by alternate occlusion in order to allow binocular viewing of the target. The vergence stimulus was introduced before the right eye and following completion of the counting task, five readings of the accommodative response were taken from the left eye using the infra-red optometer. The vergence stimulus was then changed and the cycle repeated. The counting task was performed continuously for a period of three minutes. Each individual cycle of the experiment took approximately 20 seconds and therefore three values of accommodative response were obtained for each vergence stimulus.

9.3 RESULTS

The values of CA/C ratio for the 0-6Δ vergence stimulus range are illustrated in Fig. 9.2 and are tabulated in Appendix 7. Values of CA/C are shown in units of dioptres accommodation/6Δ vergence stimulus as this approximates to units of dioptres/metre angle (D/MA).

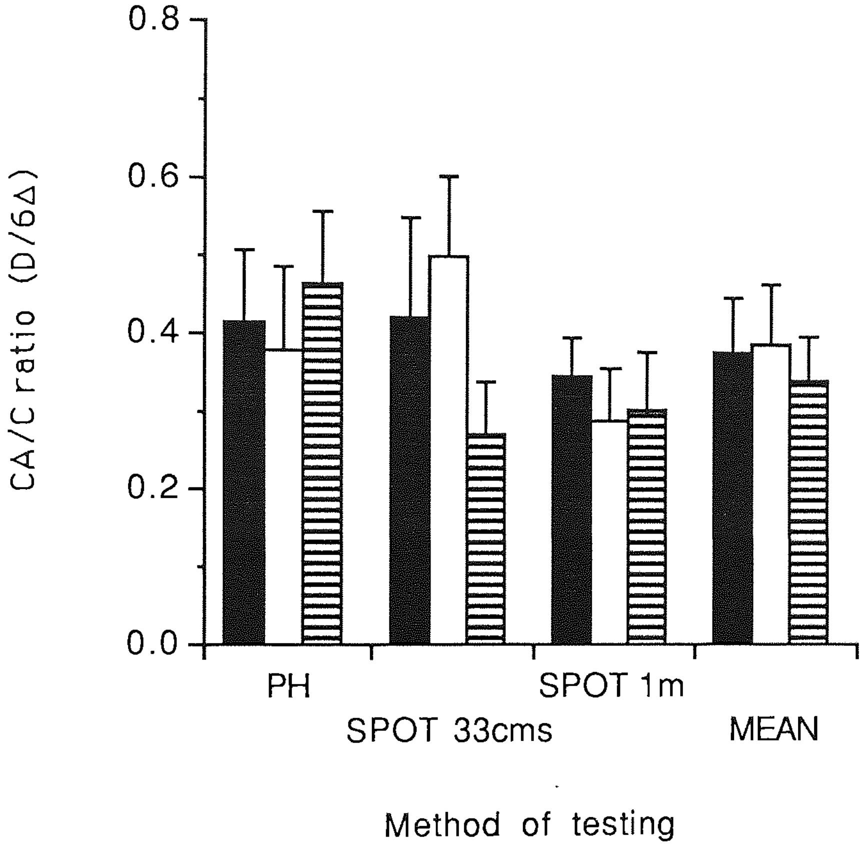

Fig. 9.2. Values of convergent accommodation/convergence (CA/C) ratio for each of the three refractive groups (Black bars: emmetropes; White bars:LOMs; Striped bars: EOMs) for the three techniques of measurement. PH: viewing near-type at a distance of 33cms through 0.5mm diameter pinholes. Spot 33cms: viewing 0.1mm diameter spotlight at viewing distance of 33cms. Spot 1m: viewing 0.1mm diameter spotlight at a viewing distance of 1m. Mean: mean value of CA/C from three techniques of measurement. Error bars indicate 1 SEM.

It is demonstrated in Fig. 9.2 that there was no significant difference in CA/C between the three refractive groups, nor was there any difference between the three methods of measuring the CA/C ratio. Two-factor analysis of variance (method, refractive group) indicated that neither of these factors was significant (method F= 1.11; df= 2,89; p=0.33: refractive group F=0.26; df=2,89; p=0.78). The mean values of CA/C for the three refractive groups (mean of three testing methods) were as follows: emmetropes 0.38D/6Δ (sd=0.21); LOMs 0.39D/6Δ (sd=0.25); EOMs 0.34D/6Δ (sd=0.17).

The values of CA/C ratio for the 0-3Δ vergence stimulus range were very similar to that recorded for the 0-6Δ stimulus range. The mean values of CA/C for the three refractive groups (mean of three testing methods) were as follows: emmetropes 0.39D/6Δ (sd=0.19); LOMs 0.38D/6Δ (sd=0.16); EOMs 0.41D/6Δ (sd=0.23). Two-factor analysis of variance (method, refractive group) again indicated that neither of these factors was significant (method F= 2.96; df= 2,89; p=0.06: refractive group F=0.06; df=2,89; p=0.94).

9.4 DISCUSSION

No significant difference in CA/C has been demonstrated between the three refractive groups examined. Thus the differences in disparity-induced accommodation previously demonstrated under closed-loop conditions between LOMs and emmetropes (see Chapter 8) cannot be accounted for by variations in the CA/C ratio.

Differences in disparity-induced accommodation may relate to variations in the relative proportions of blur-driven and disparity-induced elements of the aggregate closed-loop accommodative response. The net accommodative response of LOMs may contain a greater proportion of disparity-induced accommodation and less blur-driven accommodation when compared with emmetropes.

It should be noted that the values of CA/C ratio recorded in this study are significantly lower then the value of 1D/MA reported by Fincham and Walton (1957). However a number of other studies have also reported values of CA/C of less then 1D/MA e.g. Schor and Kotulak (1986) obtained CA/C ratios of 0.55D/MA and 0.45D/MA for two subjects from a step vergence stimulus of 10Δ. Hung and Semmlow (1980) reported a mean value of CA/C of 0.62D/MA in 4 subjects having an age range of 18-37 years and interestingly the lowest value of CA/C (0.47D/MA) occurred in the youngest subject. Morgan (1954) measured his own CA/C ratio using a similar technique to that of Fincham and Walton (1957) and obtained a value of 0.4 D/MA. It should be noted that Morgan described himself in that study as "pre-presbyopic", having an amplitude of accommodation of 5.5 D. Tsuetaki and Schor (1987) measured the CA/C ratio in six subjects, using both dynamic retinoscopy and an objective infra-red optometer to measure the accommodative response. They reported a mean value of 0.05 D/Δ for both measurement techniques. Taking a value of 6Δ = 1MA, this equates to a CA/C ratio of 0.3D/MA. Kersten and Legge (1983) noted that calculation of the slope of the convergence-accommodation relationship shown in the study of Miller (1980) would give a mean CA/C ratio of 0.53D/MA for 10 subjects.

It would seem likely that the aggregate accommodative response contains a proportion of the potential blur-driven and disparity-induced accommodative elements combined with tonic components. It is possible that the relative contribution of blur- or disparity-driven accommodation within the combined response may vary between different refractive groups while the CA/C ratio remains unaltered. This variation may account for the differences in disparity-and blur-induced accommodation previously demonstrated (see Chapter 8). These variations combined with differences in response AC/A (see Section 6.3) may account for differences between the near-response of the three refractive groups.

It has been suggested (Schor, 1983a) that CA/C ratios should be determined using base-in prism as this induces less prism adaptation when compared with base-out prism.

However Sethi (1986a) stated that on average, the rate of adaptation to base-in prism is faster at near although there was large inter-subject variation. However the effect of prism adaptation on CA is unclear. Schor (1983b) proposed that CA receives its main input from phasic (reflex) vergence but not from tonic (adaptive) vergence (see Section 8.4). As evidence for this proposal, Schor cited the study of Owens and Leibowitz (1980) which examined the effect of oculomotor adaptation on dark-focus (DF) and dark-vergence (DV). In that particular study, 60 subjects performed varying tasks for a twenty minute period while viewing through spectacles containing both -1.25DS lenses and 4Δ base-out prisms. This combination of lenses and prisms was adopted in order to stimulate approximately equivalent increases in accommodation and vergence. DF was assessed with a laser optometer while DV was measured by the vernier alignment of dichoptic lines produced by laser speckle patterns. Owens and Leibowitz observed that there was a significant increase in post-task DV (a mean increase of 43% for all task conditions) with respect to the pre-task level, but there was no significant change in DF. Schor (1983b) therefore concluded that prism adaptation (demonstrated by the increase in DV) has no significant effect upon DF.

Schor (1986) stated that the amplitude of CA is directly dependent upon the proportion of the vergence response driven by phasic (reflex) vergence. This implies that CA would vary inversely with the proportion of the response controlled by tonic (adaptive) vergence. Thus one would predict that the onset of adaptive vergence would, with the concomitant reduction in reflex vergence, produce a fall in the output of CA. In order to examine this proposal, a study was undertaken which measured CA during the course of a sustained near-vision task.

9.5 THE EFFECT OF VERGENCE ADAPTATION ON CONVERGENT ACCOMMODATION †

According to the model of accommodation-vergence interaction proposed by Schor (1983b), the stimulus initiating tonic (adaptive) vergence is the output of phasic (reflex) vergence. The onset of adaptive vergence is accompanied by a simultaneous reduction in reflex vergence in order to maintain the aggregate vergence response. Schor (1986) suggested that an analogous system may also exist for accommodation such that reflex accommodation provides a stimulus to adaptive accommodation. It has been suggested that the role of the adaptive components of the oculomotor response serve to maintain sustained single, clear binocular vision without excessive fatigue (Rosenfield and Gilmartin, 1988a) . Thus the reflex elements of accommodation and vergence are poised to respond to any subsequent rapid change in accommodation-vergence stimulus.

A number of independent studies have provided evidence for adaptation of both accommodation and vergence during periods of sustained near-vision. It has been demonstrated that adaptive changes in dark-focus (DF), see Section 2.5Aiii and dark-vergence (DV), see Section 3.7Aiii may be induced by periods of sustained near-vision. Immediately following the removal of a sustained near-vision stimulus, the reflex components of accommodation and vergence will dissipate rapidly (within 1-2 seconds) whilst the adaptive components will, due to their slower time course, exhibit a reduced rate of decay. It is likely therefore that the increases in DF and DV demonstrated following sustained near-vision tasks, relate to the output of adaptive accommodation and vergence respectively.

Further evidence for the adaptability of the vergence mechanism comes from the observation of adaptation to induced changes in heterophoria (for a review of vergence adaptation see Owens and Leibowitz, 1983 and Sethi, 1986a). Henson and North

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† This study will be published in the April 1988 edition of Ophthalmic & Physiological Optics (see Appendix H).

(1980) noted that, following the introduction of a 6Δ base-out prism in 8 subjects, the induced change in heterophoria was virtually abolished following 3-5 minutes of binocular viewing through the prism. Furthermore North and Henson (1985) observed adaptation to the heterophoria induced by negative spherical lenses. A -2.25DS lens was introduced for distance (4m) viewing in 4 subjects and they recorded a mean percentage adaptation to the induced esophoria of 49.5% after 3.5 mins of binocular viewing. North and Henson also examined adaptation to the heterophoria induced by ± 2.00DS lenses while viewing a near target (0.4m). Following 3.5 mins of binocular viewing they recorded mean percentage adaptation of 46.5% and 38.75% to the induced exophoria and esophoria respectively. Sethi (1986b) stated that heterophoria represented the adapted position of the vergence system, noting that with prolonged monocular occlusion (4 hours) there was a gradual increase in exophoria from the pre-occlusion level produced by the slow decay of adaptive vergence.

Neurophysiological evidence for vergence adaptation is evident from the work of Mays and Tello (1986). They monitored the electrical activity of a single convergence cell in three rhesus monkeys. Adaptive vergence was stimulated by an increase in vergence stimulus of 6° or 8°, heterophoria being periodically assessed in order to indicate adaptation. The relationship between the frequency of the cell's firing rate and the vergence requirement was computed and they demonstrated that vergence adaptation produced a reduction in this ratio. Approximately 80% of the convergence cells examined showed evidence of adaptation.

Neurophysiological evidence for accommodative adaptation is provided by the study of Törnqvist (1967) who observed the accommodative response in five adult cynomologus monkeys following electrical stimulation of the preganglionic oculomotor nerve. Törnqvist noted that in response to the optimum stimulation frequency, accommodation was fully developed in 1-2 secs and thereafter the accommodative response decreased for 10-30 secs until a steady state was reached. The decrease in accommodation during continuous oculomotor nerve stimulation was greater for the higher stimulation frequencies where a decrease in accommodation response of 1-2D was observed.

In this study convergent accommodation (CA) was measured during the course of a three minute near-vision task. Heterophoria was measured before and after the task in order to verify that vergence adaptation had indeed occurred. Thus any changes in stimulus to the near-response cross-links will be revealed as a change in the CA/C ratio.

9.6 METHOD

The accommodation loop was opened using the method described and evaluated by Ward and Charman (1987) and described in Section 9.3. The subject binocularly viewed near-type through 0.5mm pinholes at a viewing distance of 33cms. Convergent accommodation (CA) was examined in ten emmetropic subjects (3 male, 7 female), all of whom were staff or students in the Department of Vision Sciences, Aston University. The mean age of the subject group was 25.8 years (age range 21.2-31.8 yrs.; sd=3.66). All subjects had unaided distance visual acuity of at least 6/6 with either eye and a mean sphere refractive error not greater than ±0.50D (and astigmatism not exceeding 0.50D).

Convergence was induced by the introduction of a 6Δ base-out prism before the right eye. In a second condition (the control) the subject viewed the target through a plano lens (0Δ). The accommodative response of the left eye was measured objectively using the Canon Autoref R-1 infra-red optometer. Measures of accommodative response were calculated as mean spheres (i.e. sphere + half cylinder power). No correction factor was added to the optometer reading.

The subject was required to view a line of four high contrast (≈80%) two digit numbers, size equivalent to N6, which were placed at 33cms from the eyes. The subject viewed the near-target continuously for a three minute period. The numbers were printed onto a clear transparency and illuminated as previously described. A 0.5mm diameter pinhole was placed before each eye and subjectively aligned by alternate occlusion in order to allow binocular viewing of the target. Subjects were instructed to concentrate on a specific number selected by the experimental operator and to keep the target " sharply focused" at all times.

The vergence stimulus was introduced before the right eye and the accommodative response of the left eye was measured at approximately one second intervals over a three minute period. Before and after the near-vision task, assessment of the heterophoria was made using a Maddox rod which was placed before the right eye and in front of both the vergence stimulus and the 0.5mm pinhole. A small spotlight was introduced before the near-type (viewing distance 33cms) and a prism bar was used to measure the deviation of the streak. On completion a five minute rest period was allowed during which the subject was encouraged to look around the laboratory in order to dissipate previous adaptational effects. The experiment was then repeated for the second vergence stimulus. The vergence stimuli were introduced in random order.

9.7 RESULTS

Pre-and post-task values of heterophoria are illustrated in Fig. 9.3. A paired t-test indicated that the difference in pre-task heterophoria for the two vergence stimulus levels was significant ($t = 5.48$; $df = 9$; $p<0.001$). Introduction of the 6Δ base-out prism produced a mean difference in pre-task heterophoria of 6.7Δ. ($sd = 3.41$) However the two values of post-task heterophoria were not significantly different ($t = 0.68$; $df = 9$; $p = 0.52$) . These findings indicated that adaptation to the introduction of the 6Δ base-out prism had occurred within the three minutes of binocular viewing and supports the findings of Henson and North (1980).

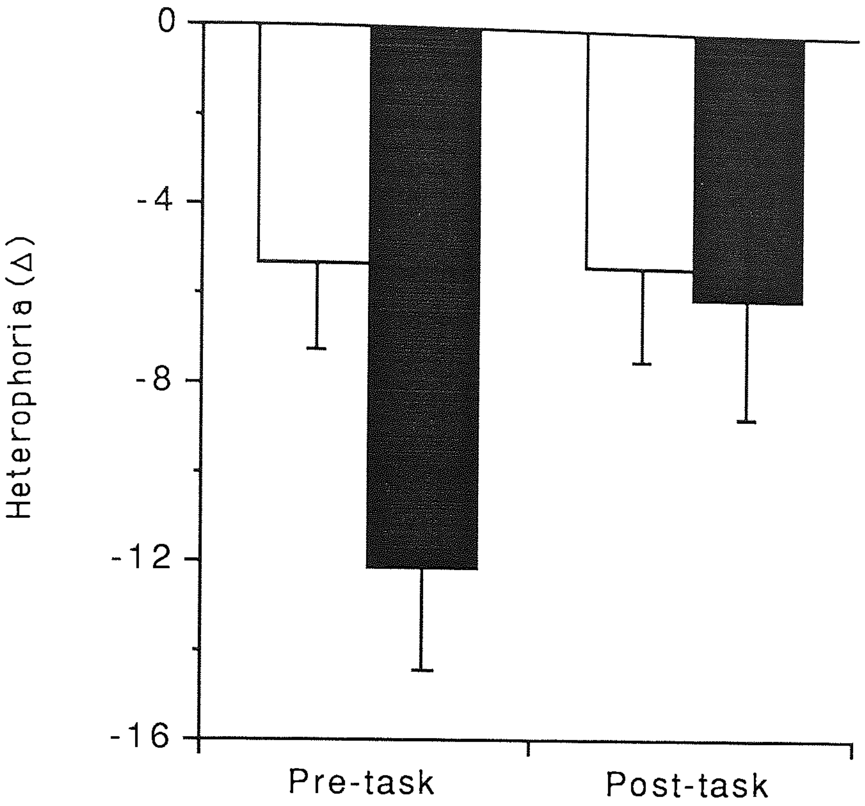


Fig. 9.3 Mean pre-and post-task measures of heterophoria (10 emmetropic subjects) measured for the two vergence stimulus levels(white bars: 0Δ; black bars: 6Δ base-out) measured with a Maddox rod and prism bar (viewing distance 33cms). Negative values indicate exophoria. There was no significant difference in post-task measures of heterophoria whereas the pre-task values were significantly different. This finding indicates that adaptation to the 6Δ base-out prism had taken place. Error bars represent ±1 SEM.

The accommodative responses for the two vergence stimuli are shown in Fig. 9.4. The mean accommodative response was calculated for each 10 sec period of fixation. Two-factor analysis of variance (vergence stimulus, time) indicated that the difference in accommodative response for the vergence stimuli was significant ($F=14.35$; df = 1, 16 ; $p<0.01$). Neither the time factor nor the interaction of time and vergence were significant in this analysis. It may be observed in Fig. 9.4 that for the 0Δ condition, there was a reduction in accommodative response during the first 90 secs of the task. However one-factor analysis of variance indicated that this reduction was not statistically significant ($F = 0.50$; df= 8, 89; $p=0.85$).

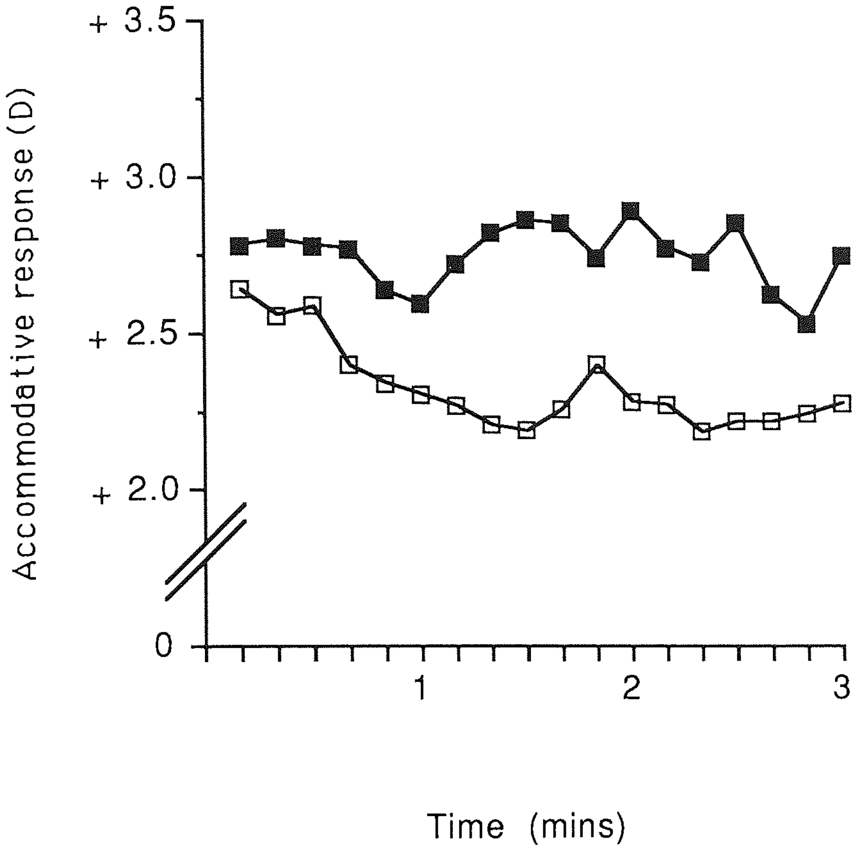


Fig. 9.4 Mean values (N=10) of accommodative response over the course of the 3 min near-vision task for the two vergence stimuli (open squares: 0Δ condition; closed square: 6Δ condition). The difference between the two accommodative responses represents the induced convergent accommodation (CA). Error bars have been omitted for clarity but SEMs were of the order of ±0.30.

The value of convergent accommodation (CA) may be calculated from the difference in accommodative responses for the two vergence stimuli. The level of CA during the course of the 3 min task is illustrated in Fig. 9.5. One-factor analysis of variance indicated that the change in CA with time was not significant (F=0.51; df=17, 179; p=0.95). As this value of CA is obtained from a vergence stimulus range of 6Δ ,the data shown in Fig. 9.5 represents the convergent accommodation/convergence (CA/C) ratio measured in units of D/6Δ. The mean value of CA/C during the three minute viewing period was 0.48 D/6Δ (sd = ±0.18). 1 metre angle (MA) is approximately equal to 6Δ,

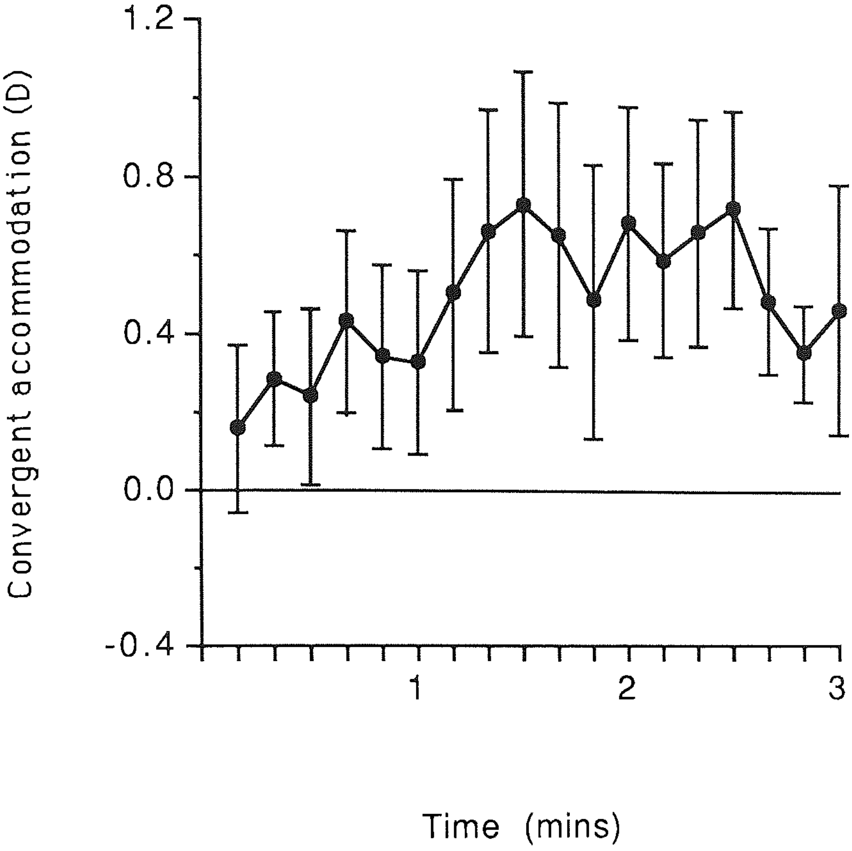


Fig. 9.5 Mean value (N=10) of induced convergent accommodation (CA) calculated from the difference in accommodative responses for the two vergence stimulus levels. As this value of CA is calculated from a vergence stimulus range of 6Δ, the illustrated values represent the CA/C ratio in units of D/6Δ. Taking 6Δ=1 metre angle (MA), this graph therefore represents the CA/C ratio in units of D/MA. Error bars represent ±1SEM.

therefore this value approximates to a value of CA/C ratio in units of D/MA. This compares with our previously reported value of 0.38D/6Δ (sd = ±0.21) for an emmetropic population (Rosenfield and Gilmartin, 1988c see Section 9.3) and is of a similar value to that reported by other studies (e.g. Hung and Semmlow ,1980; Schor and Kotulak, 1986; Tseutaki and Schor, 1987). The individual values of CA during the course of the near-vision task are presented in Appendix 8.

