OCULOMOTOR FUNCTION IN INCIPIENT PRESBYOPIA

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Doctor of Philosophy

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Summary

The incipient phase of presbyopia represents a loss in accommodative amplitude of approximately 3 dioptres between the ages of 35 and 45 and is the prelude to the need for a reading addition. The need to maintain single binocular vision during this period requires re-calibration of the correspondence between accommodation and vergence response. No previous study has specifically attempted to correlate change in accommodative status with the profile of oculomotor responses occurring within the incipient phase of presbyopia.

Measurements were made of the amplitude of accommodation, stimulus and response AC/A ratios, CA/C ratio, tonic accommodation, tonic vergence, proximal vergence, vergence adaptation and accommodative adaptation of 38 subjects. Twenty subjects were aged 35 to 45 years of age and 10 subjects were aged 20 to 30 years of age at the commencement of the study. The measurements were repeated at four-monthly intervals for a total of two years.

The results of this study fail to support the Hess-Gullstrand theory of presbyopia with evidence that the effort to produce a unit change in accommodation increases with age.

The data obtained has enabled the analysis of how each individual oculomotor function varies with the decline in amplitude of accommodation. *MATLAB/SIMULINK* software has been used to assist in the analysis and to allow the amendment of existing models to represent accurately the ageing oculomotor system.

This study has proposed that with the decline in the amplitude of accommodation there is an increase in the accommodative convergence response per unit of accommodative response. To compensate for this increase, evidence has been found of a decrease in tonic vergence with age. If this decline in tonic vergence is not sufficient to counteract the increase in accommodative convergence, it is proposed that the near vision response is limited to the maximum vergence response that can be tolerated, with the resulting lower accommodative response being compensated for by an increase in the subjective depth-of-focus. When the blur due to the decrease in accommodative response can no longer be tolerated, the first reading addition will be required.

Key words: Accommodation, convergence, adaptation, near vision, model.

To Richard, thank you for everything.

Beware you be not swallowed up in books! An ounce of love
is worth a pound of knowledge. John Wesley (1703-1791)

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CHAPTER 1

THE INTERACTION BETWEEN THE ACCOMMODATION AND VERGENCE MECHANISMS

1.1 INTRODUCTION

The oculomotor response to a near visual stimulus consists of three distinct components, accommodation, convergence and pupil constriction. These three responses are collectively termed the 'near triad' and occur in order to obtain clear, binocular single vision. The components of the near triad share a common link in innervation from the parasympathetic nervous system leading to interactions between the responses. This chapter describes the accommodation and vergence mechanisms, their anatomy, components and interactions.

1.2 ACCOMMODATION

Accommodation is the change in the refractive power of the eye that enables objects to be seen clearly at varying distances.

1.2.1 Anatomy of the accommodative mechanism

1.2.1.a The crystalline lens

The crystalline lens is a transparent bi-convex structure situated between the iris and the vitreous chamber. The dimensions of the crystalline lens change throughout life with the diameter of the lens increasing from 6.5mm at birth to 10.0mm in adulthood. The axial thickness of the lens changes from around 3.5mm at birth to 5.0mm in old age. In the non-accommodating adult eye the anterior lens surface has a radius of curvature of between 8.0 and 10.0mm and the posterior surface is significantly steeper with a curvature between 4.5 and 7.5mm (Snell and Lemp, 1989; Patterson and Delamere, 1992).

The crystalline lens consists of three main parts:

1. The capsule, which surrounds the entire lens, is an elastic basement membrane that is thickest at the equatorial regions of the anterior and posterior surfaces and thinnest at the posterior pole.

2. The lens epithelium is found on the anterior surface of the lens beneath the capsule. The epithelium consists of cuboidal cells that become elongated near the equator and at the equator the epithelial cells become lens fibres.

3. The lens fibres account for the majority of the lens mass. The fibres are hexagonal in cross-section and are about 10mm in length, running from the posterior to the anterior lens surface in a U shape. The fibres in the centre of the lens are those formed during embryonic development, the earliest fibre mass is described as the embryonic nucleus that is then surrounded by the fetal nucleus; both these nuclei remain constant in size after birth. The adjoining adult nucleus is composed of the lens fibres formed after birth and the size of this nucleus increases throughout life. Surrounding the adult nucleus is the lens cortex that contains the lens fibres that are most recently formed from the epithelial cells.

Figure 1.1 Section through the crystalline lens and capsule (from Pipe and Rapley, 1984).

1.2.1.b The zonules

The crystalline lens is held in position by the zonules, a series of radially arranged fibres that connect the ciliary processes to the lens capsule. There are three distinct sets of zonular fibres; the two major sets attach to the posterior and anterior capsule respectively, about 1.5mm from the equator and the other smaller, finer set attaches to the equator itself.

1.2.1.c The ciliary body

The ciliary body is continuous with the choroid posteriorly and the iris anteriorly forming a ring around the inside of the anterior sclera. The ciliary body consists of the ciliary epithelium, ciliary stroma and ciliary muscle.

The ciliary muscle forms the bulk of the ciliary body and is made up of smooth muscle fibres. The muscle fibres can be divided into three groups, although their action is simultaneous:

1. Longitudinal fibres, which are closest to the sclera and run parallel to it, extend from the scleral spur into the stroma of the choroid.
2. Radial fibres, which have an oblique orientation, radiate out from the scleral spur through the ciliary body.
3. Circular fibres, which are the most internal fibres, lie near the lens periphery and are circular in orientation forming a sphincter around the iris.

Figure 1.2 Diagram showing the muscle fibres in the ciliary body (from Snell and Lemp, 1989).

1.2.1.d Innervation of the ciliary muscle

The ciliary muscle is primarily innervated by the parasympathetic fibres from the IIIrd (oculomotor) cranial nerve. Information on image quality is sent from the receptive fields of the retina via the optic nerve and chiasma, synapsing in the lateral geniculate nucleus, then via the optic radiations to the visual cortex. The efferent path from Brodmann's area 19 sends excitatory or inhibitory impulses to the hypothalamus and then to the Edinger-Westphal nucleus in the midbrain. The axons of the preganglionic nerve cells travel with the branch of the oculomotor nerve supplying the inferior oblique muscle and then synapse in the ciliary ganglion. The majority of the postganglionic parasympathetic fibres reach the ciliary muscle via the short posterior ciliary nerves however some also travel within the long posterior ciliary nerves.

There is also sympathetic innervation of the ciliary muscle believed to originate in the superior cervical plexus reaching the short and long posterior ciliary nerves via the carotid plexus (Kaufman, 1992). Gilmartin (1986) reviews the evidence for the role of this sympathetic innervation of the ciliary muscle and concludes that this inhibitory innervation is relatively small, slow and a function of the concurrent level of parasympathetic innervation.

1.2.2 Mechanism of accommodation

1.2.2.a Early theories

A review of the early theories of accommodation is outlined by Fincham (1937). Descartes (1677 cited by Fincham, 1937) proposed that the eye is able to change its focus from a distant to a near object by changing the curve of the lens, this being enabled by the 'tendons' that suspend the lens. Descartes had no experimental evidence to prove his theory, so the view that the change in focus of the eye was in fact due to a change in axial length was widely believed until around 1800. In 1801, Young (1801 cited by Fincham, 1937) showed in a series of conclusive studies that the crystalline lens was responsible for accommodation. Young considered that the lens itself was muscular despite the suggestion by Porterfield (1759 cited by Fincham, 1937) that the ciliary body contained muscular elements. By the mid 19^{th} century the use of catoptric images, first described by Purkinje (1823 cited by Fincham, 1937), allowed observers such as Langenbeck (1849 cited by Fincham, 1937) and Cramer (1851 cited by Fincham, 1937) to more accurately study changes in the ocular surfaces during accommodation. By this time Bowman (1849 cited by Fincham, 1937) and Brücke (1847 cited by Fincham, 1937) had also shown the existence of the ciliary muscle.

Cramer (1851) proposed that the contraction of the ciliary muscle during accommodation exerted a traction on the choroid that pushed the vitreous forward causing it to press upon the back of the lens. Cramer thought that as the pupil contracted the iris exerted a force on the peripheral anterior lens surface, opposing the vitreous forces, but allowing the lens to bulge forward in the free pupillary area. Graefe (1861 cited by Fincham, 1937) disproved Cramer's theory with his account of a patient who had complete aniridia, but a normal amplitude of accommodation.

Theories of accommodation by Tscherning (1894 cited by Fincham, 1937), that relied on the tension exerted by the zonules on the lens being increased during accommodation, were disproven by Fincham (1937) who presented evidence that this tension decreased.

A hydraulic theory was also proposed which describes the contracting ciliary muscle exerting pressure upon the aqueous in the posterior chamber where it is confined by the iris as the pupil contracts to the lens surface. The equatorial regions of the lens would become compressed resulting in the bulging forward of the anterior lens. This theory was again found to be invalid due the presence of accommodation in aniridic patients and also due to the need for the posterior chamber to be watertight, which is impossible (Hill, 1920 cited by Fincham, 1937).

1.2.2.b Current theory of accommodation

The widely accepted theory for the mechanism of accommodation is based on the theory of Helmholtz (1855 cited by Fincham, 1937) although in subsequent years the theory has been modified to support new experimental evidence (Fincham, 1937; Koretz and Handelman, 1982; Koretz and Handelman, 1983; Coleman, 1970; Coleman, 1986).

When the eye is in its unaccommodated form the elastic lens capsule is under tension from the zonules, keeping the lens in a flattened shape. As the eye accommodates, the ciliary muscle contracts. The longitudinal fibres of the ciliary muscle pull the choroid and ciliary body forward and the circular fibres, acting as a sphincter, move the ciliary body inward. This ciliary muscle movement reduces the tension of the zonules on the lens allowing the anterior, posterior and internal lens surfaces to become steeper and the lens diameter to decrease. The posterior lens surface remains in a fixed position, attributed to the hydraulic pressure from the vitreous humour (Coleman, 1970; Koretz and Handelman, 1982), with a forward movement of the anterior pole as the axial lens thickness increases. Optically, the increased lens thickness, the steepening of the lens curvatures and the closer proximity of the cornea to the anterior lenticular refracting surface increase the refractive power of the eye.

Schachar and co-workers (Schachar, 1992, Schachar and Anderson, 1995) have proposed an alternative mechanism of accommodation showing that during ciliary muscle contraction there is increased tension in the equatorial lens zonules pulling the lens equator nearer to the sclera with a relaxation of the anterior and posterior lens zonules. These forces result in the lens becoming a spindle shape, thinnest at the equator and more steeply curved centrally. Although Schachar has published mathematical proof and experimental evidence in support of his hypothesis (Schachar *et al.*, 1993b; 1993a; 1994) it is still a contentious theory.

1.2.3 Stimulus to accommodation

In binocular vision, accommodation is primarily stimulated by two reflexes (Fincham and Walton, 1957). When the eyes converge to fuse the retinal images of a near object, innervation will also be sent stimulating accommodation. Where this stimulus is not adequate to give clear vision or during monocular viewing, the detection of retinal blur or defocus of the image will stimulate accommodation. This reflex accommodation cannot be solely stimulated by blur, since blur is a scalar quantity and therefore does not indicate whether an increase or decrease in accommodation is required for clear vision. In engineering terms, blur is an even-error stimulus rather than an odd-error stimulus which would provide directional and magnitudinal information. Chromatic aberration has been found to be a factor in directing the accommodative mechanism. If an object is too close the image of a point will appear as a light disc surrounded by a red fringe, whilst if it is too far away the disc will be surrounded by a blue fringe (Fincham, 1951; Kruger and Pola, 1986; Kruger *et al.*, 1993). Other possible directional clues can be gained from spherical aberration (Campbell and Westheimer, 1959), object size (Kruger and Pola, 1985; 1986; 1987), microfluctuations in accommodation (Charman and Heron, 1988; Heron and Schor, 1995) and minute scanning movements (Fincham, 1951).

1.2.4 Amplitude of accommodation

Amplitude of accommodation is a measure of the maximum amount of accommodation that an individual can produce. Clinically, it is measured from infinity to the closest point of subjective clear vision although this may overestimate the true value. The amplitude should actually be measured from the far point of the eye, the farthest point that is conjugate with the retina with minimum accommodative effort; this point will be closer than infinity due to a 'lead' of accommodation. An allowance should also be made for the depth of focus of the eye. Methods of assessing amplitude of accommodation are discussed in section 3.5.

1.3 TONIC ACCOMMODATION

According to the theory of accommodation proposed by Helmholtz, Gullstrand and Fincham when the accommodative mechanism of an emmetropic eye is at rest, it will be focused at optical infinity. However, it is now known that in the absence of adequate visual stimuli, the accommodative mechanism of the eye instead rests at an intermediate distance.

1.3.1 Terminology

Many terms have been used to describe this intermediate position of the accommodative mechanism.

The term *dark-focus* is often used (Leibowitz and Owens, 1975a; 1975b; Miller, 1988; Ebenholtz, 1992; 1983). However, it is not only under dark conditions that this state arises and the use of the word 'focus' has been criticised since it incorrectly suggests it is an attempt to reduce blur via a feedback loop (Rosenfield *et al.*, 1993). Similarly the term *dark accommodation* is misleading since it suggests the need for darkness.

Rosenfield *et al.* (1993) cites the studies such as that of Kotulak and Schor (1987) investigating microfluctuations of accommodation as reason for not using the expression *resting state of accommodation*. The expression suggests this is the position where there is minimum physiological activity but in terms of microfluctuations this is not the case.

A bioengineering term *ABIAS* is sometimes used when describing models of accommodation but it is not used extensively since it does not fit in with other terms used in clinical literature.

The term *tonic accommodation* (TA) will be used throughout this thesis to describe this open-loop accommodative response. It must be stressed however that the accommodative level may reflect more than the tonic innervation of the ciliary muscle (see section 1.3.3.b).

1.3.2 Historical evidence for the intermediate resting position of the accommodative mechanism

1.3.2.a Night myopia

Night myopia was first described by astronomers such as Maskelyne (1789 cited by Levene, 1977) and Rayleigh (1883 cited by Levene, 1977) who found it easier to see stars when using a concave lens in addition to their telescope; they did not need this myopic correction in daylight.

The spherical and chromatic aberrations of the eye and the change in sensitivity of the eye in the transfer from photopic to scotopic luminance (the Purkinje shift) were initially favoured as the explanations for night myopia.

Spherical aberration increases under dim light conditions as the pupil size increases. Koomen *et al.* (1951) suggested that there would be a myopic shift as the relative amount of light entering the eye through the peripheral pupil increased. Conversely, Ivanoff (1947) suggested that the eye actually assumed the intermediate resting position in order to suppress spherical aberration. However, Miller (1988) found that varying pupil size had no effect on the refractive state of the eye. If variations in spherical aberration do have a role in the myopic shift in darkness, the role is not of major significance (Rosenfield *et al.*, 1993).

As the eye becomes more sensitive to the shorter wavelengths of light under scotopic conditions it will appear to be more myopic since these wavelengths are those most refracted by the eye. Wald and Griffin (1947) found an average increase in power of the eye in dim light of 0.59D (range +1.4 to –3.4D) but only 0.4D of this was calculated as being due to chromatic aberration and the Purkinje shift.

Otero and Duran (1941; 1942 cited by Mellerio, 1966) demonstrated 2.0D of night myopia using subjective techniques and found that the instillation of the muscarinic receptor antagonist homatropine virtually eliminated the myopia, evidence that night myopia is accommodative.

By photographing the third Purkinje image (reflection from the front surface of the crystalline lens) Otero *et al.* (1950 cited by Mellerio, 1966) were able to measure a mean figure of just over 1.00D of accommodation in the dark. This figure is similar to that found by Campbell and Primrose (1953) who found that the state of the crystalline lens in darkness corresponds to about 0.8D, again using Purkinje image photography.

1.3.2.b Empty-field myopia

Other stimulus conditions can induce the regression of accommodation towards the tonic accommodation level.

Luckiesh and Moss (1937) devised a 'sensitometric technique' with two photographic gradient filters rotating relative to each other, allowing the presentation of targets at varying brightness and contrast levels. Luckiesh and Moss found that if the targets were presented at a subthreshold level, within a uniform field, there was no stimulus to accommodation. They determined the brightness-contrast threshold at which the target first became visible at different accommodative stimulus levels and found that the subject was most sensitive when viewing through a –1.00D lens. A subsequent study using this technique on 20 subjects found a mean maximum sensitivity with a -0.75D stimulus to accommodation (Luckiesh and Moss, 1940).

Heath (1956) examined the effect of visual acuity on the accommodative response. Heath found that as visual acuity became markedly degraded, the gradient of the stimulus-response function tended towards zero. Under the most degraded stimulus conditions the mean accommodative response was 1.25D. Heath suggested that it was the reduction in target contrast rather than the reduction in target illuminance that led to the reduction in accommodative response.

Further evidence of empty-field myopia came from the work of Whiteside (1953) who found a mean accommodative response of between 0.5 and 2.0D when viewing a bright empty-field. Westheimer (1957) found a level of myopia under bright empty-field conditions that was equivalent to that found in darkness (0.75-1.75D).

1.3.2.c Instrument myopia

Hennessy (1975) studied instrument myopia, a persistent state of over-accommodation found when using an optical instrument such as a telescope or microscope. Hennessy found a range of myopia of –0.96 to -2.78 in the 15 subjects studied, similar to that found by Leibowitz and Owens who found a range from –0.7 to 4.0D for a group of 30 subjects (Leibowitz and Owens, 1975a).

It has been suggested that instrument myopia is due to the small exit pupil of the instrument creating a depth-of-focus sufficient to open the accommodative loop, thus the relatively myopic tonic accommodation response is assumed. However it has been shown that with a 2mm aperture, the typical size of an instrument exit pupil, accommodation is not open-loop (Miller *et al.*, 1984) and in fact a pupil as small as 0.5mm is needed to do this (Ward and Charman, 1987; Ripps *et al.*, 1962).

Thus instrument myopia may only be partly influenced by tonic accommodation. Proximal accommodation, due to the known nearness of the target viewed through the instrument, is thought to have a significant role in instrument myopia, despite the object of regard being imaged at infinity (Schober *et al.*, 1970; Rosenfield and Ciuffreda, 1991; Rosenfield *et al.*, 1993; Chiu and Rosenfield, 1994).

1.3.3 Influences on tonic accommodation

1.3.3.a Methods of opening the accommodative loop

In order to measure tonic accommodation it is necessary to open the accommodative loop, removing the blur feedback mechanism such that the level of accommodation is independent of the retinal image quality.

Dark field

Placing the subject in total darkness will remove all accommodative stimuli, with proximal, vergence and blur cues eliminated. However, despite the removal of the optical stimuli to accommodation non-optical cues such as knowledge of the size of the room and mental effort can influence the response measured (Rosenfield and Ciuffreda, 1991; Winn *et al.*, 1991) see section 1.3.3.b.

Bright empty-field

A bright empty-field or Ganzfeld has been used experimentally to open the accommodative loop. Bullimore and Gilmartin (1989) found no statistically significant difference between values of tonic accommodation recorded in a bright empty-field compared with a darkroom, a finding consistent with that of Westheimer (1957) and Leibowitz and Owens (1978).

Wolfe and O'Connell (1987) found however that the accommodative response to a bright empty-field was greater than a darkroom and suggest this is due to the subjects expecting a target to be nearer during a bright field condition leading to proximal or mental effort stimulation of accommodation.

Pinholes

Ward and Charman (1987; 1985) measured monocular accommodation responses to stimuli at vergence distances from 0 to –4.5D using a Canon R-1 infra-red autorefractor with 4 different artificial pupil diameters (0.5, 0.75, 1.0 and 3.0 mm). The results showed that a pinhole of 0.5mm or less produces open-loop accommodation over a stimulus range of 0 to –4.5D. Gray *et al.* (1998) compared the magnitude and distribution of open-loop accommodation found using a dark field, a bright field and pinholes. They found significantly higher values of tonic accommodation and a wider distribution of values with pinhole viewing than with the dark or bright field measures. As with other methods of opening the accommodative loop there is the possibility of proximal influences on the accommodative response measured when using pinholes (Rosenfield and Ciuffreda, 1990b; Rosenfield and Gilmartin, 1990; Gray *et al.*, 1998).

Difference of Gaussian targets

A difference of Gaussian target (DoG) is a spatially filtered target that is non-repetitive and contains a narrow band of spatial frequencies (see figure 3.4). In general a DoG target is created by subtracting a broad Gaussian from a narrow one (Kotulak and Schor, 1987). Kotulak and Schor found that a DoG with a spatial frequency of around 0.1c/deg did not constitute a blur stimulus to accommodation, that is the accommodative response was independent of the dioptric stimulus level. They also found that the accommodative response measured when viewing the DoG was equivalent to that measured in darkness. Rosenfield (1989b) also found that a DoG of 0.1c/deg did not provide a blur stimulus to accommodation but found that there was no significant correlation between the measurements of tonic accommodation recorded in darkness and when viewing the illuminated DoG target. Rosenfield concluded that although viewing the DoG target does open the accommodative loop the actual values of tonic accommodation may be elevated due to the proximal accommodation response.

1.3.3.b Non-optical influences on tonic accommodation

Surround propinquity

Rosenfield and Ciuffreda (1991) investigated the effect of surround propinquity, the subject's awareness of nearness, on the open-loop accommodative response in darkness. The open-loop accommodative response of 10 subjects was assessed using a Canon R-1 infra-red autorefractor on two different occasions in two different laboratories. One laboratory was 2.5m square and the other 6.75 x 2.75m. On the first occasion the subjects were aware of the dimensions and the topography of each room but for the second trial the subjects were blindfolded before being led into the room and hence were unaware of the room size. Each of the accommodative responses was measured in total darkness to ensure that accommodation was open-loop. The results showed that when the subjects were aware of the differences in room size the accommodative response in darkness was significantly higher in the smaller laboratory. When the subjects were unaware of the room dimensions or topography no significant difference in accommodative response was found. The authors therefore suggest that even in darkness prior knowledge of the room dimensions can initiate proximal accommodation.

Mental imagery

Westheimer (1957) found that instructing patients to 'think near' or think far' whilst sitting in darkness caused appropriate changes in tonic accommodation to occur.

Mental effort

Winn *et al.* (1991) investigated the effect of mental effort on open and closed-loop accommodative responses. Three task conditions were used, firstly a *passive* task where the subject read letters to themselves (no mental effort), secondly a *stimulus dependent* task where subjects had to respond to particular characters in the text and lastly a *stimulus independent* task where the subject had to undertake a mental arithmetic task whilst viewing an unrelated target. The open-loop accommodative response was found to be greater when a task involving mental effort was required, particularly when the mental activity was related to the visual stimulus (the stimulus dependent task). These findings have implications when considering the method of assessing the open-loop accommodative response since subjective methods may involve mental effort, such as the laser-optometer (see section 1.3.3.c). Post *et al.* (1985) showed that in some subjects the act of judging the motion of the laser speckle during the assessment of tonic accommodation with the laser optometer did influence the magnitude of the response measured.

1.3.3.c Method of assessing tonic accommodation

Purkinje image photography

Campbell and Primrose (1953) photographed the third Purkinje image, that is the image formed on the anterior crystalline lens surface, in order to measure the state of accommodation of the eye in darkness. They measured the size of the image for known accommodative stimuli and then compared the findings in the dark with these to calculate the accommodative response. Using 6 subjects (aged 17 to 28 years) mean tonic accommodation was found to be 0.82D.

Near retinoscopy

Owens *et al.* (1980) found that a retinoscope beam did not constitute a stimulus to accommodation and therefore could be used as a method of assessing the open-loop accommodative response. Owens *et al.* demonstrated a significant correlation between the values of tonic accommodation found by near retinoscopy (Mohindra, 1977) and by laser optometry but the values measured by near retinoscopy (mean = 0.7D) were consistently lower than those found with the optometer (mean = 1.50D). Bullimore *et al.* (1986) also found tonic accommodation levels to be lower when measured with near retinoscopy than with laser or infra-red optometry. Rosenfield (1989b) measured accommodative responses using an infra-red optometer in conditions of total darkness and when viewing a retinoscope beam in an otherwise darkened room. Although the mean values of accommodative response were similar (darkness mean = 1.77D; viewing retinoscope beam mean = 1.58D) they were not correlated. The difference in the results was believed to be due to the retinoscope acting as a blur or proximal stimulus to accommodation.

Laser optometers

A laser (He-Ne) optometer is a subjective optometer that is based on the principle that when a diffusely reflecting surface is illuminated with coherent laser light, the reflected light appears speckled due to constructive and destructive interference at the observer's retina. If the reflecting surface is moved slowly the apparent motion of the speckle pattern is related to the refractive state of the eye, with the speckles moving in opposite directions if the eye is relatively myopic or hyperopic. If the speckle pattern appears to be stationary the reflecting surface is optically conjugate with the observer's retina (Hennessy and Leibowitz, 1972). The speckle pattern itself will not act as a stimulus to accommodation since its appearance is independent of the dioptric state of the eye.

Due to laser light being monochromatic it is necessary to correct the values of tonic accommodation measured with laser optometry with a correction factor related to the chromatic aberration of the eye but this has varied between researchers. Miller (1987) suggested that since chromatic aberration will vary between individual subjects it may be advisable to consider only changes in accommodation rather than absolute values when using a laser optometer.

Leibowitz and Owens (1978) measured the tonic accommodation of 220 college students using laser optometry and found a mean value of 1.52D (range 0-4.0D). Post *et al.* (1984) compared the values of tonic accommodation found using laser and infra-red optometry. In 2 of their 5 subjects the laser optometer measured higher levels of tonic accommodation which they demonstrated was due to the metal effort involved in judging the direction of motion of the laser speckle (see section 1.3.3.b). In contrast, when Bullimore *et al.* (1986) compared tonic accommodation values with laser and infra-red optometry they found similar mean values and a high correlation between the values found with the two methods, although this did not take into account correction factors for chromatic aberration. Bullimore *et al.* suggest that the greater values that Post *et al.* found with the laser optometer may be due to the laser speckle exposure time allowing a transient accommodative response to the speckle pattern.

Rosenfield (1989a) supported the theory that the laser pattern may stimulate proximally induced accommodation and also found differences in the magnitude and distribution of tonic accommodation using laser and infra-red optometers.

Stigmatoscopy

Stigmatoscopy is another subjective method of assessing accommodative response. A small pinpoint of light is viewed through a Badal lens and will be sharply in focus (and of minimum diameter) when its dioptric stimulus (determined by its distance from the lens) corresponds to the physical distance to which the eye is accommodating. It has been shown that the values of tonic accommodation found using this technique are similar to those found using an open-field, infra-red objective technique (Wolf *et al.*, 1987, Rosenfield *et al.*, 1993) suggesting that the effect of mental effort and proximal accommodation cues are minimal.

Coincidence optometer

Although the Hartinger coincidence optometer can be used objectively to measure ocular refraction it has to be used subjectively to measure tonic accommodation levels. The optometer appears to assess relative changes in tonic accommodation accurately but baseline values are slightly elevated due to proximal and cognitive influences (Rosenfield *et al.*, 1993).

Infra-red optometer

A significant advantage of the infra-red optometer is the objective nature of the measurements and that a binocular real space view can be used. The optometer uses infra-red light to avoid any visible light inducing changes in the accommodative response and the open view prevents proximal cues to accommodation. There is an in-built correction factor necessary due to the use of infra-red light to convert the results to the equivalent white light measure and the optometer is calibrated against standard subjective refractions. At the present time the infra-red optometer is the instrument of choice when assessing tonic accommodation and will be discussed in more detail in section 3.2.1.

1.3.4 Stability of tonic accommodation

The long term stability of tonic accommodation has been widely investigated (Miller, 1978; Mershon and Amerson, 1980; Heron *et al.*, 1981; Owens and Higgins, 1983; Post *et al.*, 1984) and in the majority of subjects has been found to be stable. Except for the infra-red optometer used by Post *et al.* (1984), the studies all used laser optometers which have been questioned due to proximal or cognitive influences (see section 1.3.3.c) but should be accurate for assessing stability, since it is relative changes that are being considered.

The diurnal variation in tonic accommodation has also been found to be stable (Miller, 1978; Heron *et al.*, 1981; Krumholz *et al.*, 1986). Two studies have reported diurnal variations in tonic accommodation (Amerson and Mershon, 1988; Kurtev *et al.*; 1990) but further analysis of their data has shown their conclusions to be void (Rosenfield *et al.*, 1993).

Despite this short and long term stability in tonic accommodation, a few minutes under open-loop conditions may be necessary before taking a measurement of tonic accommodation. This period will ensure that no previous accommodative stimulus influences the open-loop response measured, since a period of sustained fixation may lead to a transient change in open-loop response (see section 1.9).

1.3.5 Physiological and pharmacological aspects of tonic accommodation

Tonic accommodation is due to the tonic innervation of the ciliary muscle, although as mentioned previously the actual response measured under open-loop conditions may reflect factors other than tonic accommodation such as proximal influences.

Tonic accommodation was once thought to represent the equilibrium position between the sympathetic and parasympathetic branches of the autonomic nervous system that innervate the ciliary muscle but this has now be shown to be incorrect (Gilmartin and Hogan, 1985; Gilmartin, 1986). Gilmartin and Hogan (1985) used the muscarinic antagonist tropicamide to block the parasympathetic innervation of the ciliary muscle. The magnitude and distribution of tonic accommodation was found to reduce to almost zero after the installation of this drug, evidence that it is predominantly the variations in the parasympathetic branch of the autonomic nervous system, rather than the sympathetic branch, that are responsible for inter-subject differences in tonic accommodation. Gilmartin *et al.* (1984) did however show that the sympathetic branch has a role to play in tonic accommodation but its significance is mediated by the concurrent parasympathetic activity.

1.3.6 Effect of age on tonic accommodation

Simonelli (1983) measured the 'dark focus' of 301 subjects aged 17 to 67 using a Bausch and Lomb Orthorator. The subjects were divided into 5 subgroups each representing a decade of age range (17-26,27-36 etc.) and the mean dark focus was then plotted against the mean age. The dark focus reduced from a mean of 0.74D in the youngest group to 0.18D in the oldest group.

Rosenfield *et al.* (1995b) measured tonic accommodation using a Canon R-1 autorefractor in complete darkness. The tonic accommodation of 41 subjects aged 20 to 70 years of age was assessed. It was found that tonic accommodation reduced by 0.013D per year. Mordi and Ciuffreda (1998) also assessed tonic accommodation using the Canon autorefractor. The mean tonic accommodation after 2 minutes in complete darkness was found for 30 subjects aged 21 to 50 years. Tonic accommodation was found to decline at a rate of 0.04D per year.

Ramsdale and Charman (1989) undertook a longitudinal study of the static accommodative response over a ten-year period. The study did however only include one subject, who was aged 41 years at the commencement of the study. The accommodative response to stimuli ranging from 0 to –5D was measured using a laser optometer and the push-up method. Tonic accommodation was calculated by finding the difference between the accommodative response at which the accommodative stimulus and response were equal and the accommodative response to a distant target. Added to this data was data from the same subject taken from previous studies, which together showed that with increasing age there was a decline in tonic accommodation.