9.8 DISCUSSION

It has been demonstrated in Fig. 9.3 that adaptation to the 6Δ vergence stimulus has taken place within the three minute period of binocular viewing. However Fig. 9.5 clearly indicates that there is no reduction in the output of CA. Therefore one may conclude that CA is not driven by reflex vergence alone. As there is no reduction in CA over the course of the 3 minute task, it would seem reasonable to assume that CA is driven by the combined effects of the initial reflex vergence and the subsequent adaptive vergence.

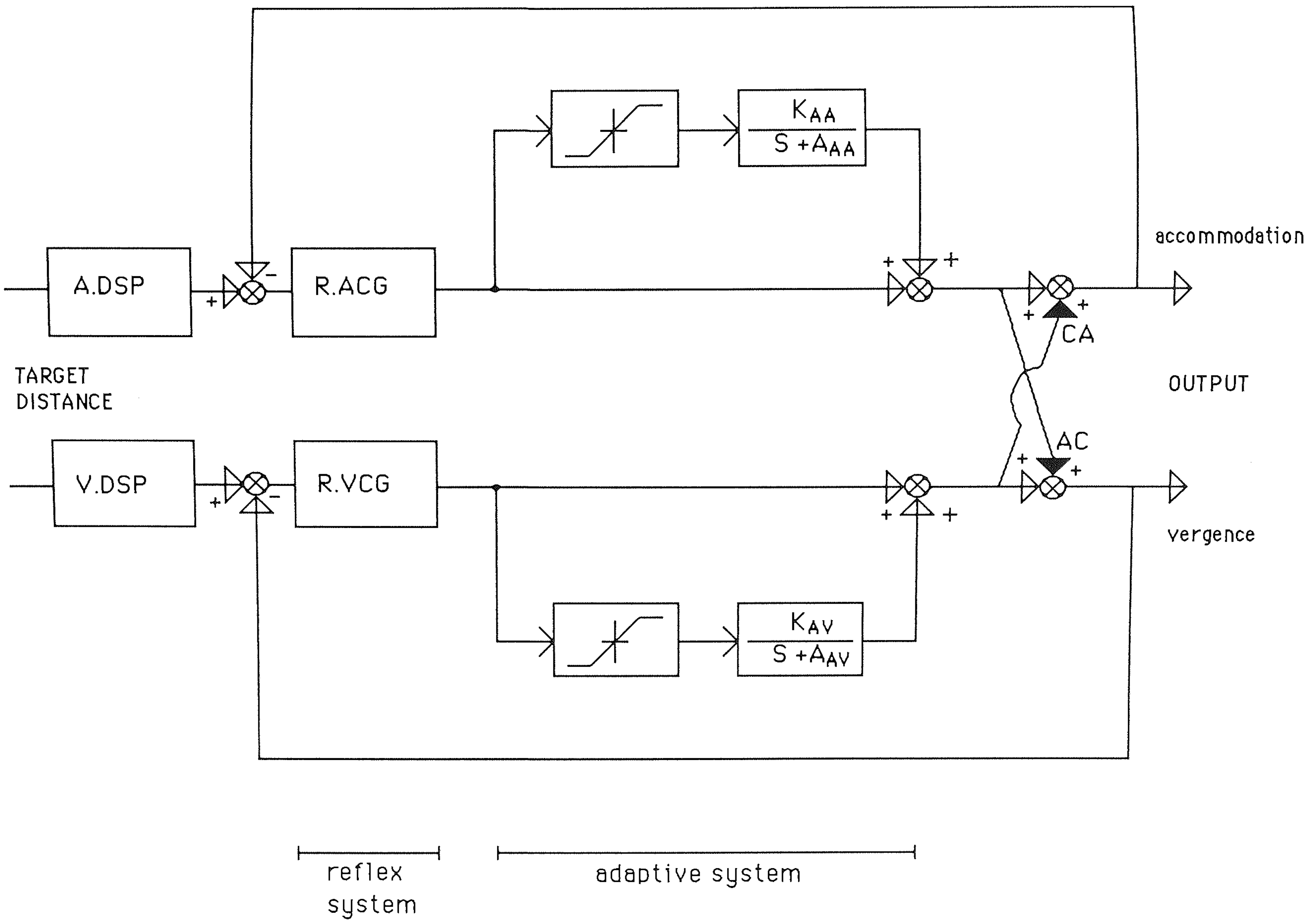
One might speculate that an analogous situation exists with regard to the accommodative response, that is AC is driven by both reflex and adaptive accommodation. Thus following adaptation to a sustained near-vision stimulus, both CA and AC would continue to contribute to the aggregate accommodation and vergence responses. If this were not the case, then following adaptation the accommodation and vergence responses would contain only blur-driven and disparity-induced elements respectively. However the findings of this study indicate that during periods of sustained near-vision the cross-link interactions do contribute to the aggregate near-response.

The above finding is consistent with the model of accommodation-vergence interaction proposed by Ebenholtz and Fisher (1982) which indicated that innervation to the tonic components of accommodation and vergence occurs prior to stimulation of the near-response cross-links. A revised version of this model is illustrated in Fig. 9.6. The accommodation and vergence dead-spaces refer to the steady-state error between the respective stimulus and response i.e. the accommodative lag and fixation disparity respectively. The reflex and adaptive components of accommodation and vergence are shown as operating in parallel with a time constant included to account for the slower onset of the adaptive elements. This model differs from that proposed by Schor (1986) in that the input to the cross-link interactions AC and CA is shown occurring after oculomotor adaptation. Thus both the reflex and adaptive components of accommodation and vergence drive their respective cross-links.

In a previous study (see Section 8.5), it was observed that under closed-loop

Fig. 9.6 Model of accommodation-vergence interaction for sustained near-vision based on the results of this study and previous investigations (Ebenholtz and Fisher, 1982; Rosenfield and Gilmartin, 1987d,1988a, 1988b). The crosslink interactions accommodative convergence (AC) and convergent accommodation (CA) are shown to occur after the input to the adaptational components of accommodation and vergence. Therefore the crosslinks receive input from both the reflex and adaptive elements. The reflex and adaptive mechanisms run in parallel although a time constant is included in the adaptational system in order to account for its slower time-course. The functions K_{AA} / S + A_{AA} and K_{AV} / S+ A_{AV} represent the exponential delay in the adaptive accommodation and vergence systems respectively (Toates, 1975). K_{AA} and K_{AV} represent the respective adaptive gain constants whilst A_{AA} and A_{AV} are constants which determine the rate of decay of the respective exponential response. Additionally the primary input to accommodation and vergence adaptation is shown as coming from their respective reflex components rather than from the crosslinks.

A.DSP: Accommodative dead-space
V.DSP: Vergence dead-space
R.ACG: Reflex-accommodation controller gain
R.VCG: Reflex-vergence controller gain
K_{AA} : Adaptive-accommodation gain
K_{AV} : Adaptive-vergence gain
A_{AA} : Reciprocal of decay time constant for adaptive accommodation
A_{AV} : Reciprocal of decay time constant for adaptive-vergence
AC : accommodative convergence
CA : convergent accommodation
S : Reciprocal of Laplace transform for a unit step input (Toates, 1975).


A.DSP
R.ACG
$\frac{K_{AA}}{S+A_{AA}}$
accommodation
CA
TARGET DISTANCE
OUTPUT
AC
V.DSP
R.VCG
vergence
$\frac{K_{AV}}{S+A_{AV}}$
reflex system
adaptive system
+
-

conditions, an increase in disparity-induced accommodation produced a reduction in accommodative adaptation in 10 emmetropic subjects. Accommodative adaptation was assessed by examining the post-task shift in dark-focus (DF) with respect to the pre-task value following a 3 minute near-vision task (viewing distance 33 cms) performed at different vergence stimulus levels. Increased vergence produced a reduction in post-task DF adaptation. It was suggested that the increase in disparity-induced accommodation was accompanied by a reduction in blur-driven accommodation in order to maintain the aggregate accommodative response. The decrease in accommodative adaptation may then have resulted from this reduction in the output of blur-driven accommodation. This finding would imply that the primary stimulus to oculomotor adaptation is not derived from AC and CA but from disparity-induced vergence and blur-driven accommodation. This is also consistent with the model of accommodation-vergence interaction proposed in Fig. 9.6. In this model the primary stimulus to the adaptive elements of accommodation and vergence originates from the reflex components.

Ebenholtz and Fisher (1982) examined the effect of blur-driven accommodation on vergence adaptation. Accommodation was stimulated by the introduction of negative spherical lenses before both eyes. Subjects (N=8) were required to walk around a hallway for a 15 min period. Vergence adaptation was assessed by measurement of the post-trial shift in heterophoria, measured with respect to the pre-trial value. Ebenholtz and Fisher observed that increasing blur-driven accommodation produced a decrease in vergence adaptation. This finding is again consistent with the model of accommodation-vergence interaction illustrated in Fig. 9.6. It would be predicted that under closed-loop conditions an increase in blur-driven accommodation would induce an increase in AC. This increase in AC would be accompanied by a decrease in disparity-vergence in order to maintain the aggregate vergence response. Thus the fall in disparity-vergence will be reflected as a reduction in vergence adaptation.

It should be noted that due to the activity of the negative feedback loops, AC and CA may have a secondary effect on oculomotor adaptation as the output of the crosslinks will produce an alteration in the requirement for blur-driven accommodation and disparity-vergence. However under stimulus-free conditions adaptive changes in accommodation and vergence would be independent due to the absence of feedback information. This is consistent with the previously reported finding that under darkroom conditions, there is no correlation between adaptational changes in DF and DV (Owens and Leibowitz, 1980; Gilmartin et al, 1984; Epstein et al, 1986).

Further evidence for the suggestion that crosslink interactions do not directly stimulate oculomotor adaptation is provided from the study of Henson and North (1980) which indicated that the rate of adaptation to 6Δ prisms was reduced for near viewing (0.5m working distance) when compared with distance fixation (4m). It would be expected that AC would comprise a greater proportion of the aggregate vergence response when viewing a near target compared with distance viewing. If AC does not act as a primary stimulus to vergence adaptation, then this may account for the reduced rate of adaptation at near.

9.9 CONCLUSIONS

The findings of the latter study indicate that both reflex and adaptive components of the near-response act as stimuli to the oculomotor cross-links. Thus the output of AC and CA will not be significantly affected by accommodative or vergence adaptation respectively.

Both the findings of the study reported in Section 8.7 and the model of accommodation-vergence interaction illustrated in Fig. 9.6 indicate that the primary input to accommodative adaptation comes from the output of blur-driven accommodation. It has been suggested (see Chapter 8) that differences may exist between LOMs and emmetropes in the relative proportions of components of the combined accommodative response. In order to examine this proposal, the effect of monocular and binocular viewing on accommodative adaptation was investigated and this study is reported in Chapter 10. Additionally temporal aspects of accommodative adaptation were examined in a population consisting of LOMs and emmetropes.

The observed differences in accommodation-vergence synkinesis between LOMs and EOMs may also be related to the stability of their respective refractive errors. All of the LOMs studied were of student age and therefore their myopia was of recent onset. Thus their refractive error may be less stable than that of the EOMs. The variations in oculomotor synkinesis between LOMs and EOMs might be a consequence of the changing refractive error rather than relating to the environmental or hereditary factors which induced the onset of myopia. If this is indeed the case, then following stabilization of the refractive error, one would predict that the differences between LOMs and EOMs would become attenuated. In order to examine this proposal, it would be necessary to conduct a longitudinal study in which myopia development and accommodation-vergence synkinesis are monitored simultaneously.

CHAPTER 10

TEMPORAL ASPECTS OF ACCOMMODATIVE ADAPTATION

10.1 INTRODUCTION

The study described in Section 8.5 used pre- and post-task measures of dark-focus (DF) to assess accommodative adaptation in 10 late-onset myopes (LOMs) i.e. myopia onset at 15 years of age or later and 10 emmetropes. The degree of accommodative adaptation was assessed following 3 and 10 min near-vision tasks, the tasks being performed at a viewing distance of 33cms. The post-task regression pattern (TRP) following the 3 min near-vision task was illustrated in Fig. 8.12. It was observed that whilst emmetropes initially show a larger shift in DF, they also exhibit a steeper TRP gradient when compared with LOMs. Immediately following the removal of a sustained near-vision stimulus, it is likely that the output of the reflex components of accommodation and vergence (see Section 8.4) will dissipate rapidly whereas the adaptive components, due to their slower time course, will exhibit a reduced rate of decay. The increase in DF following a near-vision task will therefore relate to the output of adaptive accommodation. Thus the regression of DF back to the pre-task value will indicate the rate of decay of adaptive accommodation. It was shown in Fig. 8.12 that the regression of DF in emmetropes was more rapid than that of LOMs. This finding may indicate differences in temporal aspects of accommodative adaptation between LOMs and emmetropes.

Fisher et al. (1987a) investigated the adaptation of DF in 32 subjects, 16 reporting asthenopic symptoms and 16 asymptomatic subjects. They noted that the asymptomatic group showed rapid adaptation of DF during the course of a 45 min near-vision task (viewing distance 20cms); accommodative adaptation being completed within 5mins of commencement of the task. The symptomatic group however continued to show an increase in DF adaptation throughout the 45min task. Fisher et al. suggested that subjects having slow onset of adaptive accommodation would require a higher level of active (reflex) accommodation and vergence during near-vision and this may relate to the onset of asthenopic symptoms.

Whilst variations in the post-task regression of DF have been demonstrated between LOMs and emmetropes, differences may also exist in the rate of onset of accommodative adaptation. If onset occurs later in LOMs, then a greater demand will be placed upon reflex accommodation. This may lead to near-vision stress and the development of late-onset myopia could provide a means of alleviating this stress by reducing the stimulus to reflex accommodation. In order to examine this proposal, accommodative adaptation was investigated in a population consisting of emmetropes and LOMs following relatively brief near-vision tasks. Three task durations were adopted namely 15, 30 or 45s. The durations selected were shorter than have been previously examined. However Schor et al. (1984) studied the effect of two task durations on accommodative adaptation: a short-term period of less than 2 mins and a long-term period of 30 mins. An infra-red optometer was used to measure the accommodative response. They reported that the short adaptation period did not produce any consistent after-effects in 3 subjects whereas the 30min adaptation produced a mean increase in DF in 9 subjects of 0.50D (assessed 45s following the removal of the adapting stimulus).

Additionally the relative influences of individual elements of the near-response on accommodative adaptation were examined by comparing the adaptation following near-vision tasks performed either monocularly or binocularly. Comparison of monocular and binocular adaptive changes may provide information relating to the role of disparity-induced accommodation within the aggregate accommodative response. Assessment of the convergent accommodation/convergence (CA/C) ratio has obtained values ranging between 0.4-1D/MA (Rosenfield and Gilmartin, 1988c; see Section 9.4) suggesting that the contribution of disparity-induced accommodation to the net accommodative response is substantial. However these values of CA/C ratio were obtained with accommodation in open-loop state and it may be that under closed-loop conditions, the aggregate accommodative response comprises only a proportion of the total disparity-induced accommodation available. Under monocular viewing it would seem likely that the degree of accommodative adaptation would be a function of the blur-induced accommodative response. However for binocular viewing, adaptation may relate to the actions of both blur-driven and disparity-induced accommodation. In a recent report, Fisher et al. (1987c) examined accommodative adaptation in 26 subjects following 10min near-vision tasks located at viewing distances of 6 and 10D. They observed no significant difference in adaptation between monocular and binocular viewing.

10.2 METHOD *

A total of twenty subjects were used (10 male, 10 female), all of whom were staff or students in the Department of Vision Sciences, Aston University. These consisted of 10 emmetropes and 10 LOMs. The mean age of the emmetropic group was 21.6 years (sd=1.57) and of the myopic group 22.3 years (sd=0.66). Mean refractive error for the LOMs was -2.30D (sd=0.98). The mean age of myopia onset was 15.9 years (sd=0.66). Emmetropic subjects all had unaided distance visual acuity of at least 6/6 with either eye and a mean sphere refractive error not greater than one half dioptre of myopia or hypermetropia (with astigmatism not exceeding 0.50D). No subject had any major oculomotor imbalance (i.e. heterotropia, uncompensated heterophoria), asthenopic symptoms or ocular pathology. Myopic subjects were corrected with ultra-thin soft contact lenses (Hydron 06) and an adaptation period of at least 20 mins was allowed before commencing the experiment. Each subject signed a consent form prior to taking part in this study and following a full explanation of all experimental procedures.

The accommodative response was measured objectively using the Canon Autoref R-1

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* This study has been submitted for publication to the American Journal of Optometry & Physiological Optics (see Appendix I) and will be presented at ARVO, Sarasota, Florida, U.S.A. May 1988 (see Appendix J).

infra-red optometer. All measures of accommodative response were taken from the left eye and readings were calculated as mean spheres (i.e. sphere + half cylinder power). No calibration factor has been added to the optometer reading.

Pre-task values of dark focus (DF) were measured according to the method described by Gilmartin and Bullimore (1987). The subject sat in total darkness for 10 minutes and following this period 10 readings of the refractive error were taken each minute for a period of 5 minutes. This gave a total of 50 readings which were then averaged. Pre-task DF was assessed with the subject fully binocular. Under stimulus-free conditions, the vergence response will not affect measures of pre-task DF. Owens and Leibowitz (1980), Gilmartin et al.(1984) and Epstein et al.(1986) found no correlation between the regression of DF and dark-vergence (DV) under darkroom conditions. It may therefore be concluded that DV does not act as a stimulus to DF.

Following measurement of pre-task DF, the subjects performed a near-vision task which consisted of viewing a 30 x12 matrix of high contrast (≈90%) letters, size equivalent to N5, which were placed at 33 cms from the eyes. Subjects were required to determine the frequency of a particular letter selected by the operator. A target luminance of 45cd m^{-2} was provided by a source located 1m above the target.

The near-vision task was performed either monocularly or binocularly; in the monocular condition the right eye was occluded and the occluder remained in position throughout the measurement of post-task DF. The task was performed continuously for a period of 15, 30 or 45 seconds. Subjects were randomly allocated to six trials comprising the three task durations, the task being performed monocularly or binocularly.

Immediately following completion of the near-vision task the illumination source was extinguished and the regression of accommodation towards pre-task DF was measured over a 90s period. The experimental sessions were separated by a period of at least

24 hours.

10.3 RESULTS

The mean value of pre-task DF for emmetropes and LOMs was +0.42D (sd=0.41) and +0.86D (sd=1.08) respectively. One-factor analysis of variance indicated that this difference was not significant (F=1.93; df=1,18; p=0.18). The observation of a higher level of DF in LOMs does not support previous studies (e.g. McBrien and Millodot, 1987b; Bullimore and Gilmartin, 1987d; Rosenfield and Gilmartin, 1987a) who all reported lower levels of DF in LOMs when compared with emmetropes. However the small sample size used in this study should be noted.

Post-task DF was determined for each of the 90s datum points and the mean value was calculated for each 10s period following completion of the near-vision task. Pre-task DF was subtracted from each of these values and the mean post-task regression pattern (TRP) of DF was computed. The mean values of pre-task DF together with the post- to pre-task shift in DF are tabulated in Appendix 9.

The TRPs following the monocular and binocular near-vision tasks for emmetropic subjects are illustrated in Figs. 10.1 and 10.2 respectively. Similarly the TRPs for LOMs are shown in Figs. 10.3 and 10.4 respectively. The increased value of DF for the initial 10s post-task period indicated that accommodative adaptation had occurred for all task durations.

Four-factor (time, task duration, binocularity and refractive group) analysis of variance indicated that time (F=7.69; df=7,96; p<0.01), task duration (F=6.09; df=2,96; p<0.01) and refractive group (F=11.93; df=1,96; p<0.01) were significant whereas binocularity was not significant (F=0.03; df=1,96; p=0.86). The second and third order interactions were not significant.

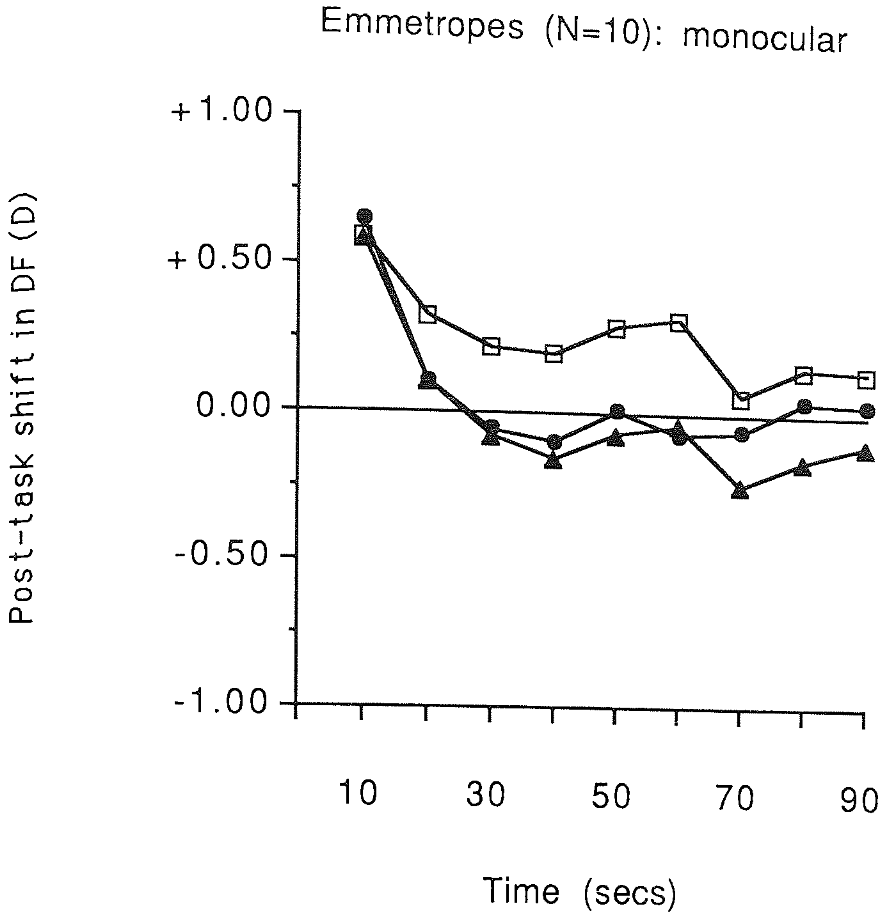

Fig. 10.1. Mean post-task dioptric shift in DF against time (monocular viewing) following 3 task durations (15s: filled circles; 30s: open squares; 45s: filled triangles) in 10 emmetropic subjects. Error bars have been omitted for clarity but SEMs were of the order of ±0.16.