Ramsdale and Charman suggested that the magnitude of tonic accommodation is equal to a constant fraction of the objective amplitude of accommodation of the subject with a finding of a level of tonic accommodation that was approximately 0.6 times the amplitude of accommodation in their study. Thus, when a subject reaches absolute presbyopia, tonic accommodation will be zero.

1.4 VERGENCE

The six extraocular muscles that produce eye movements are the superior, inferior, medial and lateral rectus muscles and the superior and inferior oblique muscles. The extraocular muscles are specialised striated muscles (Burde and Feldon, 1992) consisting of muscle fibres bound and surrounded by connective tissue. There are two basic muscle fibre types in extraocular muscle: twitch and tonic. It has been suggested that 'twitch' fibres are activated for saccades and 'tonic' fibres are activated for slower movements such as vergence, fixation and pursuit although it maybe that both types of fibre are involved in all movements but the contributions may not be equal (Mays, 1983; Spencer and McNeer, 1991).

Superior rectus
Tendon of superior oblique

Figure 1.3 Diagram showing the extra-ocular muscles of the eye from (Snell and Lemp, 1989).

Binocular eye movements can be divided into two types: versions and vergences. A version is the simultaneous movement of the eyes in the same direction. A vergence is the simultaneous movement of the eyes in opposite directions. Vergence movements occur in order to direct the foveae of both eyes to a single target at a particular distance, allowing stereoscopic vision. Vergence movements can also give information about target distance, depth judgement and sensorimotor co-ordination (Judge, 1991). Vergence movements have a velocity of around 20 deg/s, far slower than version movements which can be as fast as 400 deg/s (Feldon and Burde, 1992).

Convergence is the inward movement of the eyes produced by the contraction of the medial rectus muscles. Divergence is the outward movement of the eyes brought about by the contraction of the lateral rectus muscles and is therefore a direct action rather than simply the result of relaxation of convergence.

The medial and lateral rectus muscles both arise from the annulus of Zinn, a fibrous ring at the apex of the orbital cavity, from where they pass forward to their insertions into the sclera.

The medial rectus, the largest of the extraocular muscles, is inserted into the sclera about 5.5mm nasally from the limbus via a tendon 3.7mm long (Snell and Lemp, 1989). The medial rectus is innervated by the inferior division of the oculomotor (IIIrd) nerve. The nerve originates in the oculomotor complex in the midbrain, traverses the base of the skull, passes through the cavernous sinus and enters the medial rectus muscle around the junction of its middle and posterior thirds.

The lateral rectus is inserted into the sclera 6.9mm temporal to the limbus by means of a tendon 8.8mm long. The lateral rectus muscle is innervated by the abducens (VIth) nerve whose nucleus lies in the midpoint of the pons. The nerve passes upward and then forwards, traversing the skull and cavernous sinus inferiorly to the third nerve finally entering the lateral rectus muscle just behind its middle.

Jampal (1959) showed that electrical stimulation of Brodmann areas 19 and 22 in anaesthetised monkeys induces convergence, along with accommodation and pupillary constriction, implicating these cortical areas in the control of vergence.

1.4.1 Units of vergence

Vergence is measured in either metre angles (MA) or prism dioptres ($^{\Delta}$). A metre angle is defined as the amount of convergence required to fixate an object at one metre from the eyes in the meridian plane, but it is a relative measure dependent upon the inter-pupillary distance. Clinically, convergence is measured in prism dioptres where one prism dioptre is equivalent to a movement of 1cm at 1m. If an angle x is less than 90° then the angle in prism dioptres will be equal to $100 \tan x$. An angle y in metre angles can be converted to prism dioptres using the equation $z = y.\mathrm{PD}$ where PD is the inter-pupillary distance in centimetres and z is the angle in prism dioptres.

1.5 COMPONENTS OF VERGENCE

Maddox (1893 cited by Morgan, 1983) proposed four elements of vergence that were additive components to the overall vergence response:

- tonic
- proximal
- fusional
- accommodative (see section 1.6)

1.5.1 Tonic vergence

Tonic vergence represents the baseline activity of the vergence system and is the intermediate resting state obtained when there is no accommodative, proximal or visual stimulus to vergence (Owens and Leibowitz, 1983). Tonic vergence results from the continuous tonic innervation of the extraocular muscles. The true magnitude of tonic vergence is determined from the difference between the anatomical and the physiological positions of rest. The anatomical position of rest is defined by the mechanical properties of the eyes suspensory system. Studies using cadavers and patients under general anaesthesia have found this position to be about 15-25° divergent (Stutterheim, 1933;1934; Meyers, 1951). It is impractical to determine the anatomical position of rest of an individual and therefore in general, tonic vergence represents the physiological position of rest of the eyes. Tonic vergence underestimates the true value since it is referenced to a parallel eye position rather than the divergent anatomical position of rest (Rosenfield, 1997).

1.5.1.a Measuring tonic vergence

Distance heterophoria has sometimes been used incorrectly to measure tonic vergence (Maddox, 1893 cited by Morgan, 1983; Morgan, 1944a) but it has been demonstrated that there are significant differences between the two parameters (O'Shea *et al.*, 1988; Rosenfield and Ciuffreda, 1990a). When measuring tonic vergence there is a higher level of accommodation than when measuring distance heterophoria due to tonic accommodation, resulting in greater accommodative convergence. Tonic vergence is a more convergent position than distance heterophoria by about 2-2.5Δ.

In order to determine tonic vergence it is necessary to remove all other stimuli to vergence, that is fusion, accommodation and proximity. The easiest method of achieving these conditions is to use a totally darkened large room (Rosenfield, 1997). Under these conditions Owens and Leibowitz (1980) used a nonius alignment technique to measure the tonic vergence in 60 subjects and found a mean value of 1.16MA. Hogan (1985) also used a nonius alignment device and found a mean tonic vergence of 0.93MA (n=60). Using a dual haploscope device with two stigmata (non-accommodative stimuli) vertically displaced by 5°, values between 0.20 and 0.60MA have been found for tonic vergence (Wolf *et al.*, 1987; Fisher *et al.*, 1988; Rosenfield and Ciuffreda, 1990a).

The significantly lower values of tonic vergence found with the haploscope device when compared to the nonius alignment technique, are explained by Rosenfield (1997; Rosenfield *et al.*, 1991) as being due to the subject's perception of nearness of the nonius lines resulting in a proximal vergence response. The higher levels of tonic vergence found with the nonius lines have also been attributed to the lines acting as a stimulus to accommodation despite their brief exposure time (100ms) perhaps due to the repeatable nature of the stimulus presentation (Jaschinski-Kruza, 1990; Rosenfield, 1997).

1.5.1.b Stability of tonic vergence

Fisher *et al.* (1988) assessed the short and long term stability of tonic vergence. The tonic vergence of four subjects was measured (the authors) using a dual haploscope-optometer in complete darkness. Assessments were made every 7.5 minutes over a two-hour period, every 30 minutes over a 10-hour period and every 2 weeks over a 19-week period. Figure 1.4 shows the mean tonic vergence as a function of time for each phase of the experiment.

It can be seen from figure 1.4 that tonic vergence showed no systematic trend over the diurnal or weekly measurement period with minimal random fluctuations. However, during the two-hour period in darkness, tonic vergence exhibited a significant drift towards lower (less convergent) values. This slow decay in tonic vergence is not surprising since it represents the dissipation of vergence after-effects following adaptation to prior vergence stimuli (see section 1.10).

A

Group data (n=4)

0.9

Aston University

Illustration removed for copyright restrictions

0 15 30 45 60 75 90 105

Time in Dark in Minutes

Figure 1.4 Mean tonic vergence as a function of time over the course of the day (top), weeks (middle) and an extended period in total darkness (bottom) (reproduced from Fisher *et al.*, 1988).

1.5.2 Proximal vergence

Proximal vergence is the vergence that occurs due to the knowledge of nearness of an object (Maddox, 1893 cited by Morgan, 1983). Measurements of proximal vergence are generally expressed as a ratio of change in convergence to change in test distance (PC/T).

1.5.2.a Measuring proximal vergence

Proximal vergence is often determined by comparing the AC/A (accommodative convergence/ accommodation) ratio found by the gradient method at near to the ratio found by calculation which compares distance to near heterophoria (see section 1.6.1 for details of these methods). In the gradient method there is no proximal contribution to the vergence response since the change in the stimulus to accommodation is achieved by the introduction of positive or negative lenses with a fixed target. The PC/T (proximal vergence/test distance) value can be found by subtracting the gradient AC/A ratio from the calculated AC/A ratio for an equivalent accommodative stimulus change. Using this method mean PC/T values ranging from 0.53 to 1.7^{Δ}/D have been found (Morgan, 1950; Manas and Shulman, 1954; Ogle and Martens, 1957; Hokoda and Ciuffreda, 1983). Similar mean values of PC/T have been found by methods that include subtracting measured values of fusional, accommodative and tonic vergence from the overall vergence response, and methods involving heterophoria and fixation disparity measurements. Other studies have calculated proximal vergence by subtracting tonic convergence and accommodative convergence from total convergence using the formula:

proximal vergence = (PD x 2.5) – h + H

where PD = interpupillary distance, h = near heterophoria measured through a +2.50D lens at 40cm and H is distance heterophoria (eso is minus, exo is plus) (Wick, 1985, Sheedy and Saladin, 1975).

1.5.2.b Significance of proximal vergence

The contribution that proximal vergence makes to the overall vergence response is uncertain. Hokoda and Ciuffreda (1983) suggest that proximal vergence may account for up to 50% of the total vergence response. Morgan (1944a) analysed the convergence response of 50 college students to a vergence stimulus of 18^{Δ} and found that although 10 students had 0^{Δ} of proximal vergence the average was 3^{Δ} and the maximum was 7^{Δ}. Wick (1985) used the data of Morgan (1944b; 1950; 1944c) to compare the relative contributions to the vergence response and concluded that for Morgan's data 31% of the vergence response was proximal vergence (accommodative 31%; fusional 25%). Wick (1985) then found with his own subjects (n=20) that proximal vergence accounted for 39% of the vergence response (accommodative 32%; fusional 24%) but this was measured under dissociated conditions and when measured under associated conditions the proximal vergence contribution was even greater.

Hung *et al.* (1996) modelled the proximal contribution to the overall vergence response under both open- and closed-loop conditions. Hung *et al.* found that under dual open-loop conditions (both accommodation and vergence open-loop) the proximal vergence contribution ranged from 56 to 82 % of the overall vergence response. However, under closed loop conditions proximal vergence accounted for only 0.04% of the vergence response with the dominant contribution being from fusional vergence.

1.5.3 Fusional/disparity vergence

Fusional or disparity vergence is reflex vergence that is a response to retinal disparity and acts to maintain the singleness of the object of regard. The most significant fusional vergence movements are horizontal due to their natural generation by eye movements but vertical and torsional disparity eye movements can also be proven. Section 1.10.1 discusses the fast and slow components of fusional vergence, their relationship, stimulation and dissipation.

It has been found that a vergence response can be initiated by the retinal disparity of two grossly dissimilar targets such as a cross and circle or horizontal and vertical line (Westheimer and Mitchell, 1969). Although the dissimilar targets initiate a vergence response, fusion is not achieved unless the targets are very similar and this has led to the suggestion that a distinction should be made between fusional and disparity vergence (Stark *et al.*, 1980). Disparity is the stimulus to vergence whereas sensory fusion, a high-order perceptual process, may be the result of the vergence movement although it is not the stimulus.

1.6 AC/A RATIO

Muller (Muller, 1826 cited by Carpenter, 1988) first described how an accommodative stimulus can produce a vergence movement in the absence of retinal disparity by demonstrating how a target moved along the line of sight of one eye will produce a slow inward rotation of the covered eye. This retinal blur driven change in vergence is known as accommodative vergence.

The ratio of accommodative convergence to accommodation (AC/A ratio) is the change in vergence of the eyes that occurs as a direct result of a change in ocular accommodation. There are two different AC/A ratios that can be measured, depending on which aspect of accommodation is considered. If the stimulus to accommodation is used to calculate the AC/A ratio it represents the dioptric distance of the stimulus from the eye and may vary from the actual change in refractive state of the eye induced, that is the accommodative response. The difference between the stimulus and response accommodation values is termed either the lag or lead of accommodation depending on which value is greater. The maintenance of a clear image despite this discrepancy in the stimulus-response relationship is due principally to the depth-of-focus of the eyes. A stimulus AC/A ratio and a response AC/A ratio can thus be measured (Alpern *et al.*, 1959).

1.6.1 Measuring the stimulus AC/A ratio

In addition to experimental procedures the AC/A ratio is often measured in a clinical setting in order to further the understanding of the binocular vision of a patient. In this instance it is usually the stimulus AC/A that is required, this is the more practical of the ratios to determine and is sufficient for the purpose, but will not take into account any lag or lead in accommodative response. Outlined below are the two most frequently used clinical techniques for calculating the stimulus AC/A ratio.

1.6.1.a The heterophoria method

The heterophoria method (or calculated AC/A ratio) involves measuring both the distance and near heterophoria and then dividing this change in vergence by the change in the dioptric stimulus to accommodation. This method of stimulus AC/A ratio calculation may hence be influenced by proximal cues to accommodation and vergence.

1.6.1.b The gradient method

The gradient method for measuring the stimulus AC/A ratio is a subjective technique that involves assessing the change in near heterophoria produced by negative or positive lenses. The heterophoria is generally measured using either a Maddox wing or the Thorington technique with pairs of lenses ranging from +2.00 to –2.00DS. The slope of the curve produced by plotting the change in accommodative stimulus against the near heterophoria represents the stimulus AC/A ratio. Although this measurement technique will not be influenced by proximal cues due to variations in the target distance, the variation in lens power will alter the magnification of the target, which may lead to a proximal response.

Bhoola *et al.* (1995) compared the values of the AC/A ratio found with the heterophoria and gradient stimulus techniques with the results found by a gradient response technique. With subjects observing a Maltese cross, accommodation was stimulated with negative spherical lenses. The response AC/A ratio was calculated from the objective measurements of the accommodation and convergence responses that occurred, using a Canon R-1 autorefractor and an IRIS infrared eye movement system. The mean AC/A ratios found by the heterophoria, gradient stimulus and gradient response techniques were significantly different with values of 5.81 ± 1.03 $^{\Delta}$/D, 3.49 ± 2.17 $^{\Delta}$/D and 4.37 ± 1.31 $^{\Delta}$/D respectively. Bhoola *et al.* (1995) concluded that the gradient stimulus method is most useful when identifying very low or high AC/A ratios and that the heterophoria method may only be useful for identifying abnormally high AC/A ratios due to its susceptibility to proximal influences.

1.6.2 Measuring the response AC/A ratio

The response AC/A ratio more accurately assesses the relationship between accommodation and vergence since this reflects the actual responses of the oculomotor system and is therefore a useful experimental measurement, especially when attempting to analyse the synkinetic link between accommodation and vergence. The accommodative response is found using a form of optometer, either a subjective optometer such as a stigmatoscope (Rosenfield *et al.*, 1995a; Ciuffreda *et al.*, 1997) or ideally an objective optometer such as an autorefractor (Bhoola *et al.*, 1995; Bruce *et al.*, 1995).

Vergence can again be determined with an assessment of heterophoria or using a haploscope technique although an objective measurement of eye movement such as an eyetracker may allow a greater accuracy of measurement.

1.6.2.a Fixation disparity technique

The fixation disparity technique enables the calculation of the AC/A ratio by dividing the amount of prism required to induce a certain fixation disparity by the spherical lens power that produces the same disparity. The main advantage of this method of measurement is that the viewing conditions required are more natural since fusion is maintained, although good subject co-operation and accurate observations are required.

1.6.3 Normal values of the AC/A ratio

The mean stimulus AC/A ratio is around 3-4$^{\Delta}$/D (0.5-0.65MA/D) (Morgan and Peters, 1951; Ogle and Martens, 1957; Ciuffreda *et al.*, 1997) and the mean response AC/A ratio is typically 4-6$^{\Delta}$/D (0.65-1.00MA/D) (Hofstetter, 1942; Morgan, 1944a; Bruce *et al.*, 1995; Ciuffreda *et al.*, 1997), the difference between the ratios represents a lag in accommodation.

1.6.4 Linearity of the AC/A ratio

Westheimer (1955) investigated the linearity and stability of the AC/A ratio using a haploscope-optometer with two trained observers. Measurements of the accommodative and vergence responses to accommodative stimuli of +1.00 to +5.00D were made on two separate occasions. One subject showed a non-linear relationship between accommodation and convergence on both testing occasions with the other subject showing a non-linear relationship on one visit. Westheimer stressed that his results were not intended to show undoubtedly that the AC/A ratio was non-linear, but that further investigation was required.

Ogle and Martens (1957) assessed the stimulus AC/A ratio of 28 subjects using the gradient technique with a sequence of positive and negative spherical lenses and then using a heterophoria method comparing the heterophoria found at various testing distances. A linear relationship was found between accommodation and vergence when the testing distance was varied (heterophoria method). When the gradient method was used a linear trend was again evident although in half the subjects the use of positive lenses led to a non-linear relationship; Ogle and Martens therefore concluded that negative lenses should be used when assessing the AC/A ratio with this technique. Martens and Ogle (1959) measured the AC/A ratio of 250 patients using the fixation disparity method and found that the AC/A ratio was linear in 92% of the cases.

Alpern *et al.* (1959) measured the stimulus and response AC/A ratios of 4 pre-presbyopic subjects over a wide range of accommodative stimuli (-4 to +10D) at stimulus intervals of 0.5D. The accommodative and vergence responses were measured using a haploscope optometer. Graphs of accommodative stimulus against accommodative response, convergence against accommodative stimulus (stimulus AC/A) and convergence against accommodative response (response AC/A) were plotted and are shown in figure 1.5.

Figure 1.5 The relationship between accommodative stimulus, accommodative response and vergence response for two subjects (Alpern *et al.*, 1959).

It can be seen that over the central portion of the accommodative stimulus range there is a linear relationship between accommodative stimulus, response and vergence response but that at the higher and lower levels of stimulus the response is non-linear.

Flom (1960a) assessed the stimulus AC/A ratio of 12 college students using a refractor. The change in heterophoria that occurred with the introduction of +1.00 and –1.00D lenses was assessed. The stimulus and response AC/A ratios of the subjects were also assessed using a haploscope-optometer where the accommodative response was subjectively measured by stigmatoscopy. Flom found that for intermediate accommodative stimuli (0-6.25D) the stimulus and response AC/A ratios were non-linear but concluded that this non-linearity was of no practical significance since the departures from linearity were consistent, small and showed no distinct trends with time. Ciuffreda and Kenyon (1983) criticise the work of Flom for several reasons. Firstly only two thirds of the subjects showed the small non-linearities reported and only 1 of the 12 subjects showed this non-linearity in both measurement techniques. Secondly the correlation co-efficients were extremely high. Finally if the data from the lowest accommodative stimuli were removed, the graphs presented by Flom show even higher linearity and it is known that at both the lower and higher levels of accommodative stimuli the relationship between accommodation and vergence is non-linear (Alpern *et al.* 1959).

1.6.5 Stability of the AC/A ratio

Manas and Shulman (1954) investigated the variability of the AC/A ratio in response to previous work that had indicated that the standard deviation was equal to about a half of the mean value. A study was undertaken that involved the assessment of the stimulus AC/A ratio of 22 college students 20 times over a seven-week period. The AC/A ratio was measured by two techniques, the gradient technique using positive lenses and the heterophoria method. Manas and Shulman conclude that the AC/A ratio is not a constant due to the variability in measurements that they found, particularly using the gradient method. The authors point out that the AC/A ratio depends on the difference between heterophoria values and heterophoria values are also not considered to be constant.

In an editorial footnote to the Manas and Shulman paper, Hirsch (1954) comments that the study only demonstrates the inherent variability of the AC/A ratio. He states that the data does not allow conclusions to be drawn as to whether this is due to experimental error or other factors.

Ciuffreda and Kenyon (1983) criticise the work of Manas and Shulman primarily because only the *stimulus* AC/A ratio was considered. The changes in heterophoria measured in calculating the AC/A ratio will be dependent on the actual accommodative response, which was assumed to have equalled the accommodative stimulus. Measuring the response AC/A ratio may thus have reduced the variability observed. The use of positive lenses when performing the gradient method may have led to non-linearities in the responses (Ogle and Martens, 1957). Ciuffreda and Kenyon also comment on the authors' lack of consideration of the errors in measurement and the limit of precision of the measurements since these would have influenced the variability. Manas did however consider this in a second paper (Manas, 1955).

The work of Manas and Shulman was also criticised by Morris (1957), particularly their use of the gradient and heterophoria methods of AC/A measurement. He used graphical analysis, involving the study of the field of clear single binocular vision, to calculate the AC/A ratio of over a hundred subjects, each tested on two or more occasions. Morris concludes that the AC/A ratio is stable when measured by a clinically adequate technique.

Flom (1960b) measured both the stimulus and response AC/A ratios of four students every week for 9 to 10 weeks. The standard deviations of the stimulus and response AC/A ratios were found to be 0.18^{Δ}/D and 0.12^{Δ}/D respectively with the average variability never exceeding 0.25^{Δ}/D. Flom concluded that the AC/A ratio was relatively stable and that random error of measurement and biological variation could account for any variability observed.

The affect of age on the AC/A ratio will be discussed in detail in section 2.6.

1.7 CA/C RATIO

Donders first described convergence accommodation (Donders, 1864 cited by Kent, 1958). Convergence accommodation is defined as the amount of accommodation that results from or occurs with an innervation to convergence, when the need for exact focusing has been eliminated (Pascal, 1930; Fry, 1948 cited by Schor and Narayan 1982).

Convergence accommodation is expressed in a similar manner to accommodative convergence by measuring the amount of accommodation that occurs for every unit of convergence stimulus or response, the CA/C ratio.

1.7.1 Measuring the CA/C ratio

Fincham and Walton (1957) described the difficulties that there are in attempting to measure convergence accommodation. In order to determine the accommodation that results from vergence alone it is necessary to remove the direct stimulus to accommodation, blur, whilst still presenting a stimulus which is adequate to allow binocular fusion and control of convergence. Methods for opening the accommodative loop and for measuring the CA/C ratio are described in more detail in section 1.3.3.a.

With the accommodative loop open it is then necessary to change the vergence stimulus and measure the accommodative and vergence response. For example, Fincham and Walton (1957) used artificial pupils to open the accommodative loop and then measured the accommodative and vergence responses to changes in vergence stimuli with a co-incidence optometer and haploscope.

1.7.2 Normal values of the CA/C ratio

Fincham and Walton (1957) and Balsam and Fry (1959) both used haploscope-optometers with artificial pupils to measure the CA/C ratio and found that in young adults the ratio was approximately equal to convergence in metre-angles ($\approx 0.167D/^{\Delta}$).

Morgan (1954) himself was the only subject in his assessment of the CA/C ratio. A haploscope and stigmatoscope were used to measure the vergence and accommodative responses to different vergence positions with the stimuli viewed through artificial pupils. He found the CA/C ratio to be around 0.40D/MA (0.07 $D/^{\Delta}$). Kent (1958) used the same experimental techniques as Morgan to measure the CA/C of 17 subjects aged 9 to 48 years old. A mean CA/C ratio of 0.13 $D/^{\Delta}$ ($\approx$0.8D/MA) was found.

More recently mean CA/C ratios ranging from 0.07 to 0.22 D/$^{\Delta}$ (0.4 to 1.3D/MA) have been found by a variety of methods (Kent, 1958; Kersten and Legge, 1983; Tsuetaki and Schor, 1987; Rosenfield and Gilmartin, 1988a; Wick and Currie, 1991; Bruce *et al.*, 1995).

1.7.3 Stability of the CA/C ratio

Bruce *et al.* (1995) assessed the CA/C ratio of 23 subjects with two sets of prisms on two consecutive days allowing the assessment of the repeatability of the results. The mean CA/C ratio was found to be 0.075 D/$^{\Delta}$ (0.45D/MA) with a mean difference in CA/C ratio between the two days of 0.00 D/$^{\Delta}$ (±0.01) showing a high repeatability of the results.

1.7.4 Linearity of the CA/C ratio

Morgan (1954) found that convergence and convergence accommodation were not linearly related, although in the range of 15 $^{\Delta}$ to 40$^{\Delta}$ the departure from linearity was small.

Both the studies Fincham and Walton (1957) and Balsam and Fry (1959) found that accommodation was linearly related to convergence angle except at the lower levels of convergence.

Small non-linearities in the CA/C ratio were shown by Kent (1958) but these were minimal in the convergence stimulus range of 10 to 30$^{\Delta}$. Wick and Currie (1991) also found small but statistically significant non-linearities in the CA/C ratios of 3 of their 6 subjects but concluded that these were clinically insignificant.

It would appear that all the evidence suggests that a linear relationship does exist between convergence and convergence accommodation within the intermediate range of convergence stimulus with any departures from linearity within this range being very small and not significant.

1.7.5 The effect of age on the CA/C ratio

Several cross-sectional studies have examined the effect of age on the CA/C ratio. Fincham and Walton (1957) assessed the CA/C ratio of 22 subjects using a haploscope optometer with small entrance pupils to open the accommodative loop. The results showed that upto the age of around 24 the CA/C ratio was fairly stable at 1D/MA (around 0.17D/$^{\Delta}$) but after this age there was a steady decrease as age increases. This result is shown along with others described below in figure 1.6.

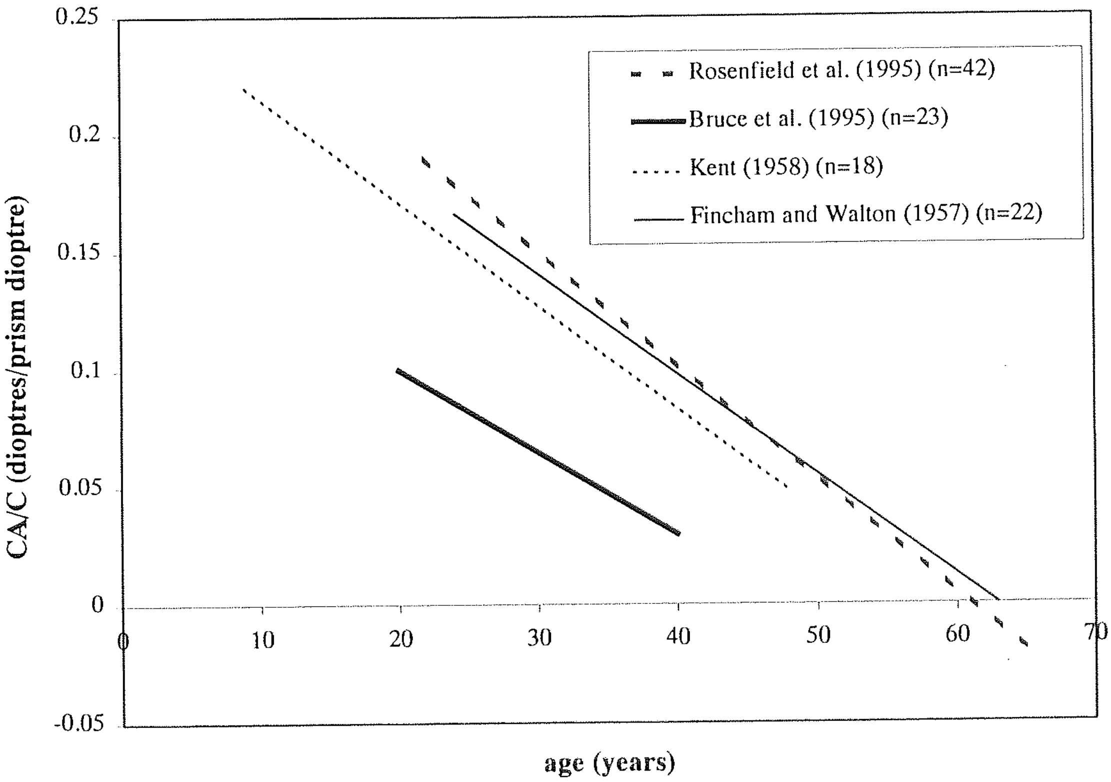

Figure 1.6 Graph of CA/C ratio against age from earlier investigations

Kent (1958) assessed the CA/C ratio of 18 subjects aged 9 to 48 years and found a negative correlation between the CA/C ratio and age but a more significant negative correlation was found between amplitude of accommodation and CA/C ratio. Kent found that when the amplitude of accommodation dropped below 10D the CA/C ratio decreased rapidly. Wick and Currie (1991) only found a weak correlation between amplitude of accommodation and CA/C ratio with a slight decrease in CA/C as the amplitude declined. The Wick and Currie study is not included in figure 1.6 since no correlation was found between age and the CA/C ratio in the 40 subjects assessed.

Two more recent studies have shown a strong negative correlation between age and CA/C ratio. Bruce *et al.* (1995) used a Canon R-1 infra-red open view autorefractor and IRIS eye movement monitor to measure the CA/C ratios of 23 subjects aged 17 to 42 years of age. Pinholes were used to open the accommodative loop. Their results showed that the CA/C ratio substantially declined with age, from approximately 0.1 $D/^{\Delta}$ at age 20 to 0.03 $D/^{\Delta}$ at age 40, an average of 0.003 $D/^{\Delta}$ (0.018D/MA) per year. Rosenfield *et al.* (1995a) assessed the CA/C ratio using the Canon autorefractor to assess the accommodative response whilst viewing a DoG stimulus through a series of prisms. The CA/C ratio of 42 subjects aged 22 to 65 was calculated. It was found that the CA/C ratio declined with age at a rate of 0.006 $D/^{\Delta}$ (0.036D/MA) per year.

1.8 MODELLING ACCOMMODATION AND VERGENCE

Toates (1975) describes a model as ‘a representation of a system in a form that, while being different from the real system, none the less exhibits its essential features’. A mathematical model uses mathematical operators to depict the structure of a system and its performance. Modelling is a two-way process, when modelling a biological system, experimental evidence is used to develop and alter the structure of a model but at the same time the model may generate information that requires experimental investigation. A comprehensive review of the development of the modelling of accommodation and vergence and their interaction is given by Eadie and Carlin (1995).

1.8.1 Negative feedback control systems

Control theory is used in engineering to design and analyse systems allowing engineers to predict and control how the input and output are related.

Natural control systems such as the regulation of body temperature are negative feedback control systems where the output of the system is compared to the desired value via a negative feedback loop allowing the accurate control of the system. Figure 1.7 below shows the components of a negative feedback control system.

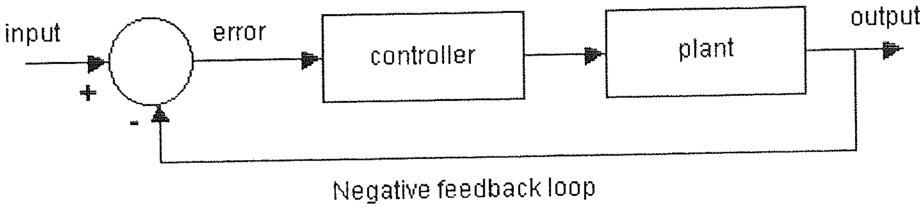

Figure 1.7 Negative feedback control system

The input to the system is the desired value, so in terms of the regulation of body temperature this would be the desired body temperature. The input is compared to the output of the system from the negative feedback loop, producing an error signal. The error signal is then passed via the controller to the plant, which modifies the output to make it closer to the desired value thus reducing the error signal. The control system is hence able to monitor its own performance by monitoring the error and can make any necessary changes to compensate for changes in external disturbances or changes in the input signal (i.e. desired value).