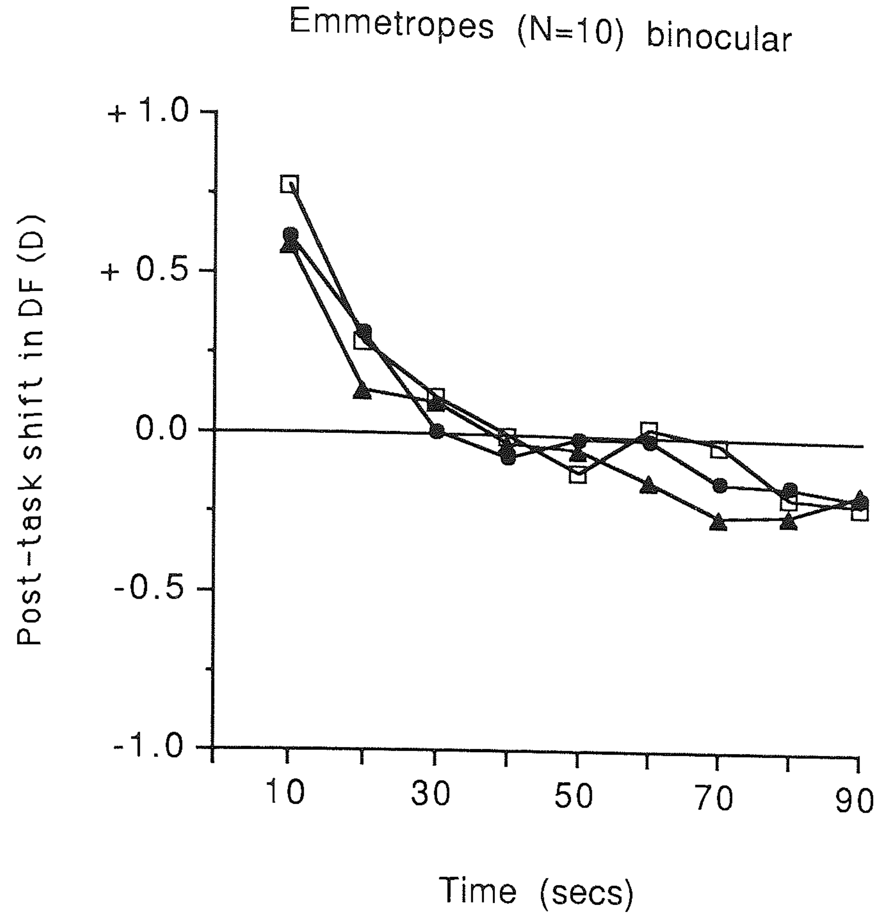

Fig. 10.2. Mean post-task dioptric shift in DF against time (binocular viewing) following 3 task durations (15s: filled circles; 30s: open squares; 45s: filled triangles) in 10 emmetropic subjects. Error bars have been omitted for clarity but SEMs were of the order of ±0.13.

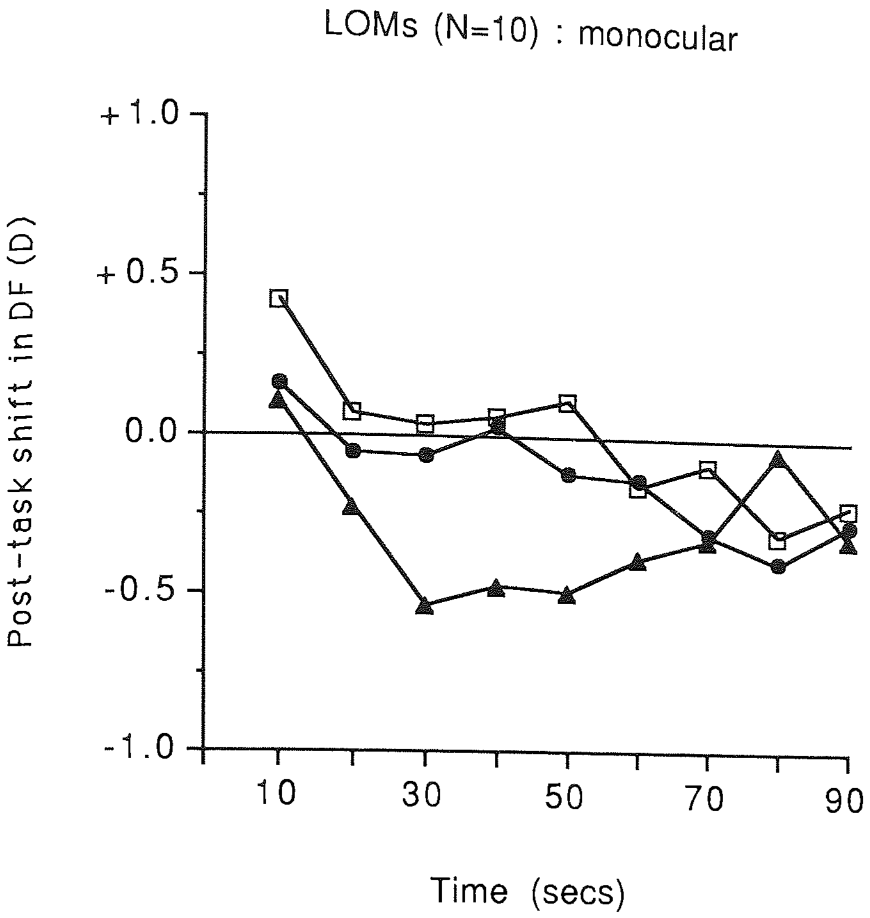

Fig. 10.3. Mean post-task dioptric shift in DF against time (monocular viewing) following 3 task durations (15s: filled circles; 30s: open squares; 45s: filled triangles) in 10 LOMs. Error bars have been omitted for clarity but SEMs were of the order of ±0.37.

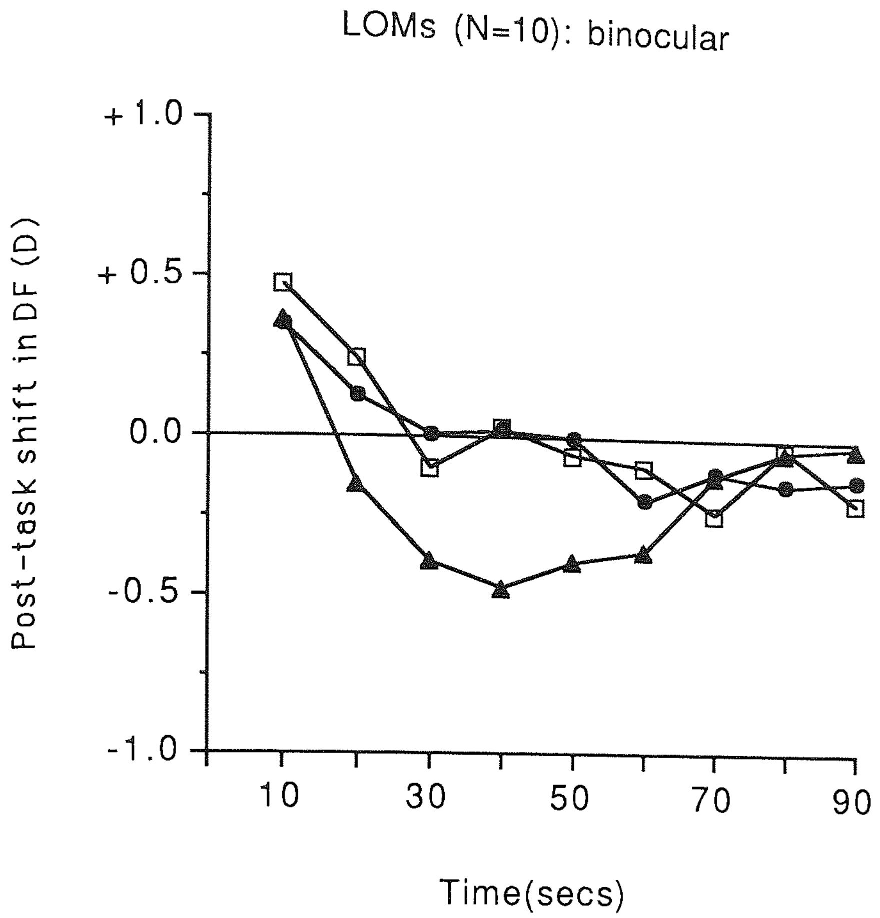

Fig. 10.4. Mean post-task dioptric shift in DF against time (binocular viewing) following 3 task durations (15s: filled circles; 30s: open squares; 45s: filled triangles) in 10 LOMs. Error bars have been omitted for clarity but SEMs were of the order of ±0.21.

A comparison of monocular and binocular accommodative adaptation following the 45s near-vision task is illustrated in Figs. 10.5 (emmetropes) and 10.6 (LOMs). Clearly there was no significant difference between monocular and binocular adaptation. However it should be noted that LOMs exhibited a marked negative shift in DF during the 10-50s post-task period following the 45s task which was not observed in emmetropes. Furthermore the shift in DF measured between 30 and 40s following completion of the near-vision task (45s duration) was negatively correlated with pre-task DF ($r = -0.85$; df $=19$; $p<0.001$). This correlation is illustrated in Fig. 10.7.

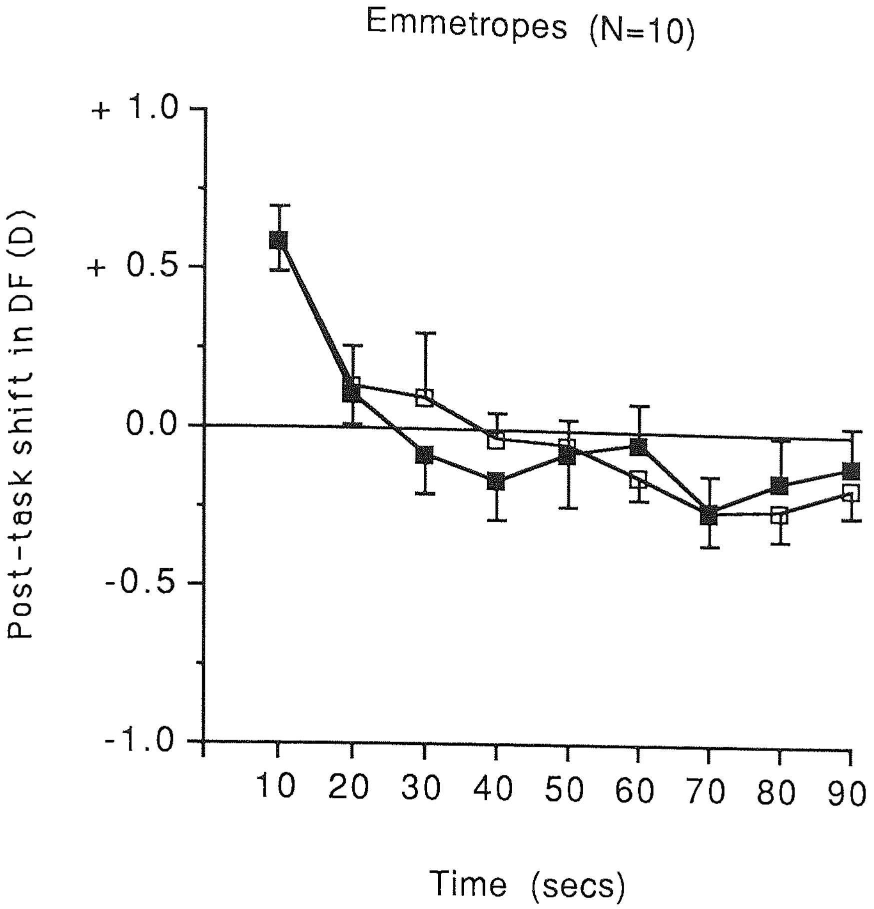

Fig. 10.5 Mean post-task dioptric shift in DF against time for 10 emmetropic subjects following completion of a 45s near-vision task, the task being performed monocularly (closed squares) and binocularly (open squares). Error bars indicate ±1SEM.

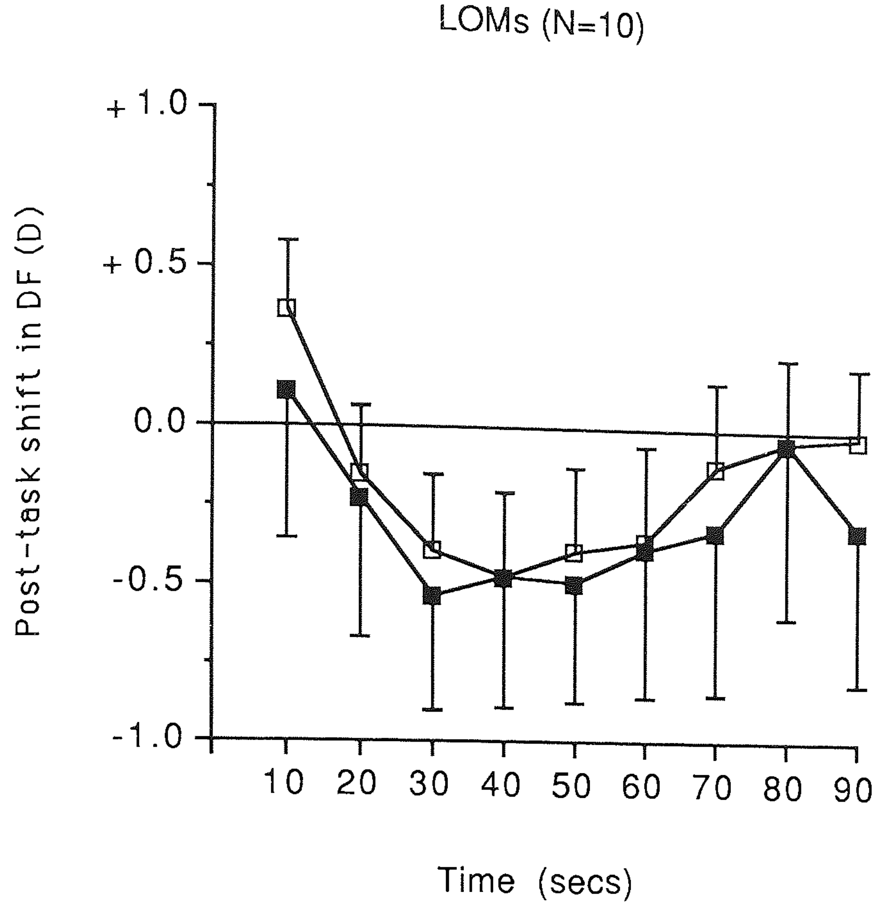

Fig. 10.6 Mean post-task dioptric shift in DF against time for 10 LOMs following completion of a 45s near-vision task, the task being performed monocularly (closed squares) and binocularly (open squares). Error bars indicate ±1SEM.

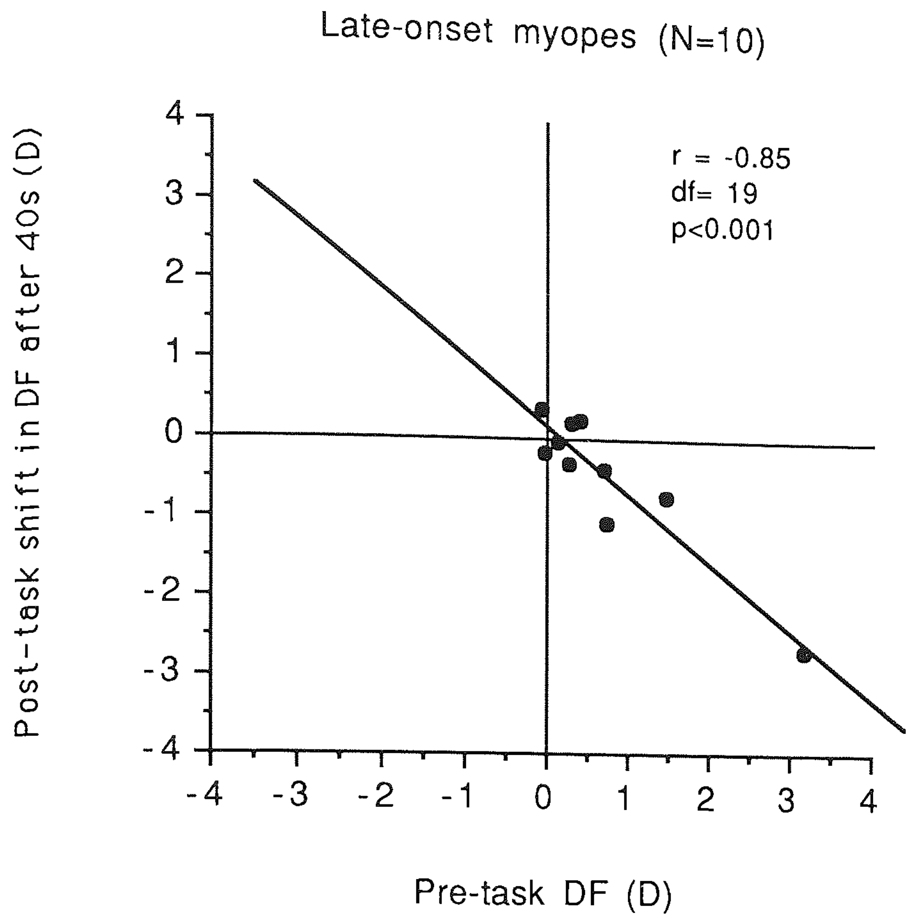

Fig.10.7 The relationship between pre-task DF and the post-task shift in DF measured between 30 and 40s following completion of a 45s binocular near-vision task in 10 late-onset myopes. This significant correlation supports the findings of Gilmartin et al. (1984) and Gilmartin and Bullimore (1987).

Gilmartin and Bullimore (1987) noted that subjects having pre-task DF levels greater than +0.55D were vulnerable to beta-adrenoceptor antagonism during the 50s following completion of a near-vision task. They demonstrated that timolol maleate (0.5%), a non-selective beta-adrenergic receptor antagonist, significantly modified the regression of DF following the near-task in these subjects. Additionally in an earlier paper, Gilmartin et al. (1984) observed that the effect of timolol on DF (measured using a laser optometer) was positively correlated with pre-task DF. These findings would suggest that the negative shift observed in LOMs following the 45s task (see Fig. 10.6) may relate to the output of adrenergic innervation to the ciliary muscle.

In order to examine this proposal, the effect of timolol maleate (0.5%) on post-task regression of DF following a 45s binocular task was investigated in 8 of the 10 LOMs previously examined. Two of the LOMs were not used as they reported a history of asthma and timolol may cause relaxation of bronchial smooth muscle and consequently is contra-indicated in asthmatics (Zimmerman and Boger, 1979).

The effect of timolol on the regression of DF is illustrated in Fig. 10.8. Timolol attenuated the negative shift previously shown following the 45s near-vision task. It may therefore be concluded that the negative shift in DF is mediated via adrenergic innervation to the ciliary muscle. Two-factor (time, drug) analysis of variance indicated that both of these factors were significant (time: F=2.12; df=8,14; p<0.05, drug: F=4.57; df=1,14; P<0.05). The second order interaction was not significant. It may be observed from Fig. 10.7 that one myopic subject had a considerably higher level of pre-task DF when compared with the rest of the LOM group (subject AE, mean pre-task DF= +3.18). It was

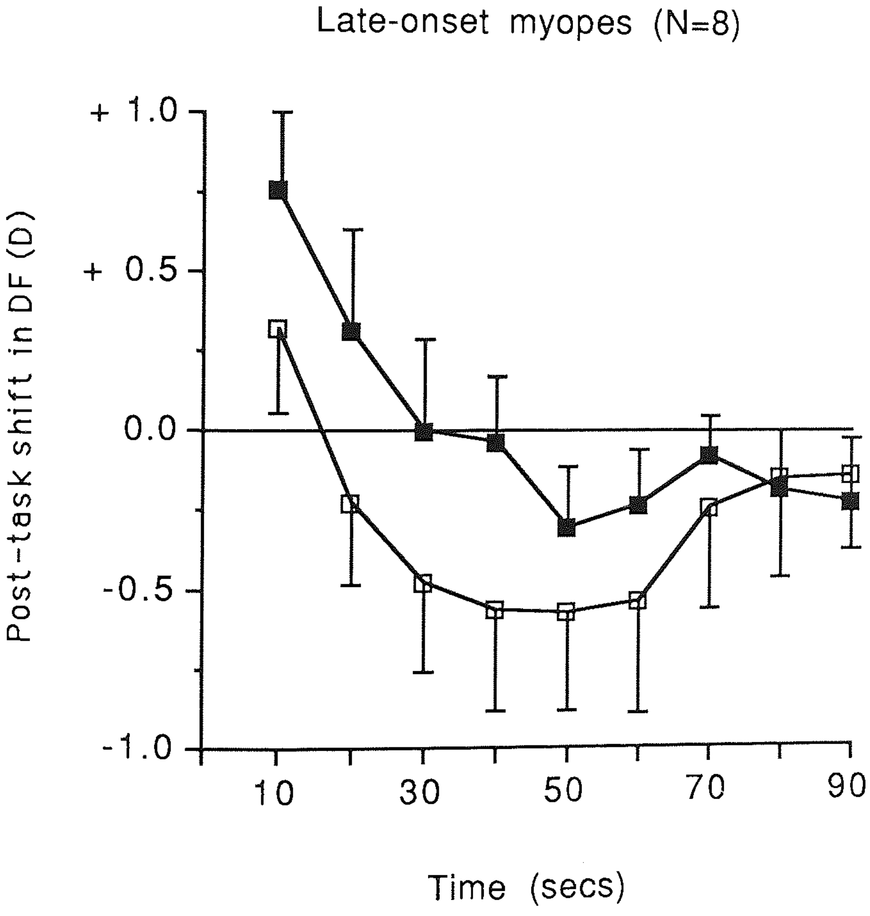

Fig. 10.8 The effect of timolol maleate (0.5%) on the mean post-task dioptric shift in DF against time for 8 LOMs following a 45s binocular near-vision task. Closed squares indicate timolol trial; open squares indicate control trial. Error bars represent ±1SEM.

also indicated in Fig. 10.7 that this subject showed a larger post-task negative shift in DF than the other LOMs. The post-task regression of DF for subject AE and the effect of timolol maleate on this TRP is illustrated in Fig. 10.9.

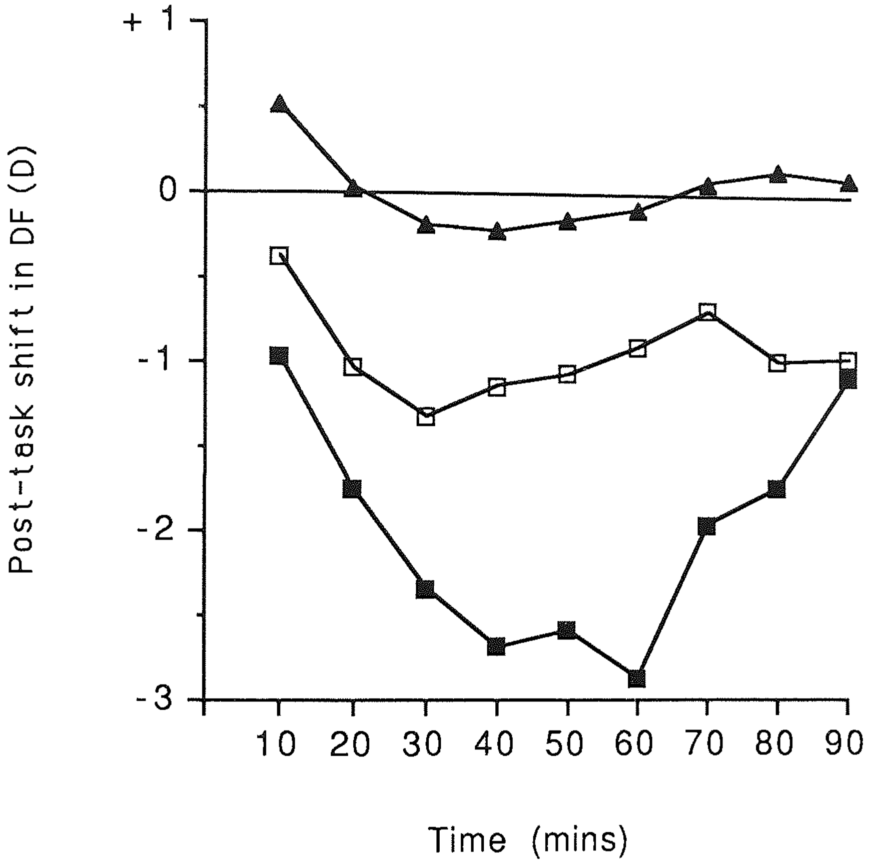

Fig. 10.9. The effect of timolol maleate (0.5%) on the post-task dioptric shift in DF against time for late-onset myope subject AE (mean sphere refractive error -2.50D) following the 45s binocular near-vision task. Open squares indicate timolol trial; closed squares indicate control trial. The closed triangles represent the mean data for the remaining 9 LOMs following the control 45s binocular task.

10.4 DISCUSSION

It has been demonstrated that accommodative adaptation may occur for task durations as brief as 15s. This time course is shorter than has been previously reported. However Schor et al. (1984) compared the value of pre-task DF with post-task DF measured 45s following completion of the near-vision task and it may be observed from Figs 10.1 and 10.2 that post-task DF has already regressed to the pre-task value by this time. Furthermore there was no significant difference in adaptation following the 15s task between LOMs and emmetropes (F=0.20; df=1,162; p=0.66).

The effect of timolol maleate (0.5%) on post-task adaptation following the 45s task indicated that the negative shift in DF previously observed in LOMs was produced by beta-adrenergic innervation to the ciliary muscle. The data illustrated in Figs. 10.3 and 10.4 supports the findings of Törnqvist (1967: see Section 2.4B) who demonstrated that the decrease in accommodative response induced by cervical sympathetic nerve stimulation in cynomologus monkeys developed slowly with a maximum effect after 10-40s. The findings of this present study suggest that sympathetically mediated changes in accommodative adaptation occur between 30 and 45s following commencement of the near-vision task. Furthermore the observation of this shift in LOMs (mean pre-task DF=+0.86) but not in emmetropic subjects (mean pre-task DF=+0.42) is consistent with the findings of Gilmartin and Bullimore (1987).

The observed time-course of sympathetically-induced accommodation is clearly too slow to contribute to the rapid changes in accommodative stimulus normally encountered in the typical visual environment. The role of adrenergic innervation to the ciliary muscle remains unclear (see Gilmartin, 1986 for review). However Gilmartin and Hogan (1985) suggested that the function of sympathetic innervation may be to attenuate the accommodative hysteresis which may follow sustained near-vision tasks. The findings illustrated in Figs. 10.8 and 10.9 would appear to support this proposal. It has been suggested that the role of the adaptive components of accommodation and vergence serve to maintain sustained single, clear binocular vision without excessive fatigue (Rosenfield and Gilmartin, 1988a). The results of this and previous studies would imply that adaptive accommodation represents a parasympathetically-mediated response following sustained reflex accommodation which is subsequently modified by sympathetic innervation to the ciliary muscle.

It has been proposed (see Section 7.5) that the aetiology of late-onset myopia may relate to the presence of a reduced adrenergic inhibitory facility. Clearly in the case of the LOM sample investigated in this particular study, this is not the case. Indeed it may be concluded that this group of LOMs exhibited greater sympathetic input to the ciliary muscle than the emmetropic subjects. However in view of the definition of late-onset myopia which has been adopted, it is likely that several catagories of myopia will be included (see Chapter 5). The small sample size (N=10) should also be noted. The findings of this study would not support the proposal that environmentally-induced myopia is associated with a reduced adrenergic inhibitory facility. However the possibility that this may be a factor in the development of some late-onset myopias cannot be entirely excluded.

10.4A MONOCULAR VERSUS BINOCULAR ACCOMMODATIVE ADAPTATION

No significant difference in accommodative adaptation was demonstrated following monocular or binocular near-vision tasks. This observation supports the recent findings of Fisher et al. (1987c).

It has previously been suggested that accommodative adaptation is primarily produced by changes in blur-driven accommodation (see Section 8.8). If this is the case then the findings of this present study would imply that the output of blur-driven accommodation remains unchanged for either monocular or binocular viewing. However Semmlow and Heerema (1979) stated that under binocular viewing conditions, the increased output of convergent accommodation (CA) when compared with monocular viewing may require a reduction in blur-induced accommodation in order to maintain the aggregate accommodative response.

Additional factors which should be considered are the proximal cues to accommodation and vergence. Ogle and Martens (1957) noted that values of the proximal convergence/accommodation (PC/A) ratio differ depending on whether the heterophoria was measured under total dissociation (Maddox rod) or partial dissociation (fixation disparity method). Ogle and Martens observed a mean value of PC/A obtained with the Maddox rod technique in 28 subjects of 0.9Δ/D. When the fixation disparity method was used to assess changes in vergence, the mean value of PC/A for 104 subjects was 1.52Δ/D. Ogle and Martens suggested that the binocular field-of-view provided by the fixation disparity method may enhance the stimulus for psychic awareness of distance. Thus the suspension of binocular vision may alter the proximal input to accommodation and vergence. Under closed-loop conditions, variation in proximal input may interact with other oculomotor components (e.g. blur- and disparity-induced accommodation) and induce compensatory changes. For instance increased proximal vergence may require a reduction in disparity-vergence in order to maintain the net vergence response. However the reduction in disparity-vergence may produce a fall in the output of CA. This may require an increase in blur-driven accommodation in order to maintain a clear retinal image. Thus the amount of blur-driven accommodation, and hence accommodative adaptation may remain unchanged under monocular and binocular viewing conditions.

Clearly the closed-loop accommodative response is produced by the interaction of various oculomotor constituents and under steady-state conditions an equilibrium must be established between these components. Semmlow and Hung (1980) observed that a major problem in the investigation of the human vergence system is the inability to measure the individual elements which combine to produce the net vergence response. A similar problem exists for the accommodative mechanism. Whilst a number of studies have investigated the individual components of the near-response by opening either the accommodation or vergence loops, these measurements may not reflect their relative contribution under closed-loop conditions. It would seem likely that suspension of binocular vision would produce changes in the relative proportions of these individual components. However the exact nature of these changes remains unclear.

10.5 CONCLUSIONS

It has been demonstrated that accommodative adaptation occurs for tasks as short as 15s duration. However no significant difference in adaptation was observed between LOMs and emmetropes following the 15s near-vision task. Thus differences in the regression of DF between LOMs and emmetropes would not appear to be induced by variation in the rate of onset of accommodative adaptation. It has also been shown that for task durations of 45s or longer, accommodative adaptation may be modified by beta-adrenergic innervation to the ciliary muscle in those subjects having higher levels of pre-task DF. Furthermore no differences were observed between monocular and binocular adapting stimuli. However it is difficult to determine the composition of the accommodative response under closed-loop conditions due to the inability to measure individual elements of the response. Clearly further work is required in order to quantify the relative composition of the aggregate closed-loop accommodation and vergence responses.

CHAPTER 11

DISCUSSION

11.1 REVIEW OF RESULTS

The findings presented in Chapter 6 demonstrated differences in response accommodative convergence/accommodation (AC/A) ratio between late-onset myopes (LOMs) and early-onset myopes (EOMs), the variation in AC/A resulting from increased accommodative convergence (AC) in EOMs. No significant difference in response AC/A was observed between LOMs and emmetropes. It was suggested that this difference between the two myopic groups may relate to variations in the accommodative controller gain (ACG) i.e. the ratio between the effective accommodative stimulus (after consideration of the dead-space) and the output to the accommodation and accommodative convergence effector plant. It remains unclear whether the variations in ACG are directly induced by a change in accommodation or indirectly via increased convergence. However differences in accommodation-vergence synkinesis have been demonstrated between the two myopic subgroups. Whilst the definition of late-onset myopia is of an arbitary nature, these findings indicate that those subjects having myopia of relatively recent onset show different near-response characteristics when compared with those subjects whose myopia is more established. This may provide evidence for variations in myopia aetiology between these two subgroups.

An important point which should be noted is that the vast majority of subjects used throughout this thesis were aged between 18 and 24 years. Therefore the LOMs had probably been myopic for between 3 and 9 years whereas the EOMs had probably been myopic for considerably longer. Comparison of an older group of LOMs who had been myopic for the same length of time as the EOM control group might provide different findings. However due to the practical difficulties in obtaining a sufficient number of older LOMs as well as the gradual loss of accommodative facility which occurs with increasing age, subjects of student age were used for all of the studies described in this thesis.

It has been suggested (Gilmartin and Bullimore, 1987) that differences in beta-adrenergic innervation to the ciliary muscle may be related to the aetiology of late-onset myopia. McBrien and Millodot (1987b), Bullimore and Gilmartin (1987d) and Rosenfield and Gilmartin (1987a) have all demonstrated a lower level of pre-task dark-focus (DF) in LOMs when compared with emmetropes. Furthermore Gilmartin and Bullimore (1987) noted that subjects having pre-task levels of DF greater than +0.75D (measured using an infra-red optometer) were more vulnerable to beta-adrenoceptor antagonism when compared with subjects having pre-task DF values less than +0.75D. It might be inferred from these findings that there is a lower level of sympathetic innervation to the ciliary muscle in LOMs. Alternatively LOMs may possess the same potential adrenergic innervation as emmetropes but might require different stimulus conditions for this sympathetic output to operate.

It was demonstrated in the study described in Sections 7.1 to 7.4, that adrenergic innervation to the ciliary muscle may be monitored during the course of a near-vision task via the response AC/A ratio. Timolol maleate (0.5%), a non-selective beta-adrenergic receptor antagonist produced a significant reduction in AC during the first 4 minutes of a near-vision task in an emmetropic population. Following this initial 4 min period, it was conjectured that adaptational processes occurred in order to restore the previous synkinetic link between accommodation and vergence, and thus provide evidence for the adaptability of the AC/A ratio. The maintenance of this synkinesis may be a prerequisite in order to sustain clear, binocular, single vision of a near-target over a relatively prolonged period of time. Alteration of the synkinetic link may lead to near-vision stress and additional adaptational processes may subsequently be required in order to eliminate this stress. The development of late-onset myopia may itself provide a means of alleviating near-vision stress by reducing the effective accommodative stimulus.

The previous investigation indicated that sympathetic innervation to the ciliary muscle may be monitored via AC in a population of emmetropic subjects. In an attempt to determine the role of adrenergic innervation to the ciliary muscle during sustained near-vision in a myopic population, the effect of timolol on the AC of LOMs, EOMs and emmetropes was studied (Sections 7.5-7.8). Timolol produced no significant change in the AC of LOMs or EOMs during the course of a 15 min near-vision task. However timolol induced a reduction in AC during the initial stages of the task in the emmetropic group, so confirming the previous findings. No direct evidence could therefore be provided to support the proposal of a reduced adrenergic inhibitory facility to the ciliary muscle during sustained near-vision in LOMs.

All the investigations described above examined accommodation-vergence interaction with the vergence system in an open-loop state. However it was observed in Section 4.8 that opening one of the oculomotor loops will alter the synkinetic link between accommodation and vergence. Thus further investigations were carried out in order to examine the synkinesis with both oculomotor systems closed-loop. The study described in Sections 8.1-8.4 required subjects to view monocular targets via a single-mirror haploscope and Badal optometer. Two forms of accommodative stimulus (AS) were used, blur-induced accommodation i.e. where AS resulted from a change in retinal blur and disparity-induced accommodation i.e. that AS resulting from a change in disparity-vergence. It was observed that LOMs exhibited higher levels of disparity-induced accommodation compared with EOMs and emmetropes. Furthermore EOMs showed lower values of blur-driven accommodation when compared with the other two refractive groups. It was suggested that increased disparity-induced accommodation in LOMs may relate either to the presence of an increased convergent accommodation/convergence (CA/C) ratio or to variations in the interaction between disparity-induced and blur-driven accommodation.

In order to clarify this issue the CA/C ratio was measured in a population of LOMs, EOMs and emmetropic subjects by placing the accommodative system into an open-loop condition (see Sections 9.1-9.4). This was achieved either by viewing the target through 0.5mm pinholes or by observing a 0.1mm spotlight in an otherwise dark room. No significant differences in CA/C ratio were observed between the three refractive groups. Thus the differences in disparity-induced accommodation previously observed under closed-loop conditions cannot be accounted for by variations in the CA/C ratio.

The effect of disparity-induced accommodation on accommodative adaptation was investigated in an attempt to provide further information on the role of this component within the aggregate closed-loop accommodative response. It was observed that in emmetropes, increasing disparity-induced accommodation produced a reduction in accommodative adaptation. It was also noted that the introduction of a disparity-stimulus did not produce any significant change in the accommodative response during the course of a sustained (10min) near-vision task in these subjects. Thus it may be implied that the increase in disparity-induced accommodation is accompanied by a reduction in blur-driven accommodation in order to maintain the aggregate accommodative response at a constant level. As the decrease in blur-driven accommodation results in a reduction in accommodative adaptation, this would suggest that within-task changes in adaptive accommodation are only stimulated by the actions of blur (i.e. non-vergence) reflex components of the accommodative response. Additionally differences in accommodative adaptation were observed between LOMs and emmetropes. LOMs showed a reduced post- to pre-task shift in DF following the near-vision task and a reduced rate of decay of post-task DF when compared with emmetropes. This may indicate differences in the temporal characteristics of accommodative adaptation between LOMs and emmetropes.

The findings of the previous study suggested that the adaptive components of accommodation and vergence were only stimulated by blur-driven accommodation and disparity-induced vergence respectively and not by the output of the respective oculomotor cross-links. Thus one might predict that in a model of accommodative-vergence interaction, the near-response cross-links i.e. convergent accommodation (CA) and accommodative convergence (AC) would be situated after the inputs to adaptive accommodation and vergence respectively. This would imply that CA would be driven by both reflex and adaptive vergence. In order to investigate this proposal, the effect of vergence adaptation on CA was investigated in 10 emmetropic subjects (see Sections 9.5-9.8). It was observed that both reflex and adaptive vergence act as stimuli to CA suggesting that the near-response cross-links do indeed occur after the input of the adaptive components of the oculomotor response. The revised schematic model was illustrated in Fig. 9.6.

The final study of this thesis (Chapter 10) investigated the effect of relatively brief near-vision tasks (15, 30 and 45s duration) on accommodative adaptation. It was demonstrated that adaptation may occur for periods as short as 15s duration in both LOMs and emmetropic subjects. Furthermore there was no significant difference in adaptation between monocular and binocular adapting stimuli. However it was again pointed out that under closed-loop conditions, the composition of the net accommodation and vergence responses remains unclear. It was also observed in this study that those subjects having higher levels of pre-task DF (greater than +0.75D) showed a marked negative shift in post-task DF following the 45s near-vision task. This negative shift was again equivalent for both monocular and binocular viewing conditions and further was negatively correlated with pre-task DF. The negative shift observed following the 45s task was attenuated following instillation of the non-selective beta-adrenergic receptor antagonist, timolol maleate (0.5%), indicating that the shift was induced by beta inhibitory sympathetic innervation to the ciliary muscle.

11.2 DISCUSSION

Evidence has been provided to indicate differences in the near-response characteristics of LOMs and EOMs. Under closed-loop conditions, LOMs exhibit increased disparity-induced accommodation and decreased blur-driven accommodation when compared with EOMs (Section 8.3). Furthermore when the vergence loop was opened, it was observed that EOMs had significantly higher response AC/A ratios than LOMs (Section 6.3). These variations confirm the presence of subgroups within the myopic population. The fact that attempts to alter myopia progression (e.g. using bifocals, cycloplegic drugs or prisms) have had mixed success (see Goss, 1982 for a review) may relate to this lack of homogenity within the myopic population. Pre-selection of candidates prior to attempts to modify the progression of myopia may enhance the efficacy of these techniques. One particular form of treatment may be more effective in controlling myopia of a given aetiology. Whilst this is purely speculative at this stage, a number of longitudinal studies have been carried out in order to examine various modes of myopia control. The Houston myopia control study (Grosvenor et al.,1985; Young et al.,1985; Grosvenor et al.,1987) examined the effect of bifocals on myopia control over a period of 3 years. No significant difference was observed between subject groups fitted with bifocals containing a +1.00D reading addition, a +2.00D addition or a control group fitted with single-vision spectacles. A study is currently in progress (Perrigin et al., 1987) to examine the effect of silicone-acrylate contact lenses on myopia control. Unfortunately these longitudinal studies do not fully monitor accommodation-vergence synkinesis during the trial. It might be observed that the efficacy of a particular form of treatment is higher in one group displaying certain pre-trial accommodation-vergence characteristics or perhaps a lower initial level of dark-focus.

Differences in accommodative adaptation have been demonstrated between LOMs and emmetropes (see Sections 8.7 and 10.3). The cause of these variations is unclear but it may relate to differences in the relative proportions of individual components of the closed-loop accommodative response. The aggregate accommodative response in

LOMs may contain a greater proportion of disparity-induced accommodation (see Fig. 8.3) and less blur-driven accommodation (see Fig. 8.4). The reduced output of blur-driven accommodation may be responsible for the decreased level of accommodative adaptation observed in LOMs (see Fig. 8.12). However it has already been noted that under closed-loop conditions it is difficult to quantify individual components of the accommodation and vergence responses. Opening one of the oculomotor loops will provide information relating to these individual constituents of the oculomotor response but may also produce changes in the synkinetic interaction between accommodation and vergence.

Indirect evidence has been found to suggest that LOMs exhibit lower levels of vergence adaptation when compared with emmetropic subjects. Recent work by North (personal communication) would appear to confirm this proposal. This may indicate that the composition of the closed-loop vergence response also differs between LOMs and emmetropes. If this is indeed the case then it remains unclear whether the primary basis of late-onset myopia relates to the accommodation or vergence components of the near-response. The nature of oculomotor adaptation may be modified by variations in the synkinetic relationship e.g. an increase in disparity-induced accommodation will reduce the requirement for blur-driven accommodation. This may then be reflected as a fall in the output of accommodative convergence which in turn will increase the demand for disparity-vergence in order to maintain single vision. These changes in the output of blur-driven accommodation and disparity-vergence may be reflected as variations in the adaptational mechanisms of accommodation and vergence respectively. Clearly further work is required in order to determine the effectivity of the various constituents of the near-response in stimulating accommodative and vergence adapatation.

It would appear that the role of sympathetic innervation to the ciliary muscle during sustained near-vision is related to the output of adaptive accommodation. The findings illustrated in Fig. 10.4 indicated that sympathetically-mediated changes in accommodative adaptation take place between 30 and 45s following commencement of the near-vision task. This finding supports the observations of Törnqvist (1967) and clearly indicates that the time-course of sympathetically-induced accommodation is too slow to contribute to the rapid changes in accommodative stimulus normally encountered in the typical visual environment. Gilmartin and Hogan (1985) proposed that the role of the sympathetic innervation to the ciliary muscle is to attenuate the accommodative hysteresis that may follow sustained near-vision tasks. However no direct evidence has been presented in this thesis to support the proposal that the aetiology of late-onset myopia is related to a reduced level of adrenergic innervation to the ciliary muscle. Indeed the data presented in Chapter 10 indicated that the group of LOMs selected for that particular study had both higher levels of pre-task DF and showed a greater negative shift in post-task DF following the 45s near-vision task when compared with the emmetropic group. These findings would indicate that for the populations examined in that particular study, there was greater adrenergic innervation to the ciliary muscle during the course of the near-vision task in the LOM group when compared with the emmetropic subjects.

It has been observed that the definition of late-onset myopia is of an arbitary nature and probably represents a gross oversimplification in an attempt to divide subjects into those whose myopia is more likely to relate to envionmental factors when compared with genetically-induced myopia. It should also be noted that as the full refractive history of the subjects used was not known, it was impossible to determine what their refractive error had been during their childhood and early teenage years. The absence of visual symptoms during this period may indicate low hypermetropia, emmetropia or indeed a low myopic refractive error. However it would seem reasonable to suggest that the myopia which develops after the cessation of bodily growth (Goldschmidt, 1968) and in particular after the eye has reached its adult emmetropic axial length (McBrien and Millodot, 1987a) may be related to the requirements placed upon the visual system. The high incidence of myopia amongst siblings of LOMs (see Tables 6.1 and 7.3) may indicate that the development of late-onset myopia could be facilitated by the presence of genetic factors, i.e. certain subjects having a predisposition to environmentally-induced myopia.

11.3 FUTURE WORK

Due to practical limitations, only cross-sectional studies have been undertaken in this thesis. It would also be valuable to perform longitudinal studies. The latter technique may be used to provide information on subjects who were initially emmetropic but go on to develop late-onset myopia. It may be possible to identify changes in individual elements of the accommodation-vergence synkinesis which take place concurrent with the development of late-onset myopia. These would provide additional information relating to the aetiology of this myopia. Indeed such a study would verify whether changes in accommodation-vergence synkinesis are a precursor to the development of late-onset myopia, or alternatively occur after the myopic shift in refractive error. Ideally, at the commencement of the study, subjects would be around 11 years of age i.e. before the onset of puberty and the project would continue until the subjects had reached full maturity, perhaps around 25 years of age.

A topic which has received relatively little attention is the role of proximal stimuli to accommodation and vergence. Proximal accommodation and vergence were discussed in Sections 2.5D and 3.7C respectively. However their relative contribution to the closed-loop oculomotor response remains unclear. It was noted in Section 10.4 that the output of proximal vergence may differ under monocular and binocular viewing conditions. One area which may be addressed relatively easily is the relationship between proximal stimuli and accommodative adaptation. Schor et al. (1986), Wolfe and O'Connell (1987) and Bullimore and Gilmartin (1987e) have compared different methods of opening the accommodation loop in order to assess accommodative adaptation following sustained near-vision tasks. These studies compared the hysteresis when the accommodation loop was opened by the subject viewing an light empty field (Ganzfeld) with that measured in total darkness. Differences in accommodative adaptation between these two methods were observed for some (though not all) subjects. It would seem likely that under light viewing conditions, proximal stimuli to accommodation and vergence would contaminate the values of DF *. In order to investigate the relationship between proximal accommodation and accommodative adaptation, the post-to pre-task shift in DF (DF being assessed in total darkness) could be measured following sustained fixation of an adapting stimulus placed at 2 viewing distances e.g. 6m and 0.33m. The size of the targets could be arranged to subtend the same visual angle at the eye. If monocular fixation of the adapting stimulus was adopted in order to eliminate the stimulus to fusional vergence and the targets viewed through a 0.5mm pinhole in order to maintain the blur-stimulus at a constant level, any observed differences in accommodative adaptation would relate to the output of the proximal stimulus to accommodation.

A further study which could be carried out in order to provide information regarding the nature of the stimulus to accommodative adaptation would investigate the relative effects of distance and near accommodative stimuli on DF adaptation. In a previous study (Rosenfield and Linfield, 1986) it was demonstrated that a relationship existed between accommodation ability for distance vision and the position of the apparent near-point. It is likely that the composition of the accommodative response during distance viewing (e.g. stimulated by viewing a target at 6m through a -3.00DS lens) would differ from that created by observing a target at 33cms due to the different proximal and vergence stimulus levels. Comparison of accommodative adapation following sustained near-vision tasks performed under these two conditions may provide information relating to the role of proximal factors within the accommodation -vergence synkinesis.

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* It should be noted that in this thesis, dark-focus(DF) is taken to represent the value of accommodative response under stimulus-free conditions. Thus although the terminology is apparently contradictory, DF may be measured in a light field.

Reflex accommodation and vergence may be investigated by inhibiting the onset of adaptational processes. This may be achieved by providing rapid changes in the accommodation or vergence stimuli over a period of time. Schor and Tsuetaki (1987) observed differences in the cross-link interactions by fatiguing the respective reflex accommodation or vergence systems. If the degree or rate of adaptation varies between different refractive groups, then the ability of their reflex oculomotor components to tolerate rapid stimulus changes may also vary.

Trachtman (1987) reviewed the use of biofeedback techniques to reduce myopia. These techniques have trained subjects to exercise voluntary control of their accommodative response. These biofeedback techniques may also allow subjects to alter the accommodation-vergence synkinesis by varying the relative proportions of one or more components of their accommodation or vergence responses. Thus if the aetiology of late-onset myopia is associated with a change in the interaction between accommodation and vergence, biofeedback techniques may be able to reverse this change in the synkinetic interaction. Alternatively it may also be possible to produce variations in the resting level of dark-focus using these techniques and thereby alter the degree of accommodative hysteresis following sustained near-vision.