1.8.2 Controllers

There are three main types of controller and control systems usually contain a combination of these. The first is the proportional controller where the controller output is proportional to the error value. The second is the integral controller, which has an output that is proportional to the previous error values. The final form of controller is the differential controller, which is dependent on the rate of change of the error. A combination of these controllers allows accurate and stable control systems (Toates, 1975).

1.8.3 Laplace transforms

In order to simplify the mathematical models and to allow easier algebraic manipulation of equations, Laplace transforms are used. The transforms convert equations from differential equations that describe the dynamics of a system with respect to time, to algebraic equations that describe systems in the frequency or ”s-domain” (s is a complex number). Thus to find a solution to a system instead of performing complex integrations, the input to a system in the time domain can be converted to an equivalent input in the s-domain. The Laplace domain equations that then comprise the transfer function can be used to produce an output that can be converted to an output in the time domain by an inverse Laplace transformation. An example of this is below.

Consider a bucket being filled at a constant rate of 1 unit/time. In order to calculate the volume in the bucket at time *t*, an integration could be performed, the integral of 1 with respect to time is *t* and thus at time *t* the volume in the bucket is *t* units.

Instead, the volume could be calculated using Laplace transforms as shown in figure 1.8. A Laplace transform of a unit step input is $1/s$. This term must be multiplied by the transfer function corresponding to integration which is $1/s$, and this gives an output-transform of $1/s^2$. The output is then inverted from the Laplace transform to the time domain. The inverse transform of $1/s^2$ is a unit ramp *t*. Thus at time *t* the volume in the bucket is *t* units.

Figure 1.8 Example of the transfer function method using Laplace transforms (Toates, 1975)

1.8.4 Accommodation and vergence

The lag between the accommodative stimulus and response represents the steady state error in the accommodation model and fixation disparity is thought to represent the vergence error signal (Schor, 1980). Toates (1970;1972) developed a model of accommodation, which included a proportional controller that utilised the lag of accommodation, to represent the static behaviour of the accommodative mechanism. A simplified model of the accommodative response is shown in figure 1.9 below. Similar models have been developed for vergence (Toates, 1974).

Figure 1.9 A model showing the essential components of the accommodation system (reproduced from Toates, 1975)

To model dynamic accommodative and vergence responses it has been necessary to include other elements in the accommodation and vergence models (O'Neill and Brodkey, 1970; Toates, 1972; Krishnan and Stark, 1975; 1977; Schor, 1979b; Hung *et al.*, 1986 and others). The current study considers only static oculomotor behaviour, in terms of modelling that is the steady state response following a step input rather than the dynamic response encountered with the response to a changing stimulus.

1.8.5 Modelling the interactions between accommodation and vergence

1.8.5.a Single interactive models

The initial model that demonstrated the interaction between accommodation and vergence (see section 1.6) was based on the assumption that retinal blur driven accommodative convergence was the primary interaction, quantified by the AC/A ratio (Maddox, 1893 cited by Morgan, 1983; Alpern and Ellen, 1956). This model (see figure 1.10) assumes that accommodative vergence adds to the other vergence components and that it is independent of binocular or monocular fixation. However, despite evidence supporting the first assumption (Semmlow and Venkiteswaran, 1976; Semmlow and Hung, 1979), work by Semmlow and Heerema (1979a; 1979b) looking at the composition of the binocular and monocular vergence responses has shown the fusional component to be greater than that predicted by the Maddox theory and the blur component to be smaller.

Figure 1.10 The single interactive model of Maddox (reproduced from Schor, 1985)

The model of interaction developed by Fincham and Walton (Fincham,1951; Fincham and Walton,1957) shows convergence accommodation (CA/C ratio) to be the primary interaction (figure 1.11). Fincham and Walton do not deny the existence of accommodative vergence but suggest that it is not actually a separate component, rather there is just one near control centre controlling both accommodative and vergence responses. Blur acts through the vergence controller to change both accommodation and vergence responses. This single interactive process would mean that the AC/A ratio and CA/C ratio should be reciprocally related and that it should be impossible for accommodative vergence and vergence accommodation to have different values at the same time since they represent the same process. However it has been shown that the ratios are not reciprocals (Rosenfield *et al.*, 1995a) and that accommodative vergence and vergence accommodation must be mediated by separate interactive processes with separate neural mechanisms (Semmlow and Hung, 1981).

Figure 1.11 The single interactive model suggested by Fincham (reproduced from Semmlow and Hung, 1981)

1.8.5.b Dual interactive models

Dual interactive models have been developed that propose that both blur and disparity drive the system, with the cross-links of accommodative vergence and vergence accommodation. The current consensus is that the cross-links in the model are after the controller but before the plant (figure 1.12).

Figure 1.12 A dual interactive model that has forward parallel cross-links (reproduced from Schor, 1985)

Hung and co-workers have produced many models over the last twenty years. The initial models concentrated on the static behaviour of the oculomotor system, using computer simulations to validate the models with comparisons to experimental findings (Hung and Semmlow, 1980; 1982; Hung *et al.*, 1984; 1986; Hung, 1990; 1991; 1998a). Models have also been developed that include tonic responses in the form of bias inputs prior to the plant, proximal components and adaptation components, which bring in an element that depends on previous responses (Hung, 1992a; Hung *et al.*, 1996; Ciuffreda and Hung, 1992).

The models developed by Schor and colleagues appear more complex, they include both phasic and tonic accommodation and vergence, with the cross-links being located between these phasic and tonic controllers (Schor and Kotulak, 1986; Schor, 1985; 1992; Schor *et al.*, 1992). Again models have been produced that include the tonic, proximal and adaptive elements of accommodation and vergence. Another model has also included the influence of spatiotopic (volitional/proximal) and retinotopic (reflex) cues (Schor, 1992).

In a recent paper, Jiang (1997) proposed the inclusion of an additional operator in the accommodation model with an accommodative sensory gain component. This sensory component was suggested as a method of accounting for the changes in the accommodative response induced by changes in stimulus conditions such as luminance, contrast or spatial frequency of the target and changes in pupil size.

1.9 ACCOMMODATIVE ADAPTATION

Following a sustained near-vision task, a transient increase in the magnitude of tonic accommodation (the resting state of accommodation) has been described (Ebenholtz, 1983; Schor *et al.*, 1984; Schor, 1986; Fisher *et al.*, 1987; Owens and Wolf-Kelly, 1987; Rosenfield and Gilmartin, 1988b; Rosenfield, 1989a; Gilmartin and Bullimore, 1991 and others). Rosenfield *et al.* (1994) provide a comprehensive review of this accommodative adaptation process.

Figure 1.13 Mean post-task dioptric shift in DF (dark-focus) against time for 10 emmetropic subjects for the 90 second-period after the completion of a 3-minute near vision task (3D). Error bars indicate ±1SEM. (reproduced from Rosenfield and Gilmartin, 1988b).

In 1976, Malmstrom and Randle (1976) found that when a pinhole was introduced to open the accommodative loop, the time taken for accommodation to reach its baseline level was dependent on the closed-loop response prior to the introduction of the pinhole. Figure 1.13 shows a typical accommodative regression after a 3-minute near vision task (at 33cm), from the study of Rosenfield and Gilmartin (1988b).

Rosenfield and Gilmartin (1988b) propose that vergence and accommodative adaptation maintain single clear binocular vision without excessive fatigue allowing the reflex elements of accommodation and vergence to respond to any subsequent change in target blur or disparity.

Analogous with vergence adaptation it has been proposed that the accommodative response is composed of two elements, a reflex, phasic element driven by blur and proximal cues (Rosenfield *et al.*, 1994) and an adaptive, tonic element stimulated by and replacing the reflex response (Schor, 1986).

The increase in open-loop accommodative response observed immediately following sustained fixation is therefore not a change in tonic accommodation itself, but represents the sum of the fixed baseline tonic accommodation and the adaptive accommodation element. The accommodation regression that follows a sustained task is thus due to the decay of the adaptive accommodative component.

1.9.1 Time course of accommodative adaptation

The time course of onset of accommodative adaptation is very fast. Fixation periods as short as 15 seconds can induce accommodative adaptation. The length of the fixation period has been found to be unrelated to the magnitude or the rate of decay of adaptation (Fisher *et al.*, 1990; Rosenfield and Gilmartin, 1989).

1.9.2 Factors affecting accommodative adaptation

1.9.2.a Magnitude and composition of the accommodative stimulus

Bullimore and Gilmartin (1989) assessed the accommodative adaptation of 10 male subjects following a 10-minute near vision task representing an accommodative stimulus of 1, 3 or 5D. The accommodative loop was opened with the subject either viewing a bright empty-field or in darkness with the accommodative response being measured using a Canon R-1 autorefractor. The results of both methods showed that the degree of adaptation observed after the task was directly related to the dioptric stimulus of the task. Despite this increase in adaptation to higher dioptric stimuli the accommodative response returned to the baseline level within the initial 50 seconds after all the tasks, thus showing the magnitude of the stimulus has little effect on the time course of the adaptive decay (Rosenfield and Gilmartin, 1989; Rosenfield *et al.*, 1994).

There is some debate as to whether accommodative adaptation occurs following distant stimuli. Ebenholtz (1983) found a 0.21D decrease in open-loop accommodation after an 8-minute period of sustained fixation at the subject's far point. However, Gilmartin and Bullimore (1987) and Fisher *et al.* (1987) failed to find any significant negative adaptation after distance fixation.

Ebenholtz looked at how accommodative adaptation was related to the magnitude of tonic accommodation and the dioptric distance of the sustained task from this tonic level (Ebenholtz, 1985; 1992). Ebenholtz found that the target-dark focus separation was critical. In subjects with low tonic accommodation (more distant), the post-task shift in tonic accommodation to a near target was greater than that of a subject with a higher (closer) value of tonic accommodation. This was also true with distant stimuli with greater adaptation to a far stimulus if the tonic accommodation level was closer. When comparing the adaptation that followed sustained fixation of a near and distant target that were at equal dioptric distances from the tonic accommodation distance, the shifts were equal in magnitude, although the shift following the near stimulus was slower to decay.

It has been suggested that it is not just the magnitude of the accommodative response during the adapting period that influences the degree of adaptation but also the composition of the response (consisting of blur induced, tonic, proximal and convergent accommodation) (Rosenfield *et al.*, 1990;1992). For example, Rosenfield *et al.* (1990) compared the adaptation that was produced by two different stimuli each representing a dioptric stimulus of 3D. One target was located at 33cm whilst the other was placed at 5m but viewed through minus lenses to provide a 3D stimulus. The results showed that the degree of adaptation to the target with proximal cues to accommodation (at 33cm) was twice that of the distance target, indicating that proximally induced accommodation does provide a stimulus to accommodative adaptation.

1.9.2.b Method of opening the accommodative loop

Several studies have investigated how the method of opening the accommodative loop influences the degree and decay of accommodative adaptation.

Ciuffreda and Kenyon (1983) cite the work of Phillips (1974) who compared the regression of accommodation towards the position of focus for three methods of opening the accommodative loop. Darkness, bright-empty field and pinhole methods were used and the regression time constants were found to be 4, 6 and 10 seconds respectively with the baseline position reached after 15 seconds for the dark conditions compared to 40 seconds for the pinhole condition.

Schor *et al.* (1986) investigated accommodative adaptation under the same three open loop conditions as Phillips using an infra-red optometer to measure accommodation. The results again showed that the most rapid adaptive decay was in darkness, with the smallest magnitude of adaptation. The empty-field and pinhole conditions both showed the most sustained after-effects and the greatest amplitude of adaptation. Schor *et al.* also found that if the adaptive decay occurring whilst viewing through the pinhole was interrupted by a period of darkness, accommodation rapidly decayed to the resting focus position. However when the luminance was returned to its original level the accommodative response returned to the adapted state. Schor concludes that this shows that accommodative adaptation did not decay more rapidly in darkness but was masked by darkness. Schor and McLin (1988) followed up this experiment by investigating the effect of luminance on the accommodative after-effect and found that adaptation was partially masked in mesopic luminance conditions and nearly completely masked in darkness or scotopic conditions.

Similar results have been found by Wolfe and O'Connell (1987) who found that 5 of 21 subjects showed a greater magnitude of accommodative adaptation under illuminated conditions (bright-empty field) than in darkness. Bullimore and Gilmartin (1989) also assessed accommodative adaptation under both bright and dark field conditions but found no difference in the post-task regression patterns.

Rosenfield *et al.* (1994) propose that the larger amplitude of adaptation that has been reported under illuminated conditions is due to proximally induced accommodation. Targets such as the Difference of Gaussian (DoG) target used by Schor and McLin (1988) will influence the net accommodative response as they provide a proximal stimulus to adaptation, as described earlier.

1.9.2.c Method of measuring open-loop accommodation

Comparing the time found by different researchers for accommodation to return to its baseline level, it is evident that the longer decay times are those found using laser optometers rather than stigmatoscopes or infra-red optometers (Rosenfield *et al.*, 1994).

When measuring the resting state of accommodation (tonic accommodation) is it known that the method of measurement can influence the result (see section 1.3.3.c). Rosenfield (1989a) attempted to show whether these variations also influenced the post-task shift in open-loop accommodative response. Rosenfield compared the accommodative adaptation recorded using a laser optometer to that measured with an infra-red optometer after 8 minutes fixation of a target located at the near point of accommodation. No significant accommodative adaptation was detected using the infra-red optometer despite the high dioptric stimulus, however 6 of the 10 subjects showed accommodative adaptation when assessed with the laser optometer (mean adaptation = +0.6D). Rosenfield comments that it may be the cognitive effort and proximal influences during measurements with the laser optometer that produce an increase in post-task open-loop response as with the assessment of tonic accommodation (Post *et al.*, 1984; 1985; Rosenfield and Ciuffreda, 1990b; Rosenfield and Gilmartin, 1990).

Rosenfield *et al.* (1994) also comment on the time it takes to record each measurement of accommodation with the laser optometer, each reading may take upto 60 seconds and this sustained assessment may contaminate the results.

1.9.3 Effect of age on accommodative adaptation

Rosenfield *et al.* (1995b) assessed the open-loop accommodation response of 41 subjects before and after a 5 minute near vision task at 33cm. The subjects were aged between 20 and 70 years of age and measurements were taken with a Canon R-1 autorefractor in the dark. Accommodative adaptation was found to decline with age at a rate of -0.034D/year. The mean zero level of adaptation was reached at 55 years of age.

1.10 VERGENCE ADAPTATION

Vergence adaptation is the process by which the oculomotor system maintains a constant vergence response to a sustained vergence stimulus.

The facility of vergence adaptation was first noted by Maddox (1893 cited by Morgan, 1983) when analysing his own tonic vergence changes after looking through base-out prisms and convex lenses. Maddox felt that these were adaptive changes in tonic vergence that occurred to relieve stress on the fusional vergence mechanism.

Vergence adaptation can be observed during a sustained reading task where there is a shift in the tonic vergence of the oculomotor system with a relatively slow return to the pre-task level after the cessation of the task (Rosenfield, 1997). Wolf *et al.* (1987) measured the tonic vergence responses of 22 students before, during and after a 45 minute near-vision task at 20cm. The mean tonic vergence response over this time is shown in Figure 1.14 with a return to the baseline level of tonic vergence after 3 minutes. Rosenfield (1997) comments that care should be taken in using the term tonic vergence when describing the pre- and post-task vergence levels. The post-task vergence response will actually be a composite response of the tonic fusional vergence responses with tonic vergence thought to remain constant.

Figure 1.14 Tonic vergence in metre angles (MA) as a function of time for the group data before, during and immediately following reading. The dashed horizontal line represents the pre-reading mean baseline. Error bars indicate ±1SEM. (Wolf *et al.*, 1987)

1.10.1 Modelling vergence adaptation

Ogle and Prangen (1953) suggested that there were two compensatory components to the vergence response. The first is a rapid stabilising response followed by a slower response that responded to stress on the faster response process. Fixation disparity represents the heterophoric state of the eyes after the first rapid response, it is then reduced by the second slower response.

Schor (1979a;1980) developed a model of the vergence adaptive mechanism that comprised of the same two main components, a fast fusional response and a slow fusional response (sometimes termed the tonic response). The fast fusional component responds immediately to a change in vergence stimulus to eliminate retinal disparity. The slow fusional component, driven by the effort of the fast fusional system, gradually increases its activity thus reducing and outlasting the fast fusional response but maintaining the same aggregate vergence response (figure 1.15).

Figure 1.15 Computer simulation of vergence adaptation showing the aggregate vergence response comprising of outputs of the fast and slow vergence mechanisms. (Schor, 1980)

The stimulus for the slow fusional vergence response cannot be retinal disparity directly, since within 1 second the fast fusional system will reduce the disparity to virtually zero (Rashbass and Westheimer, 1961) and also it takes at least 30 seconds of disparity-induced vergence to produce a prolonged change in heterophoria (Schor, 1979a; Henson and North, 1980). Thus slow fusional vergence occurs after the retinal disparity has been removed by fast fusional vergence (Schor, 1979b;1983) and so it must be the effort or output of the fast fusional vergence controller that stimulates the slow response.

A schematic representation of Schor's model is shown in figure 1.16, with fixation disparity being a steady state error of the vergence system that exists to stimulate the fast fusional response.

Figure 1.16 Schematic representation based on Schor's model of the relation of fast fusional vergence, slow fusional vergence and fixation disparity (reproduced from Owens and Leibowitz, 1983).

Schor's model is partly supported by Carter (1963;1965) who proposed that adaptation was a conditioned reflex induced by fusional vergence and hence might almost qualify as a fifth component of vergence. Hofstetter (1951) believed that it was proximal vergence that relieved the fusional vergence demand and led to adaptive changes at near. Carter (1963) comments, however, that it cannot be proximal vergence since adaptation occurs at both distance and near.

In the same way as there is a difference in the rate of onset of the two fusional components, there is a similar difference in their decay. The fast fusional response will decay rapidly in around 10-15 seconds (Ludvigh *et al.*, 1964; Schor, 1979b; Henson and North, 1980) whereas the slow fusional response has a much slower rate of decay. Hence in Figure 1.14 (from Wolf *et al.,* 1987) immediately after the removal of the vergence stimulus at the end of the near-vision task, the slow vergence response decays and the tonic vergence level is seen as returning to its baseline level (Rosenfield, 1997).

1.10.2 Orthophorisation

A high incidence of orthophoria is found in the population and this has been likened to the non-normal distribution of ametropia (emmetropisation) and has been termed orthophorisation (Sato, 1943; Crone and Hardjowijoto, 1979). It has been suggested that vergence adaptation is the process that underlies orthophorisation (Ogle and Prangen, 1953; Carter, 1965). The fact that heterophorias still exist despite vergence adaptation has been explained by some as being due to a disruption in this adaptive facility (Carter, 1963; Crone and Hardjowijoto, 1979). McCormack (1985) also proposed that heterophoria may exist despite orthophorising vergence adaptation because the adaptation may be insensitive to small or moderate degrees of heterophoria or that the innervational amplitude of vergence adaptation is not sufficiently large to completely overcome the heterophoria.

Carter (1965) concluded from his adaptation experiments that his subjects adapted approximately to orthophoria but McCormack (1985) points out that Carter's subjects all had habitual farpoint heterophorias of less than the experimental error and so may have actually adapted to a heterophoric position. McCormack (1985) cited this as evidence for 'heterophorising' adaptation and attempted to clarify whether orthophoria is the aim of vergence adaptation or whether adaptation tends to the baseline heterophoria.

McCormack measured the nearpoint heterophoria of 30 subjects and then neutralised the deviation with a prism to achieve orthophoria. McCormack proposed that if the endpoint of vergence adaptation was orthophoria then no adaptation would be expected in these subjects. However, in 23 of the 26 exophoric subjects and 2 of the 4 esophoric subjects there was either partial or complete heterophorising adaptation. Ogle *et al.* (Ogle *et al.*, 1967) also found that adaptation was to a heterophoric position, although this was in the vertical meridian. If however, the heterophoria of the subjects used in these studies is due to an abnormal adaptive mechanism (Carter, 1963, Crone and Hardjowijoto, 1979) then these subjects may not adapt in the normal way and may not correctly register the induced orthophoric position (Dowley, 1987), casting doubt on the conclusions drawn. Rosenfield (Rosenfield, 1997) also criticises McCormack's findings because prior to the assessment of the subject's initial heterophoria the subjects were allowed to read for a five minute period, this may have induced vergence adaptation influencing the pre-task heterophoria measure and hence contaminated the results.

Dowley (1987) assessed the heterophoria of 31 students before and after a 5-hour period of monocular occlusion. The aim of the study was to determine whether after the prolonged occlusion, which would allow the dissipation of any vergence adaptation, the distribution of heterophoria returned to a normal distribution. The heterophorias before the occlusion were found to show a significantly non-normal distribution as expected but after the occlusion the spread had increased significantly and orthophorisation was reduced. Dowley concludes that the prolonged occlusion experiment supports the theory that vergence adaptation is the mechanism underlying orthophorisation.

1.10.3 Prism adaptation

When a change in vergence stimulus is brought about by the introduction of a prism, the adaptation is termed prism adaptation. The oculomotor system counteracts the prism with an ocular deviation towards the original heterophoria or heterotropia. A patient with an esophoria at distance that is corrected to orthophoria with a base-out prism may for example, after a short period of wear of the prism, display the value of esophoria present originally. If the prism is then removed there will first be an increased esophoria (induced by the prism) and then this will again return to the original baseline esophoria. This is represented graphically in figure 1.17.

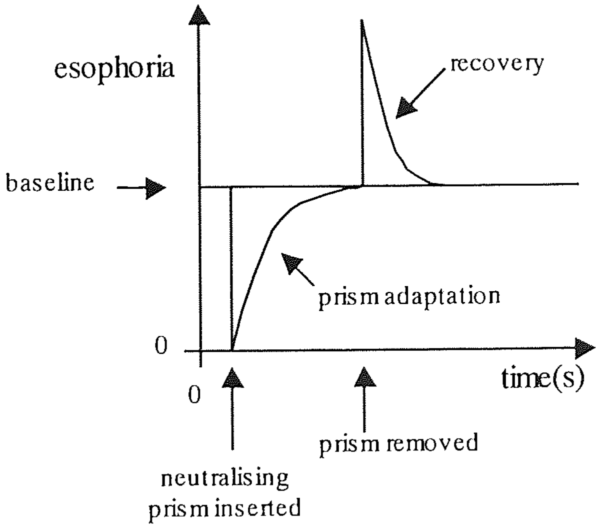

Figure 1.17 Graphical representation of prism adaptation.

In clinical practice, prisms may be prescribed to relieve asthenopic symptoms caused by a heterophoria. Practitioners are often reluctant to prescribe prism because if the patient adapts to the prism the original value of heterophoria will still be present. However as previously mentioned, it may be that the heterophoria actually results from an abnormality in the vergence adaptation mechanism and so in these patients the symptoms may be relieved by the prismatic correction since they are unable to adapt (Carter, 1965; North and Henson, 1981).

1.10.4 Measurement of vergence/prism adaptation

Fixation disparity method

Fixation disparity represents a lag in the vergence response compared to the vergence stimulus. Fixation disparity curves can be plotted with fixation disparity plotted as a function of the prism introduced as a vergence stimulus (forced duction curves). Fixation disparity is measured using a nonius alignment technique with the nonius lines surrounded by binocular targets to allow fusion. Prior to each assessment of fixation disparity it is necessary to occlude one eye for a short period to allow the fast fusional response to decay.

The studies of Ogle *et al.* (Ogle and Prangen, 1953; Ogle *et al.*, 1967), Schor (1979a; 1979b; 1980) and Carter (1965) used fixation disparity when assessing vergence adaptation by observing the effect that viewing through a prism had on the fixation disparity curve.

Heterophoria method

Maddox (1893 cited by Morgan, 1983) originally commented on vergence adaptation when observing heterophoria changes and Carter (1965) used heterophoria as well as fixation disparity techniques in his assessment of vergence adaptation. Henson and North (1980) propose that if prism adaptation occurs because of a change in innervational tonus to the extraocular muscles (Carter, 1963;1965) and heterophoria is a direct measure of this tonus (Alpern, 1969), then heterophoria measurements would be a more direct measure of adaptation.

"Flashed" Maddox rod technique

Henson and North (1980) developed a "flashed" Maddox rod technique to assess vergence adaptation after the introduction of a prism. This technique uses a tangent screen to allow the subject to give a subjective response as to the position of the Maddox rod as it is briefly presented (0.25 seconds) to directly measure the heterophoria. One eye is occluded for 15 seconds prior to each Maddox rod presentation to stabilise the heterophoria response. Following each presentation, there is 15 seconds of binocular viewing of a test chart followed by the next 15 seconds of monocular occlusion prior to the next "flash". This sequence continues for 15 presentations for a total of 3.5 minutes of binocular vision and then the prism is removed and followed by 10 presentations of the same sequence to assess recovery from the adaptation.

The 15 seconds of monocular occlusion prior to each presentation allow the fast fusional response to decay. The heterophoria value will thus represent the sum of the baseline heterophoria, the vergence stimulus (prism) and the slow vergence response (which will have only slightly decayed in 15 seconds). With the baseline heterophoria and vergence stimulus being a fixed value any change in heterophoria measured during the experimental procedure will represent changes in the slow vergence response. The results can be shown graphically (similar to figure 1.17) and then the time constants of the adaptation and recovery phases and the extent of the adaptation can be assessed.

Further details of this technique are given in section 3.3.1. This technique has now been widely used in the assessment of vergence adaptation (Henson and North, 1980; North and Henson, 1981; 1985; Sethi, 1986; Sethi and North, 1987; Winn *et al.*, 1994a and others).

1.10.5 Time course of vergence adaptation

Carter (1965) found that some subjects showed almost total adaptation to the inclusion of their maximum fusable prisms after just 15 minutes (upto 10^{Δ} base-in and 32^{Δ} base-out), with the majority of this adaptation occurring within the first 5 minutes. Ogle and Prangen (1953) showed complete adaptation to 2^{Δ} base-up or base-down within 3 to 7 minutes. Both adaptation and decay (recovery) of the slow vergence response are exponential functions

(Ogle and Prangen, 1953; Henson and North, 1980; Sethi and North, 1987) with the majority of change occurring within the first few minutes.

1.10.6 Factors affecting vergence adaptation

The amount of vergence adaptation that occurs is proportional to the magnitude of the vergence disparity, for example the size of the prism, and the rate of both adaptation and adaptive decay (recovery) is more prolonged the larger the vergence disparity (Ogle and Prangen, 1953; Mitchell and Ellerbrock, 1955; Sethi and North, 1987).

The magnitude and rate of decay of the adaptation are also related to the duration of the adaptive stimulus, with the rate of decay being inversely proportional to the length of the adapting stimulus, i.e. the longer the stimulus duration, the slower the decay (Ellerbrock, 1950; Mitchell and Ellerbrock, 1955; Ludvigh *et al*., 1964; Fisher *et al*., 1990). Rosenfield (1997) comments that this relationship between rate of decay and duration of stimulus is observable clinically, because it may take many hours, days or even weeks for the natural vergence responses, that may have been maintained for hours, to decay fully.

Carter (1965) claimed that sensory fusion (single, binocular vision) was required for vergence adaptation. When sensory fusion was not possible, due to a prism induced heterotropia causing diplopia, the reduction of the deviation was slow after the removal of the prism. When esophoria was induced by base-out prism worn before sleeping it was still pronounced upon awakening after 8 hours sleep (during which there would be no sensory fusion), but only 20 minutes of subsequent single binocular vision was required for the esophoria to disappear. Interestingly Carter says that adaptation without fusion is *slower* but not non-existent. It has been found that even when fusion was not achieved, due to the vergence stimulus exceeding the fusional vergence range, adaptation did still occur although the magnitude was reduced (Sethi and North, 1987). This is further support that the stimulus to slow fusional vergence is the effort required for fast fusional vergence.

1.10.7 Asymmetry of vergence adaptation

An asymmetry in the oculomotor system's ability to adapt has been found. Ogle *et al.* (1967) used fixation disparity techniques and found that a normal subject took 50 minutes to adapt to 6^{Δ} base-in but only about 10 minutes to adapt to 28^{Δ} base-out. Henson and North

(1980) also reported that adaptation at distance to base-out prism was significantly quicker than to base-in prism although they report no asymmetry at near. Mitchell and Ellerbrock (1955) used a fixation disparity technique and found that subjects could not fully adapt to base-out prism at near but could to base-in. Henson and North (1980) explained the asymmetries as being due to the frequency with which the oculomotor system deals with a particular type of disparity in the normal environment. Sethi and North (1987) show that adaptation is influenced by fusional ability, that is the fusional reserves, thus in the distance, adaptation will be greatest to base-out prisms the direction where the fusional reserves are greatest. At near, fusional reserves are more equal or greater for base-in prism (depending on target distance) and so adaptation to base-in and base-out prisms may be more symmetrical or greater for base-in prism.

1.10.8 Vergence adaptation and age

The vergence adaptation of 50 subjects aged 18 to 85 years was assessed using a “flashed” Maddox rod technique with a 6^{Δ} convergent and then 6^{Δ} divergent disparity stimulus (Winn *et al.*, 1994a). A comparison was made between pre-presbyopic subjects (age<37 years; N=20) and presbyopic subjects (age>54 years; N=20). The presbyopic population showed a significantly reduced adaptation response compared to the pre-presbyopic population with either a reduced gain in the slow fusional vergence system or an increase in the time constant (see figure 1.18).

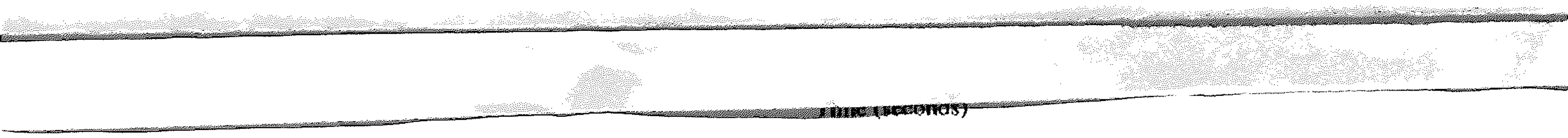

Figure 1.18 Rate of adaptation for pre-presbyopic (closed symbols: age<37 years; N=20) and presbyopic (open symbols: age>54 years; N=20) observers subjected to (a) 6^{Δ} of convergent disparity and (b) 6^{Δ} of divergent disparity. Error bars represent ±1SEM. (Winn *et al.*, 1994a)

Rosenfield *et al.* (1995b) assessed the vergence adaptation of 41 subjects aged 20 to 70 years. A haploscope-optometer was used to measure tonic vergence before and immediately after a 5-minute sustained near-vision task. The results showed no significant correlation between vergence adaptation and age.