It has been suggested that the development of late-onset myopia may relate to an alteration in the synkinetic interaction between accommodation and vergence. However the actual causative mechanism which produces the increase in refractive error, either through an increase in axial length (McBrien and Millodot, 1987a) or a change in corneal curvature (Goss and Erickson, 1987) remains unclear. It has been suggested that variations in intra-ocular pressure (IOP) may be related to myopia development (Van Alphen,1961 and 1986). Van Alphen (1961) stated that the ciliary muscle-choroid layer could be considered as a functional unit which behaved physiologically like a continuous sheet of smooth muscle and offered resistance to the intra-ocular pressure. Furthermore Van Alphen speculated that the resistance to stretch offered by the ciliary muscle-choroid combination emanated directly from the tone of the ciliary muscle. It has been demonstrated that myopic subjects generally have lower levels of tonic accommodation, as assessed by pre-task DF, when compared with emmetropes (McBrien and Millodot, 1987b; Bullimore and Gilmartin 1987d; Rosenfield and Gilmartin, 1987a). Thus the development of myopia in these subjects may relate to reduced resistance to IOP offered by the ciliary muscle-choroid layer. It would be valuable to assess the changes in IOP induced by sustained near-vision. Additionally the use of a Schiotz tonometer will provide a measure of scleral rigidity and thereby give an assessment of the ability of the sclera to resist variations in IOP (Borish, 1970). If variations in the change of IOP with near-fixation, or in the degree of scleral rigidity are observed between different refractive groups, then this may provide information relating to the causitive mechanisms that lead to the development of ametropia.

11.4 CONCLUSIONS

Evidence has been presented to demonstrate differences in the near-response characteristics of subgroups within the myopic population. It has been suggested that the aetiology of late-onset myopia i.e. myopia onset at 15 years of age or later, may be related to periods of sustained near-vision. Additionally the development of late-onset myopia may be facilitated by genetic factors i.e. environmental influences are crucial to the expression of the condition in pre-disposed subjects. At this stage the physical mechanism responsible for the myopic shift in refractive error remains unclear. However if it can be demonstrated that late-onset myopia is associated with a particular characteristic of the oculomotor near-response, then it may be possible to identify subjects who, later in life, may be susceptible to the development of this condition.

APPENDIX 1

EFFECT OF A NEAR-VISION TASK ON THE RESPONSE AC/A RATIO OF A MYOPIC POPULATION

APPENDIX1a Accommodative convergence (Δ) measured for 3.0-3.9D accommodation stimulus range.

a) Late-onset myopes (N = 17)

Time (mins)	**2**	**4**	**6**	**8**	**10**	**12**	**14**
AB	7.5	7	6	6	5	5	6
VU	5	3.5	4.5	4	4	4.5	4
RE	9	11	7	8.5	7	8	7.5
PS	6	4.5	5	5.5	4.33	4	4
HP	5.67	4.5	4	3.5	4	3	4.5
JT	6.67	7	5.5	5.5	5.5	4	6
JN	5.5	5	3.5	3.5	5	2.5	4.5
AR	4.33	5	5	5.67	4.5	5.5	6
KH	4.5	2	5	4	0.5	4	4.5
CD	2.5	2	3	2	1	4	3.5
RL	8	6.5	7	7	7	7	7
LB	9.5	11	10	10.5	11	8	10
LBRAD	2	3.5	3	3	4	3.5	3
JL	4.5	6	5	6	5.5	5	5
TM	8.5	9	9	7	5	7	7.5
AC	6.6	8	7	13	12	13	12
SL	9	8	7.5	7	8	7	6
MEAN	6.16	6.09	5.71	5.51	5.43	5.59	5.94
SD	2.17	2.66	1.93	3.57	2.96	2.49	2.28

b) Early-onset myopes (N=17)

Time (mins)	**2**	**4**	**6**	**8**	**10**	**12**	**14**
AH	8.67	7	7	6.5	5.67	6	4.67
MS	5	3.5	4	4	4.5	4	4.33
BH	3	1.5	1	3.5	1	2	2
PC	7	11	9.5	8	9.5	9	9.5
KE	6.5	6	6	5.5	5.5	5	5.5
PJ	7	4	3.5	3	4	2	2.5
AS	8.5	8	8	8	10.5	13	9
CN	7	9	8	10	9.67	8.5	10
RDH	7	10	9	8	7	6	7.5
RD	15	12	11	8	7	7.5	8.5
IH	10.5	10	11	9.5	10.5	8	8
SB	6.5	6	5.5	5.33	4.5	6.5	5
NB	9.5	8	7	9	8	9	7
MG	8	6.5	7	7	6	8	7
DMV	6	5	5.5	5	5.5	4.33	5
MH	6	6	7	7.5	6.5	7	7
JE	2.5	1	9	4	1.5	1	1.33
MEAN	7.27	6.74	7	6.58	6.28	6.28	6.11
SD	2.77	3.05	2.56	2.11	2.72	2.95	2.54

c) Emmetropes (N = 17)

Time (mins)	2	4	6	8	10	12	14
SG	9.5	9	8.5	8	8.5	9	8.5
RB	16	8	8	8	8	10	7
WG	8	7	7	7	8.5	8	7
DB	4.5	4	5	3.5	5	4	5
RT	3	1	4	4.5	3	3.5	3.5
KD	6	4.5	5	4.5	3.5	4.5	3.5
RP	6	6	5	6	6	5.5	6
SC	6	5	4.5	5.5	5.5	5.5	5.5
ST	8.33	7.5	8.5	7	7	9	8
RAB	5.5	6.5	6	5	3	4	7
SM	8.33	8	7.5	8.5	7.5	8	8
AT	6	6	4	5	4	5	3
CB	3.5	3	4	3.5	2.5	4	3.5
PC	6.67	7.5	6	6.5	7	6	0.5
BP	6.5	8	8	6.5	6.5	6.5	7.5
TM	6.5	6.5	6	7	8	8.5	7
GV	6	8	9	8	8	8.67	7.5
MEAN	6.69	6.3	6.63	6.03	6.13	6.35	6.26
SD	2.55	2.09	1.88	1.64	2.21	2.14	1.91

APPENDIX Ib

Accommodative response (D) measured for 3.0-3.9D accommodation stimulus range

a) Late-onset myopes (N = 17)

Time (mins)	2	4	6	8	10	12	14
AB	0.81	0.81	0.5	0.76	0.77	0.79	1.03
VU	1.11	1.2	0.9	1.03	1.05	0.87	0.84
RE	0.63	1.34	0.49	0.87	0.59	0.48	0.87
PS	0.58	0.19	0.73	0.5	0.58	0.44	0.78
HP	0.67	0.57	0.48	0.82	0.7	0.84	0.7
JT	0.74	0.57	0.71	0.4	0.35	0.81	0.19
JN	0.74	0.69	1.22	1.23	1.03	0.72	0.4
AR	0.78	0.8	0.61	0.55	0.66	0.61	0.79
KH	0.96	0.46	0.71	0.37	0.96	1.04	0.47
CD	1.26	1.49	1.02	0.16	0.95	0.66	0.9
RL	0.94	1.31	0.14	0.82	1.5	0.88	0.89
LB	0.82	0.59	0.79	1.04	0.34	1.00	0.8
LBRAD	0.69	0.98	0.68	0.8	0.77	1.00	0.79
JL	0.89	0.82	0.86	0.9	0.99	0.98	0.77
TM	0.45	0.6	0.4	0.92	0.68	0.96	0.58
AC	0.41	0.62	0.73	0.79	0.4	0.66	0.91
SL	0.46	0.57	1.03	0.69	1.03	0.48	0.88
MEAN	0.76	0.8	0.71	0.74	0.79	0.78	0.74
SD	0.22	0.34	0.25	0.26	0.29	0.19	0.21

b) Early-onset myopes (N = 17)

Time (mins)	2	4	6	8	10	12	14
AH	0.57	0.66	0.94	0.66	0.83	0.52	0.78
MS	0.19	0.48	0.28	1.13	1.04	0.87	0.84
BH	0.41	0.42	0.91	0.59	0.74	0.62	0.54
PC	0.7	0.82	0.82	0.85	0.88	0.61	0.83
KE	0.63	0.64	0.54	0.58	0.29	0.55	0.92
PJ	0.21	0.19	0.37	0.14	0.5	0.71	0.99
AS	0.48	0.67	0.91	0.81	0.63	0.92	0.92
CN	0.77	0.59	0.99	0.62	0.76	0.72	0.7
RDH	1.1	0.99	0.67	0.77	0.76	0.81	0.96
RD	1.15	0.3	0.72	0.66	0.67	0.48	0.74
IH	0.19	1.13	0.51	0.74	0.72	0.47	0.69
SB	1.05	0.81	0.68	0.71	0.22	0.94	0.69
NB	0.67	0.53	0.52	0.68	0.66	0.92	1.27
MG	1.38	0.64	0.91	1.08	0.5	0.95	0.89
DMV	0.82	1.27	1.06	0.99	0.71	1.08	1.13
MH	0.87	1.04	0.59	0.73	0.77	0.94	0.97
JE	0.79	0.7	0.63	0.73	0.35	0.59	0.87
MEAN	0.7	0.7	0.71	0.73	0.62	0.75	0.87
SD	0.34	0.28	0.22	0.22	0.28	0.19	0.17

c) Emmetropes (N = 17)

Time (mins)	2	4	6	8	10	12	14
SG	0.94	0.87	0.86	0.62	0.87	0.79	0.79
RB	0.81	0.96	0.87	0.88	0.67	0.46	0.33
WG	1.33	0.63	0.71	0.96	0.84	1.29	0.75
DB	0.85	1.08	0.87	1.06	0.97	0.95	0.69
RT	0.04	0.91	1.12	1.07	0.46	0.77	0.73
KD	0.82	0.71	0.58	0.64	0.66	1.27	0.96
RP	0.46	0.62	0.71	0.52	0.67	0.73	0.52
SC	0.67	0.79	0.94	0.9	1.04	0.76	0.9
ST	0.71	0.44	0.88	0.78	0.84	0.85	0.75
RAB	1.01	1.03	1.00	0.79	0.92	1.00	1.25
SM	0.97	0.86	0.85	0.88	0.85	1.03	1.04
AT	0.00	0.55	0.09	0.26	0.59	0.49	0.79
CB	0.73	0.97	0.9	1.29	1.1	0.81	1.17
PC	0.76	0.64	0.69	0.75	0.91	0.58	0.71
BP	0.87	1.07	1.00	1.00	0.94	0.94	0.94
TM	1.72	1.24	1.16	0.91	1.09	0.8	0.84
GV	0.89	0.28	0.76	0.82	0.88	0.98	1.05
MEAN	0.79	0.8	0.82	0.83	0.84	0.85	0.84
SD	0.4	0.25	0.23	0.23	0.17	0.22	0.22

APPENDIX Ic

Pre-task levels of dark-focus (DF) measured in dioptres and post-task shift in DF, measured with respect to the pre-task value at 1min. intervals following completion of the task.

a) Late-onset myopes (N = 17)

		POST-TASK LEVELS OF DF				
	Pre -task	1	2	3	4	5
AB	0.19	-0.03	-0.08	-0.24	0.17	0.39
VU	0.37	0.91	-0.07	0.61	0.75	0.24
RE	0.41	-0.06	0.2	0.88	0.14	0.62
PS	0.34	0.26	0.17	-0.1	0.22	-0.05
HP	0.24	0.06	0.04	0.37	0.29	0.41
JT	0.67	-0.36	-0.39	-0.72	-0.64	-0.16
JN	0.41	0.54	0.52	0.57	0.48	0.52
AR	-0.17	0.27	0.22	0.26	0.25	0.36
KH	0.28	-0.23	-0.41	-0.18	0.17	-0.08
CD	0.31	0.09	0.03	-0.05	-0.15	0.07
RL	0.15	-0.02	0.1	-0.04	0.1	0.04
LB	0.63	-0.53	-0.41	-0.21	-0.4	0.02
LBRAD	0.94	1.38	0.61	0.58	1.18	0.28
JL	-0.25	0.16	-0.25	0.94	-0.25	-0.18
TM	-0.41	-0.29	-0.55	-0.21	-0.77	-0.73
AC	0.14	0.06	0.67	0.33	-0.04	-0.14
SL	0.51	0.29	0.11	0.37	-0.03	-0.09
MEAN	0.28	0.15	0.03	0.19	0.09	0.09
SD	0.08	0.45	0.35	0.44	0.46	0.32

b) Early-onset myopes (N = 17)

		POST-TASK LEVELS OF DF				
	Pre -task	1	2	3	4	5
AH	1.4	2.02	0.68	0.17	-0.03	-0.56
MS	0.02	0.33	-0.09	-0.07	-0.03	0
BH	-0.27	-0.01	-0.08	-0.1	0.07	0.14
PC	1.48	0.46	0.83	0.18	0.01	-0.34
KE	0.26	0.05	-0.31	-0.16	-0.44	0.17
PJ	0.12	0.36	0.58	0.42	0.47	0.61
AS	0.39	0.31	-0.29	-0.37	-0.34	-0.07
CN	0.05	0.39	0.23	0.2	0.56	-0.05
RDH	0.62	0.03	0.2	0.94	0.14	0.12
RD	1.23	-0.2	-0.04	-0.35	-0.11	-0.49
IH	0.21	-0.08	-0.01	-0.07	0.35	-0.06
SB	0.57	0.05	0.14	-0.2	-0.04	0.57
NB	0.66	-0.05	0.29	0.7	0.63	0.42
MG	0.19	-0.04	-0.45	-0.33	0.33	0.05
DMV	-0.28	0.08	0.17	0.17	0.14	-0.09
MH	0.94	-0.46	-0.65	-0.5	-0.39	-0.5
JE	0.31	0.03	0.01	0.4	-0.19	0.03
MEAN	0.47	0.19	0.07	0.06	0.07	0
SD	0.13	0.51	0.38	0.38	0.31	0.33

c) Emmetropes (N = 17)

		POST-TASK LEVELS OF DF				
	Pre -task	**1**	**2**	**3**	**4**	**5**
SG	1.94	-0.46	0.4	0.54	0.53	0.75
RB	0.97	0.22	-0.56	1.03	1.2	0.35
WG	0.12	0.35	0.07	-0.02	0.3	0
DB	0.14	-0.11	-0.06	-0.06	-0.02	-0.05
RT	0.48	0.25	0.81	0.54	0.35	0.61
KD	0.69	0.69	2.32	2.5	1.9	1.18
RP	0.6	0.21	0.04	0.16	0.24	0.31
SC	1.93	-0.02	0.42	0.53	0.41	0.46
ST	0.56	0.35	0.18	0.38	0.38	0.34
RAB	0.58	0.11	0.1	0.07	0.11	0.06
SM	0.63	0.26	0.25	0.55	0.51	0.51
AT	0.26	-0.1	-0.08	-0.07	-0.22	-0.24
CB	1.29	-2.02	-1.2	-1.74	-1.7	-1.72
PC	1.03	0.3	0.65	0.28	0.07	0.52
BP	0.95	0.25	0.36	0.43	0.21	0.35
TM	0.39	0.21	0.39	0.43	0.16	0.29
GV	0.17	0.63	0.68	1.18	0.51	0.51
MEAN	0.75	0.07	0.28	0.4	0.29	0.25
SD	0.55	0.6	0.71	0.82	0.71	0.6

APPENDIX Id

Summary of data for 3.0-4.6D and 3.9-4.6D accommodation stimulus ranges

a) Accommodative convergence (Δ)

TIME(mins)		3.0-4.6D		3.9-4.6D	
		MEAN	SD	MEAN	SD
LATE ONSET MYOPES (N=17)	2	12.02	4.76	6.52	2.25
	4	12.09	5.15	6.64	3.22
	6	11.24	4.07	5.64	2.2
	8	10.58	4.61	5.71	2.74
	10	10.27	4.35	5.5	2.82
	12	10.68	4.17	5.14	1.94
	14	10.84	3.85	5.93	2.09
EARLY ONSET MYOPES (N=17)	2	13.19	4.62	8.89	3.04
	4	13.12	4.32	7.93	2.57
	6	13.09	5.11	7.64	2.43
	8	13.21	4.5	7.48	2.09
	10	13.16	4.64	7.12	2.22
	12	12.83	4.96	7.07	1.59
	14	12.5	4.89	6.78	2.02
EMMs (N=17)	2	12.23	4.63	5.77	2.37
	4	11.97	3.97	5.66	2.41
	6	12.59	3.67	5.96	2.1
	8	11.32	3.52	5.29	2.07
	10	12.13	3.9	6	2.24
	12	12	4.12	5.65	2.46
	14	12.16	3.53	5.9	2.04

b) Accommodative response (D)

TIME(mins)		3.0-4.6D		3.9-4.6D	
		MEAN	SD	MEAN	SD
LATE-ONSET MYOPES (N=17)	2	1.31	0.25	0.55	0.26
	4	1.36	0.32	0.56	0.26
	6	1.26	0.20	0.56	0.30
	8	1.2	0.37	0.46	0.29
	10	1.27	0.28	0.48	0.24
	12	1.25	0.31	0.48	0.22
	14	1.31	0.24	0.57	0.25
EARLY-ONSET MYOPES (N=17)	2	1.31	0.37	0.6	0.32
	4	1.3	0.2	0.6	0.18
	6	1.29	0.34	0.58	0.36
	8	1.27	0.3	0.54	0.25
	10	1.23	0.26	0.6	0.23
	12	1.29	0.31	0.54	0.34
	14	1.29	0.25	0.42	0.18
EMMs (N=17)	2	1.3	0.41	0.51	0.32
	4	1.32	0.31	0.51	0.17
	6	1.37	0.28	0.55	0.16
	8	1.3	0.34	0.47	0.27
	10	1.45	0.29	0.61	0.21
	12	1.37	0.37	0.51	0.2
	14	1.39	0.29	0.54	0.19

APPENDIX 2. THE RELATIONSHIP BETWEEN SYMPATHETIC INNERVATION TO THE CILIARY MUSCLE AND THE AC/A RATIO.

APPENDIX 2a
Accommodative convergence (Δ) for 3.0-3.9D accommodation stimulus range

i) timolol

Time (mins)	2	4	6	8	10	12	14	16
SG	7.5	8	6	7.5	8	8	9	9.5
RB	6.5	8	7.5	7	8.5	8	7	8
WG	10	8	8	7.5	8	6.5	7	7
DB	2.5	2.5	3.5	3	3	3	3.5	3.5
RT	4.5	3.5	2	3	3	1	5	4
KD	3.5	2.5	4	3.5	4.5	4.5	4	5
RP	6	6	6	6	6.5	6	6	6
SC	5.5	4.5	3	3	3.5	4	5	4
ST	6	6	7	7	6.5	6.5	7.5	7
RAB	6	2	4	6	5	5	5	6
SM	8	7.5	8	7.5	7	7.5	7.5	7
CB	4	4.5	5.5	3.5	5	3.5	5	4
PC	7	7	6.5	5	4.5	5.5	6	6
BP	6	6	7	8.5	6	8	8	8
TM	7.5	6	6	6	7	8.5	7	7
GV	7.5	9.5	8.5	9	8.5	8.5	8.5	8
MEAN	5.93	5.43	5.57	5.57	5.64	5.5	6.11	6.07
SD	1.86	2.10	1.88	1.94	1.79	2.05	1.55	1.74

ii) saline

Time (mins)	2	4	6	8	10	12	14	16
SG	9.5	9	8.5	8	8.5	9	8.5	8
RB	16	8	8	8	8	10	7	8
WG	8	7	7	7	8.5	8	7	8
DB	4.5	4	5	3.5	5	4	5	6
RT	3	1	4	4.5	3	3.5	3.5	2.5
KD	6	4.5	5	4.5	3.5	4.5	3.5	6
RP	6	6	5	6	6	5.5	6	6
SC	6	5	4.5	5.5	5.5	5.5	5.5	6
ST	8.33	7.5	8.5	7	7	9	8	8.5
RAB	5.5	6.5	6	5	3	4	7	7
SM	8.33	8	7.5	8.5	7.5	8	8	9
CB	3.5	3	4	3.5	2.5	4	3.5	2.5
PC	6.67	7.5	6	6.5	7	6	0.5	6.5
BP	6.5	8	8	6.5	6.5	6.5	7.5	8.5
TM	6.5	6.5	6	7	8	8.5	7	7
GV	6	8	9	8	8	8.67	7.5	7.5
MEAN	6.69	6.3	6.63	6.03	6.13	6.35	6.26	6.44
SD	2.55	2.09	1.88	1.64	2.21	2.14	1.91	1.99

APPENDIX 2b

Accommodation response (D) for 3.0-3.9D accommodation stimulus range

i) timolol

Time (mins)	2	4	6	8	10	12	14	16
SG	0.67	1.01	0.83	0.56	0.87	0.68	0.97	0.79
RB	0.56	0.63	0.56	0.75	0.77	0.73	0.45	0.23
WG	0.99	0.72	0.66	1.16	1.21	0.67	0.6	0.8
DB	1.00	0.81	0.68	0.75	0.55	1.08	0.88	0.69
RT	0.98	0.98	0.57	0.4	0.7	0.54	0.71	0.61
KD	0.90	0.81	0.62	0.88	0.92	0.79	1.26	0.79
RP	0.52	0.71	0.41	0.34	0.64	0.63	0.75	0.49
SC	1.12	0.75	0.48	0.96	0.87	0.65	0.71	0.84
ST	0.75	0.67	0.71	0.5	0.66	0.67	0.68	0.79
RAB	0.94	1.13	0.78	0.87	1.5	0.87	0.5	0.92
SM	0.88	0.97	1.03	0.91	1.03	0.85	0.88	0.91
CB	0.79	0.62	0.83	0.82	0.6	1.01	0.72	0.77
PC	0.88	0.98	0.67	0.54	0.58	0.5	0.81	0.71
BP	0.93	0.75	0.76	1.07	0.92	0.89	0.81	0.45
TM	1.02	1.41	0.91	0.2	1.14	1.12	1.07	1.42
GV	0.64	0.7	0.57	0.46	0.77	0.88	0.96	0.84
MEAN	0.80	0.80	0.65	0.66	0.81	0.74	0.75	0.71
SD	0.17	0.20	0.15	0.26	0.25	0.17	0.19	0.24

ii) Saline

Time (mins)	2	4	6	8	10	12	14	16
SG	0.94	0.87	0.86	0.62	0.87	0.79	0.79	0.96
RB	0.81	0.96	0.87	0.88	0.67	0.46	0.33	1.58
WG	1.33	0.63	0.71	0.96	0.84	1.29	0.75	0.64
DB	0.85	1.08	0.87	1.06	0.97	0.95	0.69	0.87
RT	0.04	0.91	1.12	1.07	0.46	0.77	0.73	0.84
KD	0.82	0.71	0.58	0.64	0.66	1.27	0.96	0.83
RP	0.46	0.62	0.71	0.52	0.67	0.73	0.52	0.79
SC	0.67	0.79	0.94	0.9	1.04	0.76	0.9	0.75
ST	0.71	0.44	0.88	0.78	0.84	0.85	0.75	0.92
RAB	1.01	1.03	1.00	0.79	0.92	1.00	1.25	0.96
SM	0.97	0.86	0.85	0.88	0.85	1.03	1.04	1.04
CB	0.73	0.97	0.90	1.29	1.10	0.81	1.17	0.72
PC	0.76	0.64	0.69	0.75	0.91	0.58	0.71	1.00
BP	0.87	1.07	1.00	1.00	0.94	0.94	0.94	0.63
TM	1.72	1.24	1.16	0.91	1.09	0.8	0.84	0.79
GV	0.89	0.28	0.76	0.82	0.88	0.98	1.05	0.77
MEAN	0.79	0.8	0.82	0.83	0.84	0.85	0.84	0.88
SD	0.4	0.25	0.23	0.23	0.17	0.22	0.22	0.23

APPENDIX 2c

Pre-task values of dark-focus (DF) and post-task shift in DF (D) measured with respect to pre-task values.

i) Timolol

	Pre-	Post-task DF (mins)			
		1	2	3	4
SG	1.15	0.2	0.5	0.57	0.47
RB	0.47	0.88	0.26	0.96	0.64
WG	0.08	0.31	0.25	0.03	-0.13
DB	0.06	0.39	0.45	0.17	0.13
RT	1.17	0.13	0.43	1.37	0.77
KD	0.44	1.83	1.59	0.8	1.04
RP	0.02	0.1	0.11	0.03	0.17
SC	2.75	0.03	-0.12	1.26	1.38
ST	0.5	0.22	0.11	0.18	0.01
RAB	0.53	0.68	0.78	0.34	0.46
SM	0.48	0.36	0.74	0.7	-0.18
CB	0.17	0.37	0.99	0.6	0.15
PC	0.78	0.08	0.19	-0.19	0.18
BP	1.59	0.68	0.25	0.24	0.06
TM	0.28	0.15	0.27	0.24	0.35
GV	0.99	0.41	-0.17	0.03	-0.19
MEAN	0.72	0.43	0.41	0.46	0.33
SD	0.68	0.43	0.43	0.45	0.43

ii) saline

		Post-task DF			
	Pre	1	2	3	4
SG	1.22	-0.46	0.4	0.54	0.53
RB	1.47	0.22	-0.56	1.03	1.2
WG	0.07	0.35	0.07	-0.02	0.3
DB	0.21	-0.11	-0.06	-0.06	-0.02
RT	1.28	0.25	0.81	0.54	0.35
KD	0.93	0.69	2.32	2.5	1.9
RP	0.02	0.21	0.04	0.16	0.24
SC	1.85	0.02	0.42	0.53	0.41
ST	0.38	0.35	0.18	0.38	0.38
RAB	0.63	0.11	0.1	0.07	0.11
SM	0.54	0.26	0.25	0.55	0.51
CB	2.41	-2.02	-1.2	-1.74	-1.7
PC	0.53	0.3	0.65	0.28	0.07
BP	1.55	0.25	0.36	0.43	0.21
TM	0.49	0.21	0.39	0.43	0.16
GV	0.66	0.63	0.68	1.18	0.51
MEAN	0.89	0.89	0.08	0.3	0.43
SD	0.66	0.66	0.6	0.7	0.82

APPENDIX 2d

Summary of data for the 3.0-4.6D accommodation stimulus range. Figures in parentheses represent 1sd.

Time (mins)	SALINE		TIMOLOL	
i) Response AC/A ratio (Δ/D)				
2	6.03	(2.63)	5.47	(2.80)
4	6.22	(2.69)	5.7	(2.74)
6	6.16	(3.02)	6.27	(3.92)
8	5.75	(2.75)	5.8	(3.44)
10	5.6	(2.88)	5.99	(3.34)
12	6	(2.91)	6.46	(2.98)
14	5.7	(3.21)	5.84	(3.14)
16	5.6	(2.99)	6.13	(2.95)
ii) Accommodative convergence (Δ)				
2	8.19	(2.05)	7.77	(2.93)
4	8.02	(2.01)	7.86	(2.15)
6	8.44	(1.98)	7.9	(2.77)
8	7.58	(2.10)	7.95	(2.25)
10	8.13	(1.88)	7.97	(1.70)
12	8.04	(2.07)	8.21	(1.96)
14	8.15	(2.10)	8.00	(2.26)
16	8.23	(2.21)	8.09	(2.34)
iii) Accommodation response (D)				
2	1.36	(0.35)	1.42	(0.33)
4	1.29	(0.33)	1.38	(0.37)
6	1.37	(0.38)	1.26	(0.39)
8	1.32	(0.24)	1.37	(0.29)
10	1.45	(0.29)	1.33	(0.26)
12	1.34	(0.36)	1.27	(0.29)
14	1.43	(0.39)	1.37	(0.34)
16	1.47	(0.28)	1.31	(0.28)

APPENDIX 3. BETA-ADRENERGIC RECEPTOR ANTAGONISM IN MYOPIA

Timolol-induced shift in accommodative convergence (Δ) for 3.3-4.8D accommodation stimulus range.

i) Late-onset myopes (N=20)

Time (mins)	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**15**
JL	1	0	-1	-1	-0.5	-2	1.5	-2
AM	-2	0	0	0	0	-2	0	0
CD	-0.5	1	-1	2	-2	0	2	0
RL	0	3	1	-1.5	1.5	0.5	0	0
KH	-1	0	1	0	1	1	1	1
JN	-1.5	0.5	-1	-1	0.5	-1	0	0
RC	-1	1	0	0	-1	-1	-2	-1
JR	-1.67	-2	-1.33	-1.5	-1.5	-0.5	1.33	1.33
LP	0	1.5	1	-0.5	1	0.5	-0.5	0.5
SL	1	0	-1	-1	0	-1	2	-0.5
PC	1.5	0	1	-0.5	0	2	1	-1
PB	2	-1	-2	-0.5	2	0	-2	1
RP	-0.5	0	-2	3	3	0	1	2
TH	1.5	3	1	6	2	2	1	1
AH	-1	0	-3.5	0	-2	-1	0	-1
WT	-1.83	0	-1	0	0	0	0.5	0.5
RN	1	-1.5	0.5	1	1	-1.5	1	-1.5
LB	-0.5	1	-0.5	-0.5	1.5	0.5	-3	-3
PBH	0	0	1	2	2	0.5	0.5	0.5
HP	0.5	0	-1	-2.5	-1	0	0	0
MEAN	-0.19	0.18	-0.21	0.2	0.29	0.1	0.27	-0.11
SD	1.26	1.16	1.34	1.82	1.35	1.51	1.29	1.18

ii) Early-onset myopes (N=20)

Time	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**15**
RDH	0.5	0	0.5	0.5	2	0.5	2	0
DT	-3.5	-1	0	2	-5.5	0.5	-2	2
NB	-1.5	1	-2	-1.5	-1.5	1	-2	0
AH	-0.5	-0.5	0.5	0.5	0.5	-0.5	3	1
JG	1.5	1	-1.5	0.5	0	-1	1.5	0
RC	-1	0.5	-1	-2	-1	-1	-1	-2
DMV	2	2.67	-3.33	1.33	1.33	0	-1.67	1.33
RD	-2.33	0.5	-1	0.5	0.5	1.5	-1	-0.5
IH	0.83	0.5	1.5	0	0.5	1.5	1.5	2
HS	-2	1	2	1	2	0	0	1
LM	-1	-1	-1.5	-1	-2.5	-1	-1	-2
CN	1.5	1	-0.17	3	1.5	0	2	1
MG	0.5	2	1	1	2	0	1	1
JE	1	3	-0.5	-0.5	0.25	1	0	0
NS	0.5	1	0	0	0	0	1	0.5
MS	-0.5	-0.5	0	-1	-2	-0.5	-1	1
PP	-1	-3	-1	1.5	-2	0	0	-3
JMC	0.5	-0.83	-2	1.17	-1	0.5	0	1
AS	0.33	1.5	1	0.5	1	1	1	0.5
KE	0.5	-0.5	0	0.5	0	0	0.5	0
MEAN	-0.18	-0.42	-0.38	0.4	-0.2	0.18	0.19	0.24
SD	1.38	1.36	1.28	1.17	0.75	1.39	1.38	1.27

iii) Emmetropes (N=20)

Time	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**15**
SG	0	-0.08	-0.25	0.67	1.17	-0.25	1.34	0.5
SS	2.67	2	2.67	2	2	2	1.67	1
CS	2.6	2.3	1.25	1.25	1.75	1.6	1	2.5
CG	2.75	3.67	2	3.67	3	2	3	4
TB	1	1.33	0	1.33	1	1.33	1.33	1
DB	3.67	4	3	3	3	3.67	3	3
PC	1.4	1.33	1	0.75	1	1.33	1	1
JD	2.25	2.5	2.5	2	2	2.67	3	2.5
AP	2.25	1	1.5	1.67	2	1.33	1.67	2.5
CB	3.8	2.5	2.25	2	2.25	2.5	2.5	3
ST	-0.75	-1	0.75	1.25	-0.33	0	-0.08	-0.5
RB	-0.25	-0.75	0.33	1.5	-0.17	-0.67	-1.25	-3
DC	2.08	0	-0.33	-0.67	-0.67	-0.34	-0.17	0
KA	-0.33	0.5	0	0	0	-0.83	-1	1
BP	0	0.17	-0.67	0.17	-0.17	-0.33	0.33	0.5
RD	0.6	-0.3	-0.67	-0.03	-1	-1.8	-0.8	0
JW	0.42	0.33	0.67	1	0.83	0.75	0.33	-0.5
LC	0.5	0	0.33	0.33	-0.33	0.33	0.67	0
JL	-2	-1	0	0	1	-2	0	-0.38
SC	-0.67	0	1.08	0.67	-0.67	-0.5	0.67	0
MEAN	-0.41	-0.26	-0.06	0.16	-0.04	-0.34	-0.08	-0.12
SD	0.75	0.47	0.68	0.76	0.77	0.73	0.66	0.96

APPENDIX 4

ASSESSMENT OF CLOSED-LOOP ACCOMMODATION-VERGENCE SYNKINESIS DURING SUSTAINED NEAR-VISION

Values of accommodation response (D) for the four accommodation-vergence stimuli.

Late-onset myopes (N=15)

i) **AR1**

TIME(sec)	10	20	30	40	50
LB	2.45	2.55	2.33	2.67	2.94
JL	2.74	2.55	2.85	2.61	2.62
RL	1.96	2.06	2.03	2.06	1.96
AC	1.36	1.51	2	1.59	0.84
CD	1.16	1.21	1.18	1.16	1.04
JN	0.86	0.9	0.3	1.04	1.34
KH	1.69	1.73	1.79	1.69	1.65
JR	2.22	2.29	2.2	2.14	2.2
LBRAD	2.08	1.78	1.9	1.86	2.31
LP	1.52	1.39	1.21	1.16	1.26
TH	2.22	2.37	1.98	1.53	1.58
AH	1.18	1.32	1.29	1.32	1.46
SL	1.22	1.39	1.36	1.29	1.48
PB	1.52	1.59	1.45	1.32	1.36
PB	2.47	2.62	2.48	2.45	2.54
MEAN	1.78	1.82	1.76	1.73	1.77
SD	0.54	0.51	0.59	0.51	0.58

ii) **AR2**

TIME(sec)	10	20	30	40	50
LB	2.53	2.63	3.01	2.8	2.5
JL	3.05	2.83	3.06	2.67	3.08
RL	2.05	2.14	2.11	2.43	2.21
AC	3.35	3.56	2.7	2.28	1.64
CD	1.81	1.72	1.3	1.00	0.96
JN	2.04	1.94	2.04	2.08	1.88
KH	1.95	1.91	1.86	1.78	1.61
JR	2.27	2.45	2.41	2.42	2.56
LBRAD	2.15	2.36	2.05	2.17	2.13
LP	1.42	1.46	1.52	1.39	1.41
TH	1.99	1.73	1.97	2.4	2.2
AH	1.45	1.81	1.58	1.65	1.43
SL	2.07	1.81	1.35	1.18	1.5
PB	1.54	1.48	1.41	1.5	1.74
PB	2.58	2.52	2.55	2.47	2.7
MEAN	2.15	2.16	2.06	2.01	1.97
SD	0.52	0.55	0.56	0.54	0.55

iii) AR3

TIME (sec)	10	20	30	40	50
LB	3.01	3.03	3.01	2.81	3.26
JL	2.84	3.18	3.36	3.39	3.49
RL	2.86	3.17	3.1	3.13	1.03
AC	1.9	1.81	1.16	1.43	1.16
CD	1.49	1.55	1.55	1.4	1.76
JN	2.26	2.04	2.18	2.5	1.89
KH	2.2	1.87	1.9	2.15	3.29
JR	2.72	2.91	2.81	2.92	2.86
LBRAD	2.75	3.1	2.8	3.13	1.16
LP	1.93	1.91	1.73	1.74	1.6
TH	2.4	2.62	2.36	2.48	2.51
AH	1.42	1.62	1.84	1.84	1.72
SL	2.09	2.33	1.46	1.82	1.81
PB	1.62	1.64	1.66	1.57	1.57
PB	3.14	3.17	3.09	2.91	2.74
MEAN	2.31	2.4	2.27	2.35	2.2
SD	0.54	0.63	0.69	0.66	0.8

iv) AR4

TIME (sec)	10	20	30	40	50
LB	2.88	3.31	3.35	3.5	2.87
JL	2.85	3.1	3.06	3.16	3.49
RL	3.07	3.08	3.13	3.11	3.37
AC	2.47	2.54	2.68	1.75	1.12
CD	2.18	1.5	1.68	1.78	2.00
JN	2.33	2.2	2.19	2.34	2.01
KH	2.64	2.59	2.49	2.34	2.36
JR	3.02	3.16	3.52	3.29	3.31
LBRAD	2.64	2.73	2.49	2.6	2.59
LP	2.06	2.14	1.97	1.91	1.9
TH	2.87	2.78	2.99	2.9	2.5
AH	2.25	2.18	2.15	1.99	2.1
SL	2.25	2.22	2.33	1.95	1.86
PB	1.89	1.92	2.31	2.62	2.4
PB	3.25	3.1	3.11	3.14	3.06
MEAN	2.57	2.57	2.63	2.56	2.46
SD	0.4	0.51	0.52	0.57	0.64

Early-onset myopes (N=15)

i) AR1

TIME(sec)	10	20	30	40	50
SC	2.22	2.16	2.18	2.04	2.01
CN	2.48	2.51	2.5	2.54	2.52
MS	1.72	2.14	2.2	1.91	1.99
RD	1.01	0.81	0.92	0.58	1.01
AH	2.43	2.55	2.15	2.98	2.89
JE	1.68	1.75	1.61	1.5	1.59
JMC	2.43	2.07	2.09	2.25	1.89
RDH	2.21	2.29	2.26	2.14	2.22
SV	1.4	1.76	1.64	1.55	1.56
IH	2.06	2.13	2.57	2.46	2.38
PP	2.64	2.41	2.5	1.91	1.99
AL	2.17	2.13	2.05	1.94	2.36
NN	2.17	2.16	1.91	1.67	2.09
JG	1.68	1.56	1.5	1.51	1.54
AS	2.39	2.32	2.29	2.6	2.16
MEAN	2.05	2.05	2.02	1.97	2.01
SD	0.44	0.42	0.43	0.56	0.45

ii)**AR2**

TIME(sec)	10	20	30	40	50
SC	2.19	2.2	2.31	2.07	2.15
CN	2.66	2.57	2.43	2.52	2.39
MS	2.68	2.3	2.53	2.36	2.88
RD	1.45	1.72	1.64	1.72	1.76
AH	2.43	2.39	2.46	2.27	2.3
JE	1.86	1.88	1.92	1.31	1.74
JMC	2.89	2.6	2.33	2.17	2.48
RDH	1.99	2.17	1.8	2.00	2.29
SV	1.93	1.75	2.05	1.88	1.87
IH	1.73	1.95	2.00	1.76	2.03
PP	2.96	2.7	2.47	2.68	2.64
AL	2.02	2.05	2.11	2.38	2.3
NN	2.09	1.96	1.34	1.46	1.6
JG	2.49	1.89	1.78	1.43	1.44
AS	2.25	2.28	2.61	2.59	2.5
MEAN	2.24	2.16	2.11	2.04	2.15
SD	0.42	0.3	0.35	0.42	0.40

iii) **AR3**

TIME(sec)	10	20	30	40	50
SC	2.54	2.47	2.58	2.64	2.29
CN	2.69	2.55	2.59	2.28	2.52
MS	2.24	2.48	2.39	1.9	2.78
RD	2.46	2.37	2.42	2.32	2.37
AH	2.48	2.47	2.43	2.48	2.5
JE	1.88	1.64	1.69	1.48	1.48
JMC	2.67	2.62	2.67	2.86	2.49
RDH	2.63	2.33	3.05	2.48	2.85
SV	2.59	2.19	2.28	2.13	2.2
IH	2.46	2.42	2.4	2.64	2.7
PP	2.32	2.5	2.89	2.82	2.83
AL	2.44	2.34	2.38	2.73	2.61
NN	2.43	1.62	1.39	1.37	1.19
JG	2.1	2.71	2.06	1.58	1.66
AS	2.97	2.96	3.09	3.04	3.06
MEAN	2.46	2.38	2.42	2.32	2.37
SD	0.25	0.35	0.46	0.52	0.53

iv) **AR4**

TIME(sec)	10	20	30	40	50
SC	3.14	2.97	3.06	3.04	3.03
CN	3.00	3.02	2.59	2.84	2.86
MS	2.77	2.76	2.41	2.68	2.57
RD	1.76	1.99	1.7	2.39	1.93
AH	2.77	2.87	2.63	2.38	2.31
JE	1.8	1.59	1.89	1.6	1.63
JMC	2.95	2.76	2.57	2.72	2.57
RDH	2.89	2.89	2.83	2.76	2.61
SV	2.9	3.04	2.87	2.55	2.95
IH	3.26	2.7	2.84	3.06	3.17
PP	3.15	2.8	2.51	2.98	3.05
AL	2.64	2.56	2.6	2.26	2.6
NN	2.09	1.88	1.6	1.55	1.68
JG	2.65	2.88	2.61	2.74	2.54
AS	3.26	3.36	3.02	3.06	3.15
MEAN	2.73	2.67	2.51	2.57	2.58
SD	0.47	0.47	0.43	0.46	0.48

Emmetropes (N=15)

i) **AR1**

TIME(sec)	10	20	30	40	50
BP	2.42	2.22	2.72	2.2	2.25
SS	1.81	1.66	1.7	1.88	1.68
CB	2.42	2.47	2.61	2.38	2.55
SG	1.82	1.58	1.72	1.67	1.84
DB	1.2	1.24	1.11	1.28	1.52
AP	1.99	2.16	1.95	2.03	1.98
RD	1.82	1.63	1.61	1.49	1.38
DC	2.38	1.78	2.39	2.16	2.11
JW	2.13	2.37	2.34	2.09	2.09
CS	1.43	1.22	1	0.98	1.09
JB	1.09	0.97	1.1	1.5	1.43
ST	1.46	1.57	1.3	1.25	1.25
KA	2.17	2.66	2.43	2.58	2.35
SB	1.95	2.39	1.94	2.23	2.34
RB	1.74	1.61	1.79	1.81	1.83
MEAN	1.86	1.84	1.85	1.84	1.85
SD	0.4	0.49	0.54	0.45	0.42

ii) **AR2**

TIME(sec)	10	20	30	40	50
BP	2.59	2.54	2.31	2.88	2.15
SS	1.81	1.94	1.94	1.85	1.87
CB	2.5	2.53	2.55	2.55	2.71
SG	1.65	1.65	1.72	1.75	1.82
DB	1.53	1.54	1.58	1.43	1.6
AP	2.2	2.07	1.86	1.85	2
RD	1.81	1.88	1.87	1.97	1.85
DC	2.25	1.95	2.11	2.18	2.19
JW	2.22	2.07	2.1	2.01	1.82
CS	2.09	1.8	1.97	2.05	2.16
JB	1.86	1.74	1.76	1.65	1.57
ST	1.68	1.28	1.62	1.75	1.78
KA	2.42	2.25	2.44	2.16	2.58
SB	2.34	2.12	2.04	2.07	1.97
RB	1.88	2.02	2.05	1.67	1.84
MEAN	2.06	1.96	1.99	1.99	1.99
SD	0.32	0.33	0.27	0.35	0.31

iii) **AR3**

TIME(sec)	10	20	30	40	50
BP	2.71	2.78	2.71	3.02	2.82
SS	2.47	2.41	2.41	2.57	2.4
CB	2.96	2.96	2.65	2.82	2.9
SG	2.11	2.09	2.29	2.4	2.4
DB	2.36	1.64	1.66	1.55	1.86
AP	2.84	2.2	2.41	2.21	2.19
RD	2.26	2.4	2.64	2.36	2.33
DC	2.15	2.11	1.88	2.31	2.2
JW	2.86	2.78	2.87	2.9	2.54
CS	2.27	2	1.93	2.07	2.55
JB	0.73	0.79	0.75	0.92	0.78
ST	2.62	2.73	2.46	2.35	2.46
KA	3.14	2.92	2.88	2.76	3.29
SB	2.39	2.14	2.11	1.75	1.9
RB	2.26	2.05	1.91	2.15	1.96
MEAN	2.41	2.27	2.24	2.28	2.31
SD	0.54	0.54	0.54	0.54	0.55

iv) AR4

TIME (sec)	10	20	30	40	50
BP	2.92	2.89	2.9	2.6	2.84
SS	2.74	2.55	2.53	2.69	2.58
CB	3	3.31	3.11	3.02	3.22
SG	2.07	2.18	2.07	2.1	2.23
DB	2.03	2.07	1.89	1.82	1.86
AP	2.39	2.51	2.49	2.7	2.55
RD	2.48	2.42	2.48	2.63	2.5
DC	2.57	2.39	2.16	2.24	2.24
JW	2.84	2.53	2.79	2.56	2.66
CS	2.31	2.05	2.61	2.38	2.22
JB	1.91	1.68	1.75	1.67	1.53
ST	2.82	2.76	2.62	2.26	2.47
KA	3.1	2.95	3.22	3.04	3.24
SB	2.59	2.08	2.14	2.11	2.17
RB	2.04	2.29	2.29	2.37	2.54
MEAN	2.52	2.44	2.47	2.41	2.46
SD	0.37	0.42	0.41	0.38	0.43

APPENDIX 5

ACCOMMODATIVE ADAPTATION INDUCED BY SUSTAINED DISPARITY-VERGENCE

Values of accommodative response (D) measured during the course of a 10 min near-vision task (3D) performed at three vergence stimulus levels.