Rosenfield (1997) suggests that the discrepancy between the findings of Winn *et al.* (1994a) and Rosenfield *et al.* (1995b) may be due to differences in the age range of the subjects tested and the vergence demand during the adapting period. The target in the Winn study was at a vergence stimulus of approximately 1.2^{Δ} with a further 6^{Δ} base-in and base-out introduced. In the Rosenfield study the subjects had to fixate a target at 33cm, a vergence stimulus of approximately 18^{Δ} which Rosenfield (1997) predicts would produce more reliable adaptation.

1.11 SUMMARY

The accommodation and vergence responses that accompany a change in stimulus distance allow the maintenance of clear, binocular single vision. Various elements of accommodation and vergence contribute to the overall oculomotor response including convergence accommodation and accommodative vergence that occur because of the synkinetic link in innervation between accommodation and vergence.

Accommodation and vergence both have fast and slow components and following a near vision task there may be accommodation and vergence after-effects that represent the regression of the slow accommodation and fusional responses respectively as they decline to their baseline (tonic) levels.

Chapter 2 will consider the affect of age on the accommodation and vergence mechanisms with details of the natural decline in the amplitude of accommodation that occurs. The anatomical changes that occur in presbyopia are considered and the impact that this decline in accommodation has on oculomotor function will be discussed.

CHAPTER 2

PRESBYOPIA

2.1 INTRODUCTION

Presbyopia is the ocular condition where the amplitude of accommodation has naturally and progressively decreased until it has reached a stage where the nearpoint has moved to a position further than the comfortable working distance. Presbyopia hence presents in clinical practice with symptoms relating to blur or ocular discomfort for nearwork.

2.2 AMPLITUDE OF ACCOMMODATION

Much work has been undertaken to find how the amplitude of accommodation varies with age (Donders, 1864; Duane, 1922; Hamasaki *et al.*, 1956; Hofstetter, 1965; Sun *et al.*, 1988; Ramsdale and Charman, 1989). Amplitude of accommodation is at its maximum at around 10 years of age with an amplitude of around 15D, with a gradual decrease in amplitude after this age. In the majority of studies, the effect of age on amplitude of accommodation was studied using subjects who represent a cross-section of age groups and conclusions are then drawn as to how the amplitude of accommodation would vary in an individual against time.

A study by Donders (1864, cited by Kent, 1958) was one of the first studies to assess the decline in the amplitude of accommodation with age, measuring the amplitude of accommodation of subjects aged 10 to 80 years using a push-up method. Duane (1922) also used the push-up method to measure the amplitude of accommodation in more than 4000 eyes, aged from 8 to 70 years of age. Both studies found that the mean amplitude of accommodation declined rapidly up to the age of 50 to 52 years and then decreased only slightly during the following years. The significant difference between the two studies was around the age of 40 to 60 years of age where Duane found higher amplitudes of accommodation, which may be due to methodological differences.

Hamasaki *et al.* (1956) also found using the push-up technique that the mean amplitude of accommodation decreased rapidly until the age of 50-52 years and then remained essentially the same until age 60 (the highest age in their study). With stigmatoscopy a similar rate of decline was found, with zero accommodation reached at age 52 years. The results from both techniques did not show a linear relationship between age and amplitude of accommodation, with a gradual tapering off of the amplitude.

The non-linear relationship between age and amplitude of accommodation has been found by other studies. Sun *et al.* (1988) used stigmatoscopy and found a gradual decline in accommodative amplitude until the age of 40 or 50 followed by a deceleration of the reduction.

Hofstetter (1965) undertook a 9-year longitudinal study of the amplitude of accommodation of himself and a colleague, aged 36 and 40 respectively at the start of the study. The measurements were taken using two techniques, one subjective (involving the detection of the blur of a target within a Badal lens system) and one objective (phoro-accommodometer). The results from both techniques for both subjects showed a linear reduction in amplitude of accommodation throughout the study period prior to a complete loss of accommodation. Hofstetter states that from the rates of decline found there is no statistical likelihood of greater rates of reduction at earlier ages. The rate of reduction in amplitude was around 0.4D per year with one subject reaching zero accommodation aged 45 and the other aged 48.

Hofstetter comments that if the results of the two subjects were plotted together (as they would be in a cross-sectional study) there would be the appearance of a lower rate of decline after 45 than before, since at this age one subject had reached and remains at zero accommodation. He postulates that this summation of individual linear relationships with the inter-subject variability in the age of onset of absolute presbyopia is the explanation for the non-linear relationship between age and amplitude of accommodation found in cross-sectional studies.

Charman (1989) was able to prove Hofstetter's explanation that the non-linear relationship found in cross-sectional studies is an artefact of the averaging process of individual linear relationships, with mathematical calculations using Hofstetter's data.

Ramsdale and Charman (1989) used a laser optometer and the push-up technique to measure accommodative responses to stimuli in the dioptric vergence range 0 to –5.00D. One of the authors (WNC) acted as the subject over a period of 10 years. At the beginning of the study the subject was 41 and the measurements were taken approximately every 6 months. The amplitude of accommodation was taken as the difference between the highest and lowest response levels. The results of both techniques showed that the subject's amplitude of accommodation declined linearly with age at a rate slightly in excess of 0.3D per year (see figure 2.1)

Figure 2.1 Amplitudes of accommodation as a function of age for the (a) right eye and (b) left eye of subject WNC. The filled symbols are objective amplitudes obtained with the laser optometers under binocular conditions of fixation. The open symbols are monocular, subjective amplitudes derived from near-point measurements with the RAF rule. The straight lines are least-squares regression line fits to the data points. (Ramsdale and Charman, 1989)

2.3 FACTORS AFFECTING AGE OF ONSET OF PRESBYOPIA

Significant differences in the age of onset of presbyopia have been found in different populations (Coates, 1955; Babalola and Szajnzicht, 1960; Rambo and Sangal, 1960;

Raphael, 1961; Miranda, 1979; Weale, 1981; 1985; Kragha, 1986; Miranda, 1987; Edwards *et al.*, 1993). The factors that influence the age at which the patient first presents with clinical symptoms of presbyopia include level of education, occupation, arm length, illumination and available eye care. More interesting are the factors that actually affect the rate of decline of accommodation such as general health, gender, solar radiation exposure, race, diet, geographic latitude, altitude and ambient temperature. With the possibility of several factors influencing the rate of decline of accommodation and many studies basing conclusions only on the age of first presentation of presbyopic symptoms the conclusions that can be drawn from some studies are weak. Other studies are further weakened by inconsistencies in their methods of measurement especially given the subjective nature of determining the amplitude of accommodation.

The two environmental factors that have the strongest evidence to support their influence on the rate of decline of accommodation, are ambient temperature and solar exposure (Miranda, 1987).

2.4 ANATOMICAL CHANGES IN PRESBYOPIA

2.4.1 Crystalline lens

Thickness of the crystalline lens

It has been found that the thickness of the crystalline lens increases with age, mainly due to an increase in thickness of the lens cortex (Brown, 1973; Koretz *et al.*, 1989) with the dimensions of the lens nucleus remaining relatively constant.

Radius of curvature of the crystalline lens

Brown (1974) used slit-lamp photography to measure the radii of curvature of the anterior and posterior lens surfaces in 100 emmetropic subjects aged 3 to 82 years. It was found that the radius of curvature of the anterior lens surface reduces with age, with the central chord reducing from a mean value of 15.98mm at the age of 8 to 8.26mm at the age of 82 years. The radius of curvature of the posterior lens surface also reduces but with a lower rate of change than the anterior surface.

Refractive index of the crystalline lens

With the increase in thickness of the crystalline lens and the steepening of the lens curvatures with age, the lens power would be expected to increase (become more myopic) but this does not occur. Hemenger *et al.* (1995) were able to prove the hypothesis of Pierscionek (1990) that changes in the refractive indices within the crystalline lens are able to explain this 'lens paradox'. Hemenger *et al.* found a steeper gradient refractive index for the crystalline lens in the older eye which results in a lower refractive power, counteracting the steepening of the lens curvatures and the increase in lens thickness that increase the lens power. Glasser and Campbell (1999a) used crystalline lenses from a human eye bank and reported that they found no evidence in support of the lens paradox, with the lens focal length being predicted by the lens curvatures independent of the age of the lenses. They also report that they found no age-dependent change in gradient refractive index.

Water content of the crystalline lens

It is often quoted that presbyopia is a consequence of the gradual dehydration or sclerosis of the crystalline lens. Bito and Miranda (1987) suggest that this idea came about from the observations of Norrby (1958 cited by Bito and Miranda, 1987) and Philipson (1969) who found that there was a loss of water with age in the lens of the rat (a non-accommodating species). However the water content of both the nucleus and cortex of the human crystalline lens have been found to remain constant well beyond the onset of presbyopia (Fisher and Pettet, 1973).

Although the water content of the lens does not change with age, Fisher and Pettet (1973) did suggest that the lens becomes more difficult to deform due to an increased adhesion between the lens fibres of the nucleus. Additionally the binding of certain structural proteins to cell membranes has been suggested as producing a more rigid cellular structure (Maraini and Fasella, 1970; Bracchi *et al.*, 1971).

Pau and Kranz (1991) measured the resistance to penetration of different lens layers and found the resistance of the lens nucleus to increase with age.

Lens elasticity

Fisher (1969a) studied how the lens capsule elasticity changes with age and found that the Young's modulus of the lens capsule reduces with age (becoming more flaccid) which results in less force being required to change the capsule shape.

Fisher (1969b) was then able to calculate how the potential accommodative energy changes with age. The findings were based on capsular parameters and the shape of the crystalline lens. Fisher found that accommodative energy reaches a maximum at about 25 years of age, this increase is due to lens flattening and the increase in thickness of the lens capsule. The potential energy then drops as Young's modulus of elasticity decreases and after age 60 the lens capsule thins resulting in around the same energy at 75 years of age as at birth.

Fisher (1971) then studied the change in elasticity of the lens substance by spinning the crystalline lens to achieve centrifugal forces mimicking the zonular tension on the equatorial and polar regions. Fisher found that the elasticity of the lens substance increased with age.

The finding of a decrease in the speed of accommodation with age is supportive of a decrease in lens elasticity (Allen, 1956; Sun *et al.*, 1988; Schaeffel *et al.*, 1993). However Heron *et al.* (1999) comment that some of these studies included stimuli that were beyond or at the extreme limits of the amplitude of accommodation of the older subjects included. In their own study, Heron *et al.* used a change in accommodative stimulus that was much lower (1.05D) and although the results showed a reduction in the speed of accommodation with age, the reduction was not so marked. Heron *et al.* comment that the reduction found was not consistent with the expected reduction in speed of accommodation predicted by the findings of Fisher (1969a; 1969b; 1971), but that it should be noted that the structure of the lens was perhaps more complex than considered in Fisher's work.

Optical changes in the crystalline lens

Glasser and Campbell (1998; 1999a; 1999b) used the lenses of human eyes to study the biometric, physical and optical properties of the crystalline lens. Glasser and Campbell (1998) found that throughout life there is an increase in the focal length of the lens and a loss in the ability to undergo changes in the focal length (accommodate). Beyond the age of 58 years no amount of zonular stretch on the lens will result in a change in focal length.

2.4.2 Ciliary muscle

Contractile ability of the ciliary muscle

Swegmark (1969) used impedance cyclography to show that the contractile ability of the ciliary muscle remained essentially unimpaired up to the age of 60 although the findings from studies of this type have been criticised by Bito and Miranda (1989). Bito and Miranda (1989) comment on the findings of Swegmark pointing out that during impedance cyclography the neuronal activity due to accommodative effort may alter blood flow. Blood flow is known to influence impedance readings and therefore the changes in electrical impedance measured may not be due to ciliary muscle force.

Fisher (Fisher, 1977) found the force of contraction of the ciliary muscle to increase with age with a maximum at age 45. Bito and Miranda (1989) criticise the conclusions drawn by Fisher because the measurements taken were on ciliary muscle *in-vitro* rather than *in-vivo* stating that 'there is no reason to assume that the magnitude of the forces required to alter lenticular shape *in-vitro* can be equated with force development by the ciliary muscle'.

Strenk *et al.* (1999) used magnetic resonance imaging (MRI) of the ciliary muscle and crystalline lens to compare the responses to accommodative stimuli of 0.1D and 8D in 25 subjects aged 22 to 83 years of age. Strenk *et al.* found that maximum ciliary muscle contraction reduces only slightly with age.

Most recently Pardue and Sivak (2000) studied the age related changes in ciliary muscle using donor eyes post-mortem. The results showed that atropine caused a shortening of the total length and posterior length of the ciliary muscle in 6 of the 7 pairs of eyes studied (age range 0 to 78 years). The authors conclude that this is evidence that the ciliary muscle retains its ability to contract throughout its lifespan.

Movement of the ciliary muscle

As Bito and Miranda (1989) and Kaufman (1992) observe though, it is not the force of contraction of the ciliary muscle but the movement of the muscle and change in shape of the ciliary body that provides the geometrical alterations needed for accommodation to occur.

It has been found that the ciliary body movement declines with age (Neider *et al.*, 1990). Tamm and co-workers (Tamm *et al.*, 1991, 1992) propose that the inward movement of the ciliary muscle is restricted by the increased rigidity of the posterior elastic anchor tissues of Bruch's membrane that attach the ciliary muscle posteriorly to the sclera. Histochemical and ultrastructural studies have supported this proposal (Tamm *et al.*, 1991, 1992).

Bito and Miranda describe a study that they and co-workers undertook using rhesus monkeys to measure the time course and extent of ciliary ring movements relative to a fixed point on the sclera (Bito *et al.*, 1987). They found a loss in ciliary body motility in parallel with the age-dependent loss of lenticular deformation and accommodative amplitude.

Strenk *et al.* (1999) found that the ciliary muscle ring diameter decreased with age. Strenk *et al.* discuss whether it could be that the increase in lens thickness with age results in the decrease in ciliary ring diameter as the muscle may be pulled inward by a decreasing lens diameter. In contrast an inverse process is suggested whereby the lens thickening may be a result of the decrease in ciliary ring diameter as the tension on the lens is reduced.

2.4.3 Zonules

The equatorial zonular fibres disappear with age. Farnsworth and Shyne (1979) analysed human eyes ranging in age from 17 to 90 years and concluded that the equatorial zonular insertions shift more anteriorly with age. Assuming that zonular attachments are fixed for life, the change in position of the lens insertions must be due to shifts in the lens capsule due to lens growth. This change in position of the zonules may alter the accommodative change resulting from ciliary muscle contraction due to the change it will induce in the geometry of the suspensory apparatus (Bito and Miranda, 1987).

2.5 THEORIES OF PRESBYOPIA

Based on the evidence of the above anatomical changes and further studies, there are generally considered to be two main theories of presbyopia, the Hess-Gullstrand and Duane-Fincham theories. Atchison (1995) stresses however, that there are important differences between the theories proposed by Duane and Fincham and that these two theories should be considered separately.

2.5.1 Hess-Gullstrand theory

Hess (1901 cited by Strenk *et al.*, 1999) and Gullstrand (1908 cited by Strenk *et al.*, 1999) proposed a purely lenticular theory of presbyopia in which the lens hardens or becomes more rigid with age making it increasingly resistant to the forces imposed upon it. Whilst accommodation is still within the stimulus range to which the lens can respond, the manifest region, the muscle's ability to change the lens shape remains constant. Above this region is the latent region where the ciliary muscle still has the ability to contract but is not able to deform the lens due to its increased stiffness. Findings in support of this theory are those such as that of Fisher (1969a; 1969b; 1971; 1973) who found that an older lens is harder to deform that its younger counterpart. The studies of Glasser and Campbell (1999a; 1999b; 1998) also showed that as the lens ages it is less able to change its focal length although their studies were not without criticism (Weale, 1999).

Figure 2.2 Diagram to show the relationship between accommodation and the stimulus to accommodation as predicted by the Hess-Gullstrand theory. The stimulus to accommodation represents the ciliary muscle effort. Reproduced from Pierscionek (1993).