a) EMMETROPES (N=10)

i) 0Δ

Mins	1	2	3	4	5	6	7	8	9	10
RB	2.37	2.73	2.7	2.75	2.72	2.72	2.47	2.8	2.29	2.72
ST	2.85	2.62	2.65	2.78	2.95	2.73	3.21	2.7	2.82	2.85
JW	2.79	2.82	3.12	3.29	3.00	3.06	3.17	3.27	3.36	3.12
SB	2.82	3.12	3.37	3.55	3.45	3.13	3.1	3.3	3.33	2.86
KM	3.03	3.04	2.84	2.97	3.00	2.82	3.1	2.81	3.14	2.83
JB	3.3	2.91	2.62	3.00	2.96	3.00	3.46	2.88	3.18	2.81
IS	3.27	3.48	3.48	3.26	3.69	3.53	3.72	3.71	3.75	3.8
SG	2.81	3.11	3.1	3.12	3.02	3.28	3.25	3.01	2.75	2.88
RS	3.12	3.37	3.21	3.33	3.61	3.14	3.36	3.6	3.54	3.06
CB	2.78	3.44	2.76	2.95	2.92	2.86	3.05	2.87	2.78	2.6
MEAN	2.91	3.06	2.99	3.1	3.13	3.02	3.19	3.1	3.09	2.95
SD	0.26	0.28	0.3	0.24	0.31	0.24	0.31	0.34	0.41	0.32

ii) 3Δ

Mins	1	2	3	4	5	6	7	8	9	10
RB	2.55	2.8	2.72	2.78	2.96	2.77	2.71	2.79	3.24	2.98
ST	3.46	3.25	2.92	3.32	2.92	2.95	3.24	3.01	2.65	3.17
JW	2.44	2.71	2.79	2.62	2.64	2.61	3.1	2.66	3.04	2.98
SB	3.06	3.12	2.92	2.68	3.05	3.12	3.17	2.76	2.57	2.99
KM	3.3	3.35	3.18	3.24	2.94	3.29	2.99	3.16	3.05	2.88
JB	2.81	2.62	2.97	2.5	2.29	2.59	2.87	3.09	2.75	2.73
IS	3.76	3.66	3.13	3.2	3.02	2.88	3.56	3.01	3.31	2.80
SG	2.48	2.76	2.87	3.05	3.5	2.88	2.57	3.01	2.67	3.07
RS	3.32	3.58	3.26	3.49	3.57	3.12	3.5	3.53	3.27	3.31
CB	2.92	3.25	3.31	3.32	3.54	3.16	3.35	3.03	2.75	2.86
MEAN	3.01	3.11	3.01	3.02	3.04	2.94	3.11	3.01	2.93	2.98
SD	0.42	0.35	0.19	0.33	0.39	0.22	0.31	0.23	0.27	0.17

iii) 6Δ

Mins	1	2	3	4	5	6	7	8	9	10
RB	2.93	2.97	3.09	3.11	3.02	2.77	2.71	2.79	3.24	2.98
ST	2.88	2.97	3.01	2.99	2.96	2.95	3.24	3.01	2.65	3.17
JW	3.04	3.09	3.45	2.68	2.88	2.61	3.1	2.66	3.04	2.98
SB	2.95	3.07	3.28	3.2	3.09	3.12	3.17	2.76	2.57	2.99
KM	3.16	3.46	3.29	3.16	3.23	3.29	2.99	3.16	3.05	2.88
JB	2.81	2.92	3.06	3.19	2.72	2.59	2.87	3.09	2.75	2.73
IS	3.93	3.26	3.34	3.3	3.21	2.88	3.56	3.01	3.31	2.80
SG	2.25	3.1	2.49	3.14	2.96	2.71	2.32	2.85	2.9	2.59
RS	3.46	3.37	3.33	3.12	3.47	3.5	3.48	2.98	3.17	3.47
CB	3.01	2.51	3.33	2.98	2.94	2.86	2.87	2.95	2.55	2.87
MEAN	3.04	3.07	3.17	3.09	3.05	3.06	3.03	3.04	3.03	3.06
SD	0.41	0.25	0.26	0.16	0.2	0.32	0.33	0.2	0.28	0.28

b) LATE-ONSET MYOPES (N=10)

i) 0Δ

Mins	1	2	3	4	5	6	7	8	9	10
JR	3.18	3.27	3.24	3.37	3.27	3.19	3.21	3.43	3.15	3.58
SL	2.71	2.68	3.02	3.17	2.59	2.65	2.49	2.56	2.73	3.09
WT	3.08	3.16	3.17	3.19	2.96	3.25	3.1	3.12	2.9	2.85
AH	2.5	2.17	2.33	2.31	2.25	2.28	2.36	2.17	2.52	1.97
TM	2.78	3.04	3.43	3.67	3.32	3.34	2.83	2.97	3.1	3.26
LP	2.35	2.27	2.79	2.63	2.53	2.8	2.56	2.7	2.69	2.74
TH	3.11	3.44	3.22	2.72	3.09	2.96	2.77	2.75	3.11	2.62
RL	2.51	2.81	3.42	3.35	3.12	2.93	2.61	3.2	3.36	3.38
RC	2.11	2.79	1.59	2.43	2.17	2.06	2.29	2.12	2.71	2.5
PB	2.52	2.47	2.45	2.58	2.48	2.75	2.16	2.25	2.38	2.25
MEAN	2.69	2.81	2.87	2.94	2.78	2.82	2.64	2.73	2.87	2.82
SD	0.33	0.4	0.56	0.44	0.4	0.39	0.32	0.43	0.29	0.48

ii) 3Δ

Mins	1	2	3	4	5	6	7	8	9	10
JR	3.01	3.14	3.08	3.18	3.73	3.62	3.58	3.56	3.93	3.32
SL	3.51	3.63	3.3	3.27	3.53	2.98	2.81	3.1	3.43	3.26
WT	3.53	3.63	3.65	3.64	3.58	3.05	4.05	3.7	3.35	3.55
AH	2.65	2.87	2.86	2.69	2.76	2.84	2.65	2.55	2.87	2.98
TM	3.99	3.53	3.5	4.06	3.4	3.89	3.22	2.31	3.26	3.51
LP	2.64	2.46	2.62	2.61	2.64	2.41	2.33	3.01	2.77	3.08
TH	2.75	3.51	3.32	2.66	3.22	2.72	3.11	3.15	2.64	3.16
RL	2.53	3.11	2.82	3.35	2.81	2.45	3.31	2.9	2.8	3.36
RC	2.38	2.03	2.5	2.27	2.26	2.73	2.75	2.56	2.83	2.71
PB	2.34	2.2	2.87	2.45	2.36	2.95	2.29	2.92	2.71	2.56
MEAN	2.93	3.01	3.05	3.02	3.03	2.97	3.01	2.98	3.06	3.15
SD	0.53	0.57	0.36	0.54	0.5	0.45	0.53	0.41	0.39	0.31

iii) 6Δ

Mins	1	2	3	4	5	6	7	8	9	10
JR	3.39	3.5	3.48	3.32	3.79	3.17	3.42	3.97	3.42	3.68
SL	2.97	2.89	3.00	2.9	3.27	3.12	2.97	3.29	3.39	3.3
WT	3.4	3.19	3.07	3.25	3.41	3.67	3.31	2.87	3.5	2.91
AH	3.14	2.35	2.72	2.9	2.56	2.73	3.00	2.76	2.48	2.62
TM	3.57	3.21	3.68	3.36	3.41	3.14	3.68	3.40	3.2	3.26
LP	2.84	2.45	2.74	2.79	2.48	2.83	3.02	2.85	2.87	2.98
TH	2.83	3.11	3.18	2.37	2.84	2.84	2.97	2.83	2.76	3.10
RL	4.34	5.32	5.17	4.86	4.42	5.48	5.45	5.23	4.5	5.47
RC	2.18	2.03	2.26	2.15	3.02	2.69	2.26	1.83	2.56	2.40
PB	1.55	2.9	3.2	2.70	2.83	2.75	2.62	2.36	2.14	2.57
MEAN	3.02	3.01	3.25	3.06	3.2	3.24	3.27	3.14	3.08	3.23
SD	0.72	0.85	0.74	0.71	0.56	0.8	0.82	0.89	0.64	0.83

APPENDIX 6

ACCOMMODATIVE ADAPTATION INDUCED BY SUSTAINED DISPARITY-VERGENCE.

PRE-TASK VALUES OF DF (D) AND POST-TO PRE-TASK SHIFT IN DF (D)

1) 3 MINUTE TASK

EMMETROPES

0Δ	PRE-	10	20	30	40	50	60	70	80	90
RB	1.31	-0.38	-0.64	-0.53	-0.74	-0.81	-0.77	-0.86	-0.86	-0.89
ST	0.6	0.19	0.14	-0.02	-0.04	-0.06	-0.11	-0.15	-0.23	-0.01
JW	0.65	1.89	1.29	0.72	0.13	0.93	0.21	-0.13	-0.24	-0.38
SB	-0.17	0.86	0.45	0.3	0.39	0.35	0.21	0.24	0.36	0.37
KM	0.15	0.12	-0.15	0.04	0.08	0.04	-0.08	0	-0.22	-0.24
JB	-0.04	0.43	0.41	0.21	0.26	0.78	0.27	0.09	0.33	0.19
IS	1	0.34	0.03	-0.29	-0.27	-0.3	-0.45	-0.6	-0.63	-0.65
SG	0.87	0.84	0.37	-0.26	-0.38	-0.48	-0.55	-0.36	-0.65	-0.5
RS	-0.33	0.54	0.68	0.46	0.37	0.2	0.33	0.24	0.39	0.19
CB	0.59	2.7	2.88	1.9	1.48	0.37	-0.07	1.09	0.6	0.97
MEAN	0.46	0.75	0.55	0.25	0.13	0.1	-0.1	-0.04	-0.12	-0.1
SD	0.51	0.86	0.91	0.65	0.56	0.51	0.36	0.5	0.48	0.52

3Δ	PRE-	10	20	30	40	50	60	70	80	90
RB	0.51	0.48	-0.02	0.07	0.22	0.1	-0.39	-0.28	-0.06	-0.03
ST	1.2	-0.28	-0.34	-0.35	-0.37	-0.49	-0.42	-0.4	-0.3	-0.36
JW	1.16	0.64	0.04	-0.12	-0.35	-0.47	-0.4	0.57	0.33	0.48
SB	0.69	-0.06	0.12	-0.05	-0.18	-0.2	-0.14	-0.13	0.09	0
KM	0.18	0.63	-0.06	0.05	-0.27	-0.28	-0.33	-0.47	-0.25	-0.18
JB	-0.05	0.47	0.32	0.15	0.19	0.23	0.18	0.16	0.21	0.24
IS	0.56	0.6	0.5	0.11	-0.05	-0.31	0.23	-0.13	-0.31	-0.19
SG	0.81	0.6	0.45	0.16	-0.32	-0.17	-0.34	0.09	0.31	0.18
RS	2.4	1.8	2.11	3.04	2.51	2.4	1.66	2.08	2.49	1.8
CB	0.05	0.89	0.3	0.5	0.92	0.47	0.27	0.38	0.05	0.16
MEAN	0.75	0.58	0.34	0.36	0.23	0.13	0.03	0.19	0.26	0.21
SD	0.68	0.53	0.64	0.92	0.85	0.81	0.6	0.71	0.78	0.58

6Δ	PRE-	10	20	30	40	50	60	70	80	90
RB	0.64	0.26	-0.23	-0.21	-0.4	-0.01	-0.17	-0.17	0.04	-0.05
ST	0.66	-0.11	-0.15	0.14	-0.08	-0.03	0.17	-0.18	-0.18	-0.14
JW	0.99	0.63	0.79	0.1	-0.13	-0.41	-0.07	0.12	-0.5	-0.64
SB	0.3	0.37	0.44	0.41	0.24	0.28	0.24	0.06	0.28	0.17
KM	0.61	0.54	-0.05	0.15	-0.11	-0.1	-0.59	-0.67	-0.73	-0.75
JB	-0.02	0.22	0.08	0.41	0.04	-0.03	0.04	0.03	0.05	0.11
IS	0.17	0.86	0.38	0.1	0.33	-0.08	0.09	0.19	0.08	0.17
SG	0.68	0.37	0.08	0.1	0.08	0.01	-0.3	0.21	0.32	0.4
RS	1.38	-1.04	-1.15	-1.29	-1.34	-1.27	-1.44	-1.44	-1.49	-1.35
CB	1.2	1.18	-0.5	0.05	-0.08	0.2	0.23	0.35	-0.4	-0.44
MEAN	0.66	0.33	-0.03	0	-0.15	-0.14	-0.18	-0.15	-0.25	-0.25
SD	0.41	0.57	0.51	0.46	0.44	0.41	0.48	0.5	0.52	0.51

LOMs

0Δ	PRE-	10	20	30	40	50	60	70	80	90
JR	0.52	0.77	0.96	1	1.16	0.83	0.87	0.63	0.84	0.8
SL	0.16	0.39	0.52	0.18	-0.09	-0.05	0.15	-0.06	0.17	0.06
WT	1.45	1.08	-0.07	-0.43	0.34	0.85	0.32	1.05	0.68	1.00
AH	1.87	0.46	0.63	0.53	-0.18	-0.61	-0.99	-1.38	-1.2	-0.93
AM	0.02	0.85	0.63	0.14	0.44	0.1	-0.16	-0.16	0.19	0.09
LP	0.33	0.3	0.01	-0.02	0.14	0.09	-0.03	0.04	-0.17	-0.07
TH	0.8	0.21	0.23	0.71	0.63	0.5	0.35	0.25	0.37	0.33
RL	0.13	0.3	0.14	-0.29	-0.34	-0.26	0.5	0.54	0.26	-0.06
RC	0.63	0.3	0.26	0.14	-0.34	-0.03	-0.17	-0.13	-0.21	-0.09
PB	-0.11	0.49	0.76	0.57	0.26	0.38	0.33	0.42	0.01	-0.18
MEAN	0.58	0.52	0.41	0.25	0.2	0.18	0.12	0.12	0.09	0.1
SD	0.61	0.27	0.32	0.42	0.44	0.44	0.47	0.61	0.53	0.51

3Δ	PRE-	10	20	30	40	50	60	70	80	90
JR	0.12	1.17	0.67	0.53	0.8	0.97	1.04	0.54	0.95	1.14
SL	0.21	1.28	1.08	0.34	0.12	-0.06	0.04	-0.2	-0.13	-0.17
WT	0.96	0.87	-0.21	-0.13	0.32	1.11	0.55	1.44	0.04	-0.81
AH	0.16	2.01	2.26	1.95	2.62	1.18	-0.1	-0.06	-0.09	0.31
AM	-0.01	0.64	0.12	0.06	0	0.22	0.05	0.31	-0.02	0.26
LP	0.46	1.06	0.31	0.24	0	0.15	-0.04	-0.07	-0.11	0.2
TH	1.06	-0.11	-0.28	-0.28	-0.04	0.3	-0.09	-0.23	-0.06	-0.11
RL	-0.21	0.83	0.68	0.65	0.37	0.43	0.32	0.23	0.14	-0.04
RC	0.25	0.28	0.3	0.09	0.11	0.13	0.04	0.18	0.09	0.11
PB	0.97	0.09	0.42	0.41	0.28	0.32	0.48	0.59	0.38	0.06
MEAN	0.4	0.74	0.49	0.35	0.42	0.4	0.21	0.25	0.11	0.09
SD	0.42	0.56	0.66	0.56	0.72	0.43	0.33	0.45	0.29	0.43

6Δ	PRE-	10	20	30	40	50	60	70	80	90
JR	0.23	1.45	0.65	0.72	0.81	1.41	1.23	1.57	1.57	0.71
SL	0.24	0.45	0.23	-0.29	0.13	0.09	0.04	-0.09	0	0.14
WT	1.22	-0.75	-1.26	-0.64	0.38	0.84	1.12	0.31	0.8	1.25
AH	0.1	0.92	0.73	0.44	0.39	0.23	0.14	-0.12	0.07	-0.14
AM	-0.26	0.89	0.28	0.65	0.42	0.3	0.25	0.42	1.18	1.09
LP	0.51	0.1	0.02	-0.42	-0.5	-0.49	-0.53	-0.71	-0.71	-0.32
TH	0.77	0.15	0.06	-0.1	-0.23	-0.29	-0.29	-0.45	-0.24	-0.36
RL	0.6	0.25	-0.01	0.55	0.45	-0.28	-0.03	0.18	0.31	0.5
RC	0	0.07	0.08	0.07	0.34	0.15	0.16	0.14	0.03	0.24
PB	0.46	-0.08	0.01	0.17	0.22	0.35	0.17	-0.02	0.28	0.47
MEAN	0.39	0.35	0.08	0.12	0.23	0.23	0.23	0.12	0.33	0.36
SD	0.4	0.58	0.51	0.44	0.35	0.53	0.52	0.58	0.64	0.52

2) 10 MINUTE TASK
EMMETROPES

0Δ	PRE-	10	20	30	40	50	60	70	80	90
RB	0.85	0.57	-0.12	-0.28	-0.48	-0.42	-0.53	-0.5	-0.34	-0.2
ST	0.74	0.1	0.07	-0.11	-0.13	0.06	0.07	-0.2	-0.24	0.03
JW	0.86	1.9	0.14	-0.36	-0.27	-0.04	0.05	-0.18	-0.17	-0.18
SB	0.6	0.15	0	-0.18	0.03	0.07	-0.29	-0.29	-0.27	0.03
KM	0.06	-0.02	0.09	-0.01	0.04	0.01	-0.06	-0.44	-0.14	-0.08
JB	0.31	-0.03	-0.14	-0.29	-0.33	-0.08	-0.09	-0.14	0.11	-0.15
IS	-0.07	1.41	0.89	0.39	0.11	0.01	0.13	-0.06	0.01	-0.25
SG	0.96	0.84	0.42	0.49	0.45	-0.09	-0.12	-0.2	-0.27	-0.24
RS	2.46	-1.95	-1.91	-1	-1.02	0.07	1.2	0.89	-1.57	-2.41
CB	0.72	3.75	4.02	1.84	1.31	0.37	0.58	0.89	1.16	1.23
MEAN	0.75	0.67	0.35	0.05	-0.03	0	0.09	-0.02	-0.17	-0.22
SD	0.66	1.41	1.4	0.71	0.58	0.18	0.45	0.47	0.62	0.83

3Δ	PRE-	10	20	30	40	50	60	70	80	90
RB	1.03	0.55	-0.25	-0.54	-0.64	-0.38	-0.22	-0.48	-0.46	-0.45
ST	0.31	0.52	0.3	0.1	-0.03	-0.06	-0.11	-0.41	-0.53	-0.46
JW	0.63	1.49	0.51	0.78	-0.45	-0.01	0.02	-0.41	-0.41	0.14
SB	0.21	0.33	0.22	0.16	0.49	0.27	0.23	-0.19	-0.27	-0.01
KM	0.56	0.58	0.38	0.79	0.44	0.22	-0.2	-0.16	0.06	-0.11
JB	0.03	0.14	-0.03	0.31	0.13	0.19	0.15	0.42	0.16	0.14
IS	0.07	0.55	0.46	0.21	0.11	0.22	0.3	0.06	0.12	0.38
SG	0.54	0.43	0.2	-0.02	0.01	0.18	0.33	0.29	0.22	0.26
RS	0.39	0.34	0.15	0.08	0.02	0.03	0.04	0.02	0.07	-0.01
CB	1.61	1.08	-0.58	-0.83	-0.23	-0.88	-0.4	0.19	0.54	-0.01
MEAN	0.54	0.6	0.14	0.1	-0.02	-0.02	0.01	-0.07	-0.05	-0.02
SD	0.45	0.37	0.32	0.47	0.33	0.34	0.23	0.29	0.33	0.26

6Δ	PRE-	10	20	30	40	50	60	70	80	90
RB	0.74	0.46	0.05	-0.21	-0.42	-0.1	-0.09	-0.28	-0.12	0.61
ST	0.61	0.06	-0.3	-0.18	-0.41	-0.16	-0.59	-0.34	-0.15	0.37
JW	1.04	2.06	0.45	0.28	-0.17	-0.31	-0.13	-0.26	-0.66	-0.47
SB	0.35	0.02	-0.15	-0.28	-0.18	-0.24	-0.23	-0.28	-0.23	-0.18
KM	-0.11	0.13	0.12	-0.06	0.06	-0.21	0.1	-0.22	-0.14	0.04
JB	0.05	0.27	0.3	0.43	0.2	0.09	0.02	-0.02	0.28	0.03
IS	0.15	1.09	0.61	-0.05	-0.11	0.04	0.01	0.37	0.09	0.22
SG	0.43	1.01	0.63	0.12	0	-0.04	0.05	0.01	0.27	0.31
RS	1.24	-0.64	-0.66	-0.62	-0.68	-0.43	-0.7	-0.72	-0.74	-0.58
CB	0.64	0.39	0.13	0.08	-0.23	-0.43	-0.62	-0.64	-0.6	-0.84
MEAN	0.51	0.49	0.12	-0.05	-0.19	-0.18	-0.22	-0.24	-0.2	-0.05
SD	0.4	0.7	0.39	0.28	0.24	0.17	0.28	0.29	0.35	0.43

LOMs

0Δ	PRE-	10	20	30	40	50	60	70	80	90
JR	1.02	0.86	0.67	0.2	0.31	0.65	0.14	-0.03	0.28	0.19
SL	0.11	0.24	0.09	-0.17	-0.08	-0.01	0.03	-0.16	-0.05	-0.14
WT	0.53	1.12	1.24	1.32	1.3	1.98	1.32	0.04	-0.11	0.1
AH	0.14	0.86	0.49	0.39	0.43	0.33	0.33	0.02	-0.05	0.19
AM	0.54	1.04	0.14	0.2	-0.02	0.25	-0.15	-0.34	-0.45	-0.65
LP	0.66	0.56	0.44	-0.17	0.18	-0.31	-0.27	-0.1	-0.25	0.16
TH	1.31	-0.12	-0.05	-0.03	-0.32	0.16	0.04	-0.2	-0.36	-0.39
RL	-0.22	0.74	0.04	-0.3	-0.05	0.09	1.13	1.85	2.37	3.13
RC	0.9	0.28	0.22	0.11	0.42	-0.38	-0.26	-0.25	-0.42	-0.01
PB	0.77	0.57	0.31	0.28	0.4	0.45	0.07	-0.18	-0.27	-0.03
MEAN	0.58	0.62	0.36	0.18	0.26	0.32	0.24	0.07	0.07	0.26
SD	0.43	0.37	0.36	0.43	0.42	0.62	0.52	0.6	0.79	0.99

3Δ	PRE-	10	20	30	40	50	60	70	80	90
JR	0.6	0.89	0.48	0.64	1.06	0.89	0.97	0.65	0.23	0.5
SL	0.17	1.51	0.74	0.19	-0.02	0.1	-0.04	0.05	0.27	0.24
WT	1.32	1.05	1	0.12	0.96	0.39	0.8	1.41	1.35	2.68
AH	0.15	0.68	0.75	0.42	0.32	0.31	0.16	0.43	0.43	0.43
AM	-0.02	1.18	0.77	1.02	0.78	0.51	0.38	0.48	0.42	0.78
LP	0.38	0.13	-0.13	-0.156	-0.07	-0.01	-0.22	0	-0.01	0.01
TH	0.92	-0.01	0.31	0.56	0.31	0.25	0.23	0.16	-0.02	0.01
RL	0	1.54	1.14	0.9	0.88	0.84	1.74	2.25	0.96	1.16
RC	0.73	0.93	0.4	0.24	0.45	0.5	0.4	0.14	0.2	0.19
PB	0.63	0.3	0.47	0.36	0.2	0.2	0.2	0.33	0.75	1.01
MEAN	0.49	0.82	0.59	0.43	0.49	0.4	0.46	0.59	0.46	0.7
SD	0.41	0.51	0.35	0.34	0.38	0.28	0.54	0.67	0.42	0.76

6Δ	PRE-	10	20	30	40	50	60	70	80	90
JR	0.82	0.84	0.8	0.65	-0.01	0.31	0.28	-0.08	-0.58	-0.19
SL	0.06	0.38	1.12	1.86	0.57	0.26	0.35	0.63	0.32	0.28
WT	1.04	0.54	1.28	1.82	0.55	0.02	2.98	2.63	2.97	2.93
AH	0.55	1.35	1.49	1.37	1.12	0.26	-0.36	0.14	0	-0.17
AM	-0.16	1.38	1.14	2.09	1.01	1.13	0.6	1.02	0.57	0.42
LP	0.72	0.33	-0.13	-0.05	-0.25	-0.51	0.02	0.31	0.26	0.19
TH	1.58	-0.24	0.25	-0.03	-0.31	-0.23	-0.32	-0.13	-0.73	-0.44
RL	-0.41	1.16	0.75	0.28	-0.06	-0.37	0.1	0.35	0.59	0.82
RC	0.01	0.4	0.36	0.35	0.28	0.11	0.09	0.02	0.18	0.3
PB	0.62	0.51	0.58	0.52	-0.11	-0.03	-0.09	-0.28	-0.19	0.06
MEAN	0.48	0.65	0.76	0.91	0.31	0.07	0.37	0.52	0.44	0.49
SD	0.57	0.48	0.48	0.77	0.48	0.43	0.91	0.81	0.97	0.9

APPENDIX 7

ASSESSMENT OF THE CA/C RATIO IN A MYOPIC POPULATION

Values of CA/C ratio (D/6Δ) for the 0-6Δ vergence stimulus range.

1) EMMETROPES

	PH	SPOT 33cms	SPOT 1m	MEAN
JW	0.39	0.13	0.58	0.37
KA	-0.03	-0.06	-0.04	-0.04
DC	0.22	0.45	0.26	0.31
PC	0.68	0.45	0.46	0.53
CS	0.45	0.91	0.3	0.55
RB	0.72	0.71	0.16	0.53
SG	0.51	0.18	0.12	0.27
JB	0.02	0.4	0.45	0.00
ST	0.77	1.14	0.33	0.75
DB	0.37	0.27	0.47	0.37
MEAN	0.41	0.46	0.31	0.39
SD	0.26	0.35	0.18	0.20

2) LOMs

AE	0.16	0.44	0.30	0.30
RL	0.65	0.30	0.70	0.55
JL	0.02	0.41	0.28	0.24
JR	0.46	0.96	0.57	0.66
AC	0.97	0.98	0.36	0.77
AM	-0.15	-0.21	-0.04	-0.13
PB	0.34	0.5	0.11	0.32
NS	0.66	0.37	0.13	0.39
TH	0.10	0.48	0.09	0.22
SL	0.57	0.77	0.39	0.58
MEAN	0.38	0.5	0.29	0.39
SD	0.33	0.33	0.22	0.25

3) EOMs

AH	0.86	0.4	0.22	0.49
CN	0.6	0.11	0.27	0.33
JG	0.49	0.49	0.77	0.58
SB	0.21	0.01	0.2	0.14
DB	0.79	0.58	0.26	0.54
SD	0.13	0.51	0.13	0.26
RDH	0.00	-0.08	0.06	0.00
BH	0.56	0.14	0.07	0.26
MG	0.54	0.43	0.4	0.46
TP	0.38	0.11	0.65	0.38
MEAN	0.46	0.27	0.30	0.34
SD	0.26	0.22	0.23	0.18

APPENDIX 8

THE EFFECT OF VERGENCE ADAPTATION ON CONVERGENT ACCOMMODATION

Values of convergent accommodation (D) measured over a 6Δ vergence stimulus range during a sustained 3 min near-vision task.

Time (secs)	RB	LN	TJ	KA	PF	DC
10	0.68	0.45	0.57	1.00	0.09	0.61
20	0.36	0.59	0.48	1.22	-0.1	0.34
30	0.48	0.42	0.54	1.49	-0.41	0.73
40	0.65	0.92	0.83	1.72	-0.11	0.96
50	0.67	0.52	0.71	1.71	-0.03	0.66
60	0.53	0.51	0.66	1.10	0.5	0.66
70	0.26	0.61	0.92	2.07	1.07	0.60
80	0.33	0.64	1.03	2.12	1.41	0.67
90	0.46	0.97	1.33	2.56	1.83	0.81
100	0.47	0.72	1.09	3.15	0.42	0.70
110	0.48	0.82	0.92	2.97	0.48	0.33
120	0.49	1.15	1.15	3.09	0.54	0.49
130	0.29	0.64	0.90	2.57	0.65	0.35
140	0.42	0.33	1.02	3.05	0.80	0.50
150	0.60	0.30	1.08	2.77	1.07	0.67
160	0.87	0.44	0.81	1.85	0.43	0.44
170	0.42	0.28	0.46	0.96	-0.04	0.68
180	0.50	0.62	0.08	1.23	0.42	-2.28

Time (secs)	CT	VV	MCS	CB	MEAN	SD
10	-0.19	-1.45	0.39	-0.16	0.16	0.68
20	0.33	-0.90	0.29	0.44	0.29	0.53
30	0.71	-1.04	0.07	-0.29	0.24	0.71
40	0.60	-1.00	0.15	0.00	0.43	0.74
50	0.42	-1.29	0.36	0.09	0.35	0.74
60	0.65	-1.65	0.09	0.56	0.33	0.74
70	0.96	-1.66	0.53	0.12	0.51	0.74
80	0.81	-1.41	1.57	-0.13	0.67	0.98
90	0.56	-1.43	1.05	-0.17	0.74	1.07
100	0.72	-0.94	1.18	-0.48	0.66	1.08
110	0.65	-0.92	0.38	-0.78	0.49	1.11
120	0.43	-0.65	0.35	0.34	0.69	0.95
130	0.52	-0.63	0.32	0.69	0.60	0.79
140	0.70	-0.43	0.78	-0.11	0.67	0.93
150	0.41	-0.31	0.33	0.75	0.73	0.80
160	0.29	-0.58	0.19	0.52	0.49	0.60
170	0.36	-0.29	0.89	-0.01	0.36	0.40
180	0.54	-0.23	0.74	0.95	0.47	1.04

APPENDIX 9

TEMPORAL ASPECTS OF ACCOMMODATIVE ADAPTATION

Pre-task values of DF (D) and post- to pre-task shift in DF (D).

1) EMMETROPES

a) MONOCULAR

15s TASK

	PRE-	10	20	30	40	50	60	70	80	90
RTW	0.14	1.04	0.43	0.27	0.57	0.36	0.31	0.18	0.24	0.29
DC	1.18	-0.27	-1.11	-1.52	-1.48	-1.29	-1.63	-1.33	-0.78	-0.7
RB	0.86	0.03	-0.25	-0.29	-0.54	-0.62	-0.73	-0.65	-0.3	-0.46
KA	0.03	2.05	1.09	0.59	0.8	1.51	1.51	1.25	1.77	1.24
JL	-0.2	0.88	0.47	0.17	-0.04	-0.01	0.06	0.09	-0.1	0.01
RS	-0.17	1.06	0.55	0.29	0.32	0.19	0.32	0.26	0.17	0.23
IB	-0.02	0.31	-0.11	-0.42	-0.4	-0.14	-0.01	0.01	0.17	0.13
CB	0.78	1.01	-0.21	-0.11	-0.22	0.02	-0.18	-0.28	-0.39	0.11
SB	0.05	0.16	-0.01	0.4	0.01	-0.11	-0.26	-0.13	-0.28	-0.36
JB	0.1	0.17	0.18	0.04	0.05	0.2	-0.02	0.05	-0.02	-0.09
MEAN	0.28	0.64	0.1	-0.06	-0.09	0.01	-0.06	-0.06	0.05	0.04
SD	0.46	0.65	0.56	0.57	0.61	0.68	0.76	0.62	0.64	0.5

30s TASK

	PRE-	10	20	30	40	50	60	70	80	90
RTW	0.07	0.9	0.72	0.5	0.27	0.38	0.42	0.16	-0.02	0.07
DC	0.99	0.45	-0.39	-0.1	-0.56	-0.33	0.02	-0.81	0.31	0.63
RB	0.56	0.35	-0.32	-0.58	-0.73	-0.63	-0.53	-0.48	-0.48	-0.54
KA	0.86	1.36	1.46	1.08	1.1	1.58	2.69	1.76	1.41	0.99
JL	-0.13	0.59	0.05	-0.15	-0.22	-0.18	-0.1	-0.15	-0.11	-0.06
RS	-0.03	0.33	0.13	0.38	1.26	0.96	0.81	0.59	0.87	1.27
IB	0.29	0.42	0.16	0.06	-0.11	-0.15	-0.23	-0.25	-0.34	-0.45
CB	0.69	0.86	1.11	0.79	0.56	1.14	0.46	0.01	-0.15	-0.36
SB	-0.1	0.36	0.22	0.21	0.11	0.22	0.09	-0.08	0.14	0.15
JB	-0.07	0.31	0.17	0.01	0.32	0.03	-0.36	-0.09	0.05	-0.13
MEAN	0.31	0.59	0.33	0.22	0.2	0.3	0.33	0.06	0.17	0.16
SD	0.41	0.32	0.56	0.46	0.61	0.67	0.87	0.66	0.54	0.18

45s TASK

	PRE-	10	20	30	40	50	60	70	80	90
RTW	0.52	1.16	0.68	0.51	0.26	0.24	0.42	0.38	0.75	0.55
DC	0.45	0.56	-0.33	-0.75	-0.8	-0.69	-0.29	-0.2	-0.69	-0.68
RB	0.63	0.67	0.15	-0.45	-0.43	-0.41	-0.38	-0.72	-0.63	-0.48
KA	1.15	0.29	-0.2	-0.41	-0.68	-0.57	-0.58	-0.73	-0.43	-0.32
JL	-0.09	0.34	-0.04	0.19	0.23	0.29	-0.07	0	-0.08	-0.13
RS	0.27	0.59	0.41	0.12	0.31	1.11	0.73	0	0.08	-0.14
IB	-0.82	0.72	0.26	0.1	0.06	-0.05	0.08	-0.14	0.25	0.56
CB	0.6	0.92	0.03	0.26	-0.02	0.05	0.2	-0.01	-0.2	0.02
SB	-0.07	0.67	0.39	0.23	0.23	0.19	-0.02	-0.23	0.07	0.03
JB	-0.11	-0.02	-0.3	-0.32	-0.35	-0.5	-0.51	-0.54	-0.55	-0.39
MEAN	0.25	0.59	0.11	-0.08	-0.16	-0.07	-0.04	-0.24	-0.15	-0.1
SD	0.51	0.31	0.32	0.39	0.4	0.53	0.42	0.34	0.45	0.41

b) BINOCULAR

15s TASK

	PRE-	10	20	30	40	50	60	70	80	90
RTW	0.26	0.31	0.1	-0.29	-0.14	-0.13	-0.12	0.01	-0.27	-0.25
DC	0.26	0.67	0.15	-0.45	-0.43	-0.41	-0.38	-0.72	-0.63	-0.48
RB	0.67	0.18	-0.42	-0.54	-0.67	-0.32	-0.52	-0.45	-0.7	-0.5
KA	0.38	1.63	2.47	1.19	1.14	1.33	1.83	0.89	0.33	-0.22
JL	-0.18	0.49	-0.06	-0.13	-0.47	-0.1	-0.1	-0.22	0.2	-0.11
RS	-0.03	1.12	0.42	0.09	0.33	0.09	-0.01	-0.02	0.01	-0.07
IB	-0.09	0.95	0.31	-0.03	-0.27	-0.4	-0.65	-0.57	-0.32	-0.72
CB	0.49	0.27	-0.03	0.17	0.06	0.06	0.25	0	0.2	0.26
SB	0.26	0.17	0.06	-0.08	-0.21	-0.22	-0.32	-0.45	-0.21	-0.14
JB	-0.57	0.4	0.16	0.13	-0.06	-0.03	-0.04	-0.12	-0.13	-0.35
MEAN	0.15	0.62	0.32	0	-0.07	-0.01	-0.01	-0.15	-0.15	-0.19
SD	0.35	0.45	0.75	0.46	0.49	0.48	0.66	0.43	0.33	0.32

30s TASK

	PRE-	10	20	30	40	50	60	70	80	90
RTW	-0.09	0.9	0.45	0.36	0.35	0.24	0.24	0.27	0.28	0.2
DC	0.56	0.69	0.21	-0.35	-0.82	-0.84	-0.39	-1.02	-1.07	-0.79
RB	0.41	0.56	-0.13	-0.17	-0.02	-0.02	0.08	0.25	0.12	0.1
KA	0.07	2.16	1.22	0.96	0.86	-0.1	-0.16	-0.07	-0.08	-0.45
JL	-0.46	0.46	-0.08	-0.13	-0.08	-0.01	-0.19	0.12	-0.24	-0.22
RS	-0.08	0.75	0.42	0.24	0.18	0.18	0.12	0.12	0.01	0.01
IB	0.25	0.84	0.27	0.4	0.38	0.04	0.1	-0.3	-0.07	-0.32
CB	0.83	1.08	0.52	-0.02	-0.27	-0.32	0.62	0.59	-0.43	-0.28
SB	-0.09	0.28	0.3	0.23	-0.02	0.1	0.18	0.15	0.08	0.21
JB	0.17	0.09	-0.3	-0.4	-0.52	-0.47	-0.36	-0.32	-0.49	-0.53
MEAN	0.16	0.78	0.29	0.11	0	-0.12	0.02	-0.02	-0.19	-0.21
SD	0.35	0.54	0.4	0.39	0.45	0.31	0.29	0.42	0.37	0.31

45s TASK

	PRE-	10	20	30	40	50	60	70	80	90
RTW	-0.16	0.8	0.55	0.47	0.43	0.4	0.35	0.38	0.33	0.47
DC	0.17	0.61	0.4	0.78	0.15	-0.26	-0.41	-0.69	-0.83	-0.65
RB	0.66	0.31	-0.17	-0.19	-0.19	-0.09	-0.18	-0.26	-0.22	-0.3
KA	-0.03	1.41	0.89	1.62	0.38	0.34	-0.16	-0.62	-0.61	-0.35
JL	0.07	0.41	-0.3	-0.48	-0.42	-0.4	-0.39	-0.68	-0.31	-0.27
RS	0.4	0.35	-0.14	-0.37	-0.05	-0.38	-0.31	-0.28	0.07	-0.39
IB	-0.05	0.77	0.31	0.17	-0.08	-0.01	0.1	0.06	-0.26	-0.09
CB	0.78	0.74	0.26	-0.45	-0.13	0.16	-0.2	-0.15	-0.14	0.04
SB	0.4	0.32	-0.29	-0.33	-0.13	-0.24	-0.25	-0.28	-0.36	-0.23
JB	0.2	0.16	-0.13	-0.25	-0.22	0	0.04	0.02	-0.04	0.11
MEAN	0.24	0.59	0.14	0.1	-0.03	-0.05	-0.14	-0.25	-0.24	-0.17
SD	0.29	0.34	0.38	0.64	0.25	0.26	0.23	0.33	0.31	0.3

2)LATE-ONSET MYOPES

a) MONOCULAR

15s TASK

	PRE-	10	20	30	40	50	60	70	80	90
JR	0.61	-0.81	-1.02	-0.82	-0.38	-0.8	-0.66	-0.65	-0.77	-0.46
AE	4.02	-3.49	-3.75	-3.08	-2.03	-3.01	-2.81	-3.33	-3.82	-3.92
PB	0.7	0.26	0.77	0.75	0.83	0.71	0.37	0.36	0.03	0.22
LP	0.4	0.33	0.3	0.3	0.23	0.22	-0.21	-0.32	-0.05	-0.04
NF	0.15	0.73	-0.01	0.25	0.59	0.67	0.98	0.88	0.83	0.9
CMD	0.47	1	0.24	0.31	-0.02	0.06	0.21	0.12	0.4	0.36
SL	0.05	0.79	0.74	0.2	0.4	0.58	0.46	0.14	0.06	0.08
AM	-0.99	1.21	0.91	0.44	0.21	0.22	0.03	-0.02	0.23	0.14
NS	0.18	0.11	0.02	-0.05	0.22	0.4	0.24	0.55	0.34	0.36
WT	1.45	1.5	1.23	1.1	0.26	-0.22	0.02	-0.81	-1.16	-0.1
MEAN	0.7	0.16	-0.06	-0.06	0.03	-0.12	-0.14	-0.31	-0.39	-0.27
SD	1.25	1.36	1.36	1.12	0.75	1.06	0.98	1.12	1.27	1.26

30s TASK

	PRE-	10	20	30	40	50	60	70	80	90
JR	0.95	0.43	-0.17	-0.48	-0.57	-0.45	-0.31	-0.32	-0.36	-0.14
AE	3.75	-2.59	-2.76	-2.5	-2.42	-2.11	-2.17	-2.34	-2.78	-1.55
PB	0.07	0.67	0.46	0.23	0.26	0.47	0.45	0.39	0.46	0.56
LP	0.53	0.62	-0.02	-0.34	0	-0.2	-0.37	0.13	-0.25	0.09
NF	-0.31	0.51	0.34	0.39	0.41	0.66	0.66	0.37	-0.33	-0.06
CMD	0.74	0.38	0.33	0.36	0.14	0.41	-0.05	-0.03	0.24	-0.14
SL	-0.07	0.23	-0.08	0.07	0.08	-0.01	-0.05	-0.01	-0.01	-0.17
AM	-0.07	1.16	0.53	0.53	0.47	0.29	0.2	-0.08	-0.05	0.1
NS	1.25	0.41	0.18	0.08	0.27	-0.04	-0.45	-0.2	0.16	-0.06
WT	0.86	2.43	1.89	1.99	2.02	2.12	0.54	1.3	-0.13	-0.66
MEAN	0.77	0.43	0.07	0.03	0.07	0.11	-0.16	-0.08	-0.31	-0.2
SD	1.11	1.17	1.09	1.06	1.04	1	0.77	0.86	0.86	0.53

45s TASK

	PRE-	10	20	30	40	50	60	70	80	90
JR	0.62	0.55	-0.27	-0.45	-0.36	-0.54	-0.62	-0.5	-0.26	0
AE	4.88	-4.17	-4.32	-3.72	-4.06	-3.81	-4.44	-4.86	-4.45	-4.42
PB	0.63	0.45	0.6	0.47	0.4	0.29	0.34	0.81	0.77	0.91
LP	0.29	0.05	-0.06	-0.01	-0.03	0.24	1.14	1.75	2.58	1.49
NF	0.4	0.24	-0.05	-0.05	-0.23	-0.23	0.03	0.19	-0.04	-0.06
CMD	0.56	1.06	0.47	-0.01	0.62	0.14	0.16	0.06	0.05	0.08
SL	0.09	0.63	0	-0.2	-0.15	0.27	-0.08	-0.23	-0.15	0.33
AM	-0.03	0.86	0.51	0.44	0.63	0.55	1.06	0.35	0.29	-0.55
NS	0.96	0.14	-0.09	-0.73	-0.26	-1.05	-0.7	-0.79	-0.12	0.09
WT	1.33	1.27	0.98	-1.09	-1.33	-0.74	-0.75	0.01	0.94	-0.72
MEAN	0.97	0.11	-0.22	-0.54	-0.48	-0.49	-0.39	-0.32	-0.04	-0.31
SD	1.36	1.47	1.42	1.15	1.31	1.21	1.49	1.65	1.76	1.58

b) BINOCULAR

15s TASK

	PRE-	10	20	30	40	50	60	70	80	90
JR	0.75	0.54	0.64	1.14	0.58	0.24	-0.07	0.19	0.35	0.23
AE	1.32	-1.06	-1.17	-1.35	-1.43	-0.57	-0.5	-0.25	-0.48	-0.73
PB	0.35	0.1	-0.18	-0.32	-0.19	-0.2	-0.11	-0.24	0.01	0.04
LP	0.22	0.64	0.11	0.03	-0.33	-0.64	-0.81	-0.68	-0.33	0.2
NF	-0.25	-0.08	-0.21	-0.1	0.07	0.14	0.04	-0.24	-0.09	-0.07
CMD	-0.49	0.58	0.62	0.72	0.69	0.82	0.09	-0.01	-0.19	-0.15
SL	0.22	0.7	1.04	0.39	0.17	-0.05	0.05	0.03	0.03	0.02
AM	0	1.12	0.52	0.5	0.88	0.66	0.33	0.54	0.26	0.57
NS	0.16	0.64	0.67	0.12	0.46	0.66	-0.06	0.01	0.09	-0.01
WT	1.71	0.34	-0.75	-1.05	-0.7	-1.08	-0.94	-0.4	-1.12	-1.32
MEAN	0.4	0.35	0.13	0.01	0.02	0	-0.2	-0.11	-0.15	-0.13
SD	0.65	0.57	0.67	0.73	0.67	0.6	0.39	0.32	0.4	0.51

30s TASK

	PRE-	10	20	30	40	50	60	70	80	90
JR	0.58	-0.24	-0.34	-0.51	-0.2	-0.19	-0.52	-0.52	-0.64	-0.87
AE	2.23	-1.11	-1.45	-1.77	-1.82	-1.64	-0.97	-0.53	-1.5	-2.06
PB	0.81	0.74	0.46	0.64	0.73	0.92	0.39	0.5	0.57	0.58
LP	0.01	0.96	0.62	-0.24	-0.41	-0.32	-0.33	-0.32	-0.19	-0.18
NF	-0.53	0.92	0.61	0.49	0.42	0.2	0.25	0.1	0.47	0.98
CMD	-0.01	0.68	0.57	0.33	0.56	0.16	0.22	0.1	0.48	0.27
SL	-0.34	0.2	-0.11	-0.16	-0.05	-0.32	-0.13	-0.28	-0.16	-0.17
AM	-0.04	0.91	0.51	0.19	-0.04	-0.08	-0.08	-0.06	0.19	-0.08
NS	0.63	0.91	1.14	0.57	0.88	0.06	-0.19	-0.17	-0.07	-0.07
WT	1.97	0.76	0.4	-0.48	0.2	0.63	0.47	-1.13	0.56	-0.34
MEAN	0.53	0.47	0.24	-0.09	0.03	-0.06	-0.09	-0.23	-0.03	-0.19
SD	0.88	0.64	0.68	0.68	0.73	0.65	0.42	0.42	0.61	0.78

45s TASK

	PRE-	10	20	30	40	50	60	70	80	90
JR	0.98	-0.25	-0.84	-0.86	-1.07	-1.04	-1.15	-1.1	-1.15	-1.09
AE	2.88	-0.97	-1.75	-2.34	-2.69	-2.58	-2.86	-1.95	-1.74	-1.08
PB	-0.17	0.27	-0.12	-0.2	0.22	-0.08	-0.26	0.28	0.38	0.16
LP	0.04	1.32	0.11	-0.27	-0.31	-0.29	-0.45	-0.29	-0.26	0.00
NF	-0.24	0.17	0.15	0.23	0.35	0.35	0.25	-0.07	0.74	0.71
CMD	0.44	0.64	0.23	0.16	0.19	0.4	0.16	0.17	0.17	0.01
SL	-0.06	0.12	0.18	0.03	-0.19	-0.33	-0.46	-0.22	-0.31	-0.39
AM	-0.11	1.52	0.86	0.41	-0.05	0.15	0.1	0.04	0.02	0.04
NS	0.94	0.43	0.06	-0.32	-0.4	0.26	0.55	0.58	0.71	0.97
WT	1.46	0.37	-0.39	-0.76	-0.76	-0.78	0.54	1.37	1.12	0.86
MEAN	0.58	0.36	-0.15	-0.39	-0.47	-0.39	-0.36	-0.12	-0.03	-0.02
SD	0.94	0.68	0.68	0.75	0.85	0.85	0.96	0.85	0.83	0.68

TIMOLOL TRIAL
45s TASK: BINOCULAR VIEWING

	PRE-	10	20	30	40	50	60	70	80	90
PB	0.35	0.46	0.04	0.53	0.84	0.67	0.81	0.44	0.68	0.87
JR	0.25	1.23	0.44	0.21	0.41	-0.12	-0.19	-0.42	-0.49	-0.34
SL	-0.5	0.56	0.08	-0.1	-0.11	-0.05	0.00	-0.2	-0.01	-0.25
NF	0.22	0.08	0.08	-0.01	-0.16	-0.2	0.05	0.13	-0.07	-0.25
WT	1.00	2.61	2.49	1.43	0.28	-0.51	-0.52	0.12	-0.03	0.01
LP	0.13	0.63	0.15	-0.78	-0.58	-0.83	-0.6	0.05	-0.23	-0.38
TM	0.33	0.84	0.24	0.22	0.21	-0.14	-0.53	-0.43	-0.32	-0.51
AE	0.68	-0.36	-1.04	-1.31	-1.14	-1.06	-0.9	-0.69	-0.99	-0.97
MEAN	0.31	0.76	0.31	0.02	-0.03	-0.28	-0.23	-0.12	-0.18	-0.23
SD	0.41	0.83	0.92	0.77	0.58	0.5	0.5	0.35	0.44	0.49

APPENDIX 10

SUPPORTING PUBLICATIONS

A Rosenfield M, Gilmartin B (1987) Oculomotor consequences of beta-adrenoceptor antagonism during sustained near-vision. Ophthal Physiol Opt 7, 127-130.

B Rosenfield M, Gilmartin B (1987) Effect of a near-vision task on the response AC/A of a myopic population. Ophthal Physiol Opt 7, 225-233.

C Rosenfield M, Gilmartin B (1987) Beta-adrenergic receptor antagonism in myopia Ophthal Physiol Opt 7, 359-364.

D Rosenfield M, Gilmartin B (1987) Synkinesis of accommodation and vergence in late-onset myopia. Am J Optom physiol Opt. 64, 929-937.

E Rosenfield M, Gilmartin B (1988) Accommodative adaptation induced by sustained disparity-vergence. Am J Optom physiol Opt. (in press)

F Rosenfield M, Gilmartin B (1988) Disparity-induced accommodation in late-onset myopia. Ophthal Physiol Opt. (in press)

G Rosenfield M, Gilmartin B (1988) Assessment of the CA/C ratio in a myopic population. Am J Optom physiol Opt (in press)

H Rosenfield M, Gilmartin B (1988) The effect of vergence adaptation on convergent accommodation. Ophthal Physiol Opt. (in press)

I Rosenfield M, Gilmartin B (1988) Accommodative adaptation to monocular and binocular stimuli. Am J Optom physiol Opt (submitted for publication)

J Rosenfield M, Gilmartin B (1988) Temporal aspects of accommodative adaptation. Paper to be presented at ARVO, Sarasota, Florida, U.S.A., May 1988. Invest Ophthalmol Vis Sci (in press).

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