Pierscionek (1993) describes how if presbyopia were due to the sclerosing of lens fibres resulting in a harder less deformable lens, it would become more resistant to moulding by the ciliary muscle. Thus a constant amount of ciliary muscle force would be required for a fixed accommodative change and a latent amount of contraction would remain after maximum accommodation is achieved. The Hess-Gullstrand theory is unique among the proposed theories of presbyopia in that it is the only theory that predicts there being an excess amount of ciliary contraction beyond that exerted at maximal accommodation thus the evidence in support of this excess muscle force opposes all other theories.

The impedance cyclography study of Saladin and Stark (1975) found ciliary muscle activity without any change in accommodative amplitude indicating that there is muscle contraction ability in reserve although there has been criticism of this and other impedance cyclography studies by Bito and Miranda (1989).

Alpern and David (1958) observed pupil constriction beyond the amplitude of accommodation which would imply concomitant ciliary muscle contraction also occurred at this stage.

The MRI study of Strenk *et al* (1999) found that the maximum ciliary muscle contractile ability reduces only slightly with age and the ciliary muscle remains active in all subjects well beyond the time when lens response is no longer possible.

Apart from the Hess-Gullstrand theory all the other theories of presbyopia, outlined below, predict that the amount of ciliary muscle force needed for each successive dioptre of accommodation increases with age and that maximum accommodation requires maximum ciliary muscle contraction.

It is this similarity in the theories that has resulted in the theories of Duane and Fincham often being combined together as the Duane-Fincham theory as opposed to the Hess-Gullstrand theory. However it is not just the theories of Duane and Fincham that predict this need for an increase in ciliary muscle effort and the hypotheses as to why this increase occurs vary significantly. Here, each theory will be considered separately although much of the evidence is either in support of the Hess-Gullstrand theory or the theories predicting an increase in ciliary muscle effort with age but cannot be used to differentiate any further between the theories

Figure 2.3 Diagram to show the relationship between accommodation and the stimulus to accommodation as predicted by theories such as the Duane and Fincham theories. The stimulus to accommodation represents the ciliary muscle effort. Reproduced from Pierscionek (1993).

2.5.2 Duane's ciliary muscle theory

Duane (1922; 1925) found that the instillation of diluted atropine drops caused an earlier reduction in the amplitude of accommodation in older subjects than in younger subjects which would not be expected if there was muscle contractile ability in reserve (oppose the Hess-Gullstrand theory). Duane explained this as being due to the weakening of the ciliary muscle with age. There is little support for ciliary muscle weakening being the sole cause for presbyopia and many studies have found ciliary muscle contractile ability to increase (Swegmark, 1969; Fisher, 1977; Strenk *et al.*, 1999) although all the studies have been criticised (Bito and Miranda, 1989). Any evidence that shows that there is increased ciliary muscle effort required per unit of accommodation with age, such as the findings regarding AC/A ratios of Bruce *et al.* (1995) outlined below, is supportive of Duane's theory but is not unique to this theory.

2.5.3 Fincham's lenticular theory

Fincham (1937) proposed that it was due to changes in the lens and capsule that the amount of ciliary muscle contraction required for accommodation increased throughout life. Fincham (1937) describes how if the lens substance becomes more rigid with age the force required by the capsule to change the lens shape will be greater as the eye ages. It is the relaxation of the zonular tension caused by the contraction of the ciliary muscle that allows the capsule to apply an increased force on the lens substance. Hence more ciliary muscle contraction will be required with age to allow a unit change in accommodation.

Fincham (1955) and Eskridge (1972) used physostigmine (anticholinesterase) to stimulate ciliary muscle activity and found an increase in the amplitude of accommodation and conversely found a decrease in accommodation with the antimuscarinic drug homatropine. These changes in amplitude would not be predicted by the Hess-Gullstrand theory since at maximum accommodation there would be muscle contraction in reserve, buffering the changes induced by the drugs. The findings are in agreement with all the other theories of presbyopia, including the Fincham theory, where maximum muscle contraction occurs for maximum accommodation.

2.5.4 Extralenticular theory

Bito and Miranda (1989) propose another theory of presbyopia. They propose that the movement of the ciliary body during accommodation may be reduced due to the posterior elastic tissue (ciliary body and choroid) becoming more *flaccid*. This would result in the uncontracted muscle being shorter due to less tension from the posterior attachments and would result in less anterior force and inward movement of the ciliary muscle on contraction. This hypothesis implies that the crystalline lens in the presbyopic eye is always in the accommodated (more spherical) form and that presbyopia represents the loss of the ability to *relax* accommodation with emmetropia maintained by a change in the lenticular refractive index.

Bito and Miranda (1989) outline the lenticular changes that occur with age and conclude that as the growth of the lens alters its geometric relationship to the ciliary body it will modify the effect of the zonules and their direction of action on the lens. Since the zonules only exert a force on the lens in its disaccommodated form they again state that presbyopia must relate to a dysfunction in the disaccommodative processes. The lens is known to take on a more accommodated shape as it ages and Bito *et al.* (1987) also found that the speed of disaccommodation declines more rapidly than does the speed of accommodation during the prepresbyopic years, further support for the disaccommodation theory.

2.5.5 Geometric theory

Koretz and Handelman (1986; 1988) and Bito and Miranda (1987) describe how the loss in accommodation with age could be explained by the changes in the shape and size of the crystalline lens. As the lens thickens and the surfaces steepen in curvature with age, the zonules become more anteriorly displaced (Farnsworth and Shyne, 1979) leading to a change in the direction of action of the force applied by the zonules on the lens. It is postulated that this change in lens and zonule geometry results in the need for greater ciliary muscle contraction to achieve the same relaxation of the zonular tension on the lens.

2.5.6 Schachar's theory

Schachar and co-workers (Schachar, 1992; 1996; 1999; Schachar *et al.*, 1993a; 1993b; 1994; 1995; Schachar and Anderson, 1995) have proposed an alternative mechanism of accommodation. During ciliary muscle contraction there is *increased* tension in the equatorial lens zonules pulling the lens equator nearer to the sclera with a relaxation of the anterior and posterior lens zonules (that act as stabilisers in the unaccommodated state). These forces result in the lens becoming a spindle shape, thinnest at the equator and more steeply curved centrally, increasing the lens power.

Schachar (1992) proposes that presbyopia occurs as the result of the normal growth of the lens. He proposes that with an increase in the equatorial lens diameter with age and no change in scleral shell dimensions, the distance between the ciliary muscle and the lens equator will decrease, reducing the tension that the zonules can exert on the lens as the ciliary muscle contracts. According to Schachar's accommodation hypothesis this will result in the decrease in amplitude of accommodation that leads to presbyopia.

Schachar was able to support this explanation of presbyopia by increasing the amplitude of accommodation of six presbyopic subjects by suturing a band of polymethylmethacrylate to the sclera of one of their eyes (the second eye acted as a control). The band stretched the sclera by 0.5 to 1.5mm in diameter to increase the distance between the ciliary muscle and the lens equator increasing the effective working distance of the ciliary muscle. All six eyes had a marked increase in amplitude of accommodation (mean of 6.6D).

Glasser and Kaufmann (1999) studied the accommodative mechanism of monkeys using both electrical and pharmacological stimulation of accommodation. They were able to observe the movements of the ciliary body, ciliary muscle and lens equator during accommodation with videographic and ultrasound imaging techniques. It was found that the ciliary body and lens equator always moved away from the sclera during accommodation. These findings are consistent with the classic mechanism of accommodation proposed by Helmholtz but contrary to the proposals of Schachar.

Mathews (1999) studied the effect of scleral expansion surgery on accommodation by analysing the accommodative responses of presbyopes pre- and post-operatively. He found no evidence of any increase in accommodative response after surgery and suggested that the increase found by Schachar (1992) may be due to the use of the same test card during the push-up test of accommodation pre- and post-operatively, resulting in improved blur recognition and memorisation. Mathews also comments that there was a significant increase in the encouragement given to Schachar's patients when measuring the amplitude of accommodation post-operatively.

2.6 THE AC/A RATIO AND THE THEORIES OF PRESBYOPIA

The AC/A ratio demonstrates the relationship between the accommodative stimulus or response and the convergence response. Due to the synkinetic link in innervation between accommodation and vergence, if more effort is required to accommodate this increase in innervation to accommodation will also be reflected in an increase in convergence and hence a change in the AC/A ratio. Thus looking at the effect of age on this ratio is useful when investigating whether ciliary muscle effort to accommodate increases with age, a distinguishing factor between the main theories of presbyopia.

If no increase in ciliary muscle effort was required to accommodate per unit of accommodation with age then the stimulus AC/A ratio would be expected to remain unchanged or slightly decline as the accommodative response to a particular stimulus does slightly decline with age. The response AC/A ratio would be expected to remain constant with age as the accommodative convergence and accommodative response would decrease proportionately. This is the relationship predicted by the Hess-Gullstrand theory whilst the accommodative stimulus remains within the accommodative amplitude range. Beyond the amplitude where there is predicted to be no accommodative response changes the response

AC/A ratio should be very large as there would be negligible accommodative response changes but the excess ciliary muscle effort would still be linked with vergence changes (Ciuffreda *et al.*, 1997; Strenk *et al.*, 1999).

All the other theories of presbyopia predict an alternative relationship between the AC/A ratios and age. If the effort to produce a unit change in accommodation increases with age this will result in an increase in the stimulus AC/A ratio as the increased effort to focus on the stimulus will cause increased convergence. The response AC/A ratio would be expected to markedly increase because even as the accommodative response to a particular stimulus declines the accommodative convergence would increase.

2.6.1 Experimental work

Several studies have been completed that show how the AC/A ratio varies with age. Figures 2.4 and 2.5 show the relationships between the stimulus and response AC/A ratios and age demonstrated in the studies outlined below.

Ciuffreda *et al.* (1997) used a subjective haploscope-optometer in order to measure the AC/A ratio of 42 subjects aged 22-65. When analysing the results the authors split the subjects into two age groups, under 45 years of age and 45 years and older. No significant correlation was found between stimulus AC/A ratio and age in the under 45 age group although a small but statistically insignificant negative correlation with age was found in the older group with the stimulus AC/A ratio decreasing by 0.04D/$^{\Delta}$ per year. For the younger group the response AC/A ratio was found to increase by 0.08D/$^{\Delta}$ per year but they found that if the older pre-presbyopes and younger presbyopes were not considered (aged 35-44) then no age-related trend was established. In the older subject group (aged 45 and over) a negative mean response AC/A ratio was found, the negative result was attributed to physiological and instrumentation noise. The authors conclude that their results support the Hess-Gullstrand theory.

Tait (1951) used his measurements of the distance and near heterophoria of 3900 subjects aged 10 to 70 years to look at the effect of age on accommodative convergence. Tait found a decrease in the stimulus AC/A ratio with age that supports the Hess-Gullstrand theory. The findings of Alpern and Larson (1960) who also found a decreasing AC/A ratio and the findings of Morgan and Peters (1951) where the stimulus AC/A ratio remained relatively constant also support this theory.

Bruce *et al.* (1995) used a Canon R-1 open-view Autorefractor and an IRIS infrared eye movement recorder to objectively measure the response AC/A and CA/C ratios of 23 subjects aged 17 to 42 years. The AC/A ratio was found to increase with age from approximately $3.5^{\Delta}/D$ at age 20 to $6.0^{\Delta}/D$ at age 40 with an average increase of $0.126^{\Delta}/D$ (0.02MA/D) per year. The CA/C ratio was found to decrease from $0.10D/^{\Delta}$ at age 20 to $0.03D/^{\Delta}$ at age 40, an average decrease of $0.003D/^{\Delta}$ (0.018D/MA) per year. Bruce *et al.* state initially that their findings are evidence against the Hess-Gullstrand theory of presbyopia, predicting instead the changes that would be expected by all the other theories of presbyopia such as the Duane-Fincham theory. However, Bruce *et al.* then go on to state that until more is known about other factors that could influence the accommodative-vergence interaction such as the adaptability of tonic vergence and accommodation the Hess-Gullstrand theory should not be rejected.

Fry (1959) collated the values of his own stimulus AC/A ratio found in a number of experiments over a twenty-year period and found there was a slight increase in the AC/A ratio before the age of 40 and then a rapid increase after this age. Eskridge (1983) used a haploscope-optometer to measure his own stimulus AC/A ratio over a twenty-year period. Eskridge also found a fairly stable or slightly increasing AC/A ratio up to about 40 years of age followed by a significant increase in the ratio after the age of 45 years.

Breinin and Chin (1973) undertook a cross-sectional study and found a constant or slightly declining stimulus AC/A ratio with age. The response AC/A ratio was found to be constant until the age of around 36 to 40 years when there was a significant increase in the response AC/A ratio that continued through these pre-presbyopic and then presbyopic years. Breinin and Chin also used data from a longitudinal study to show a definite increase in response AC/A ratio during the 4th decade of life but this time showing a slight increase in stimulus AC/A ratio. The measurements were taken within the accommodative amplitude range of each subject in all these experiments and therefore represent evidence opposing the Hess-Gullstrand theory of presbyopia with the increase in response AC/A ratio found supporting the Duane and Fincham theories and the other theories predicting increased muscle effort with age.

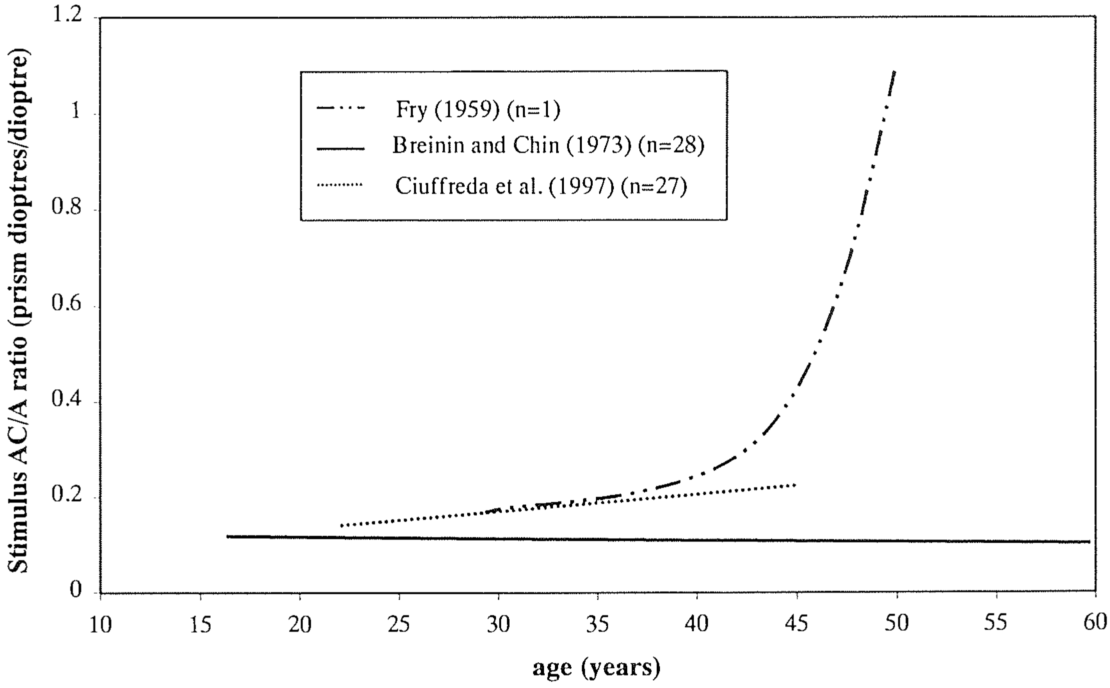

Figure 2.4 Graph of stimulus AC/A ratio against age from earlier investigations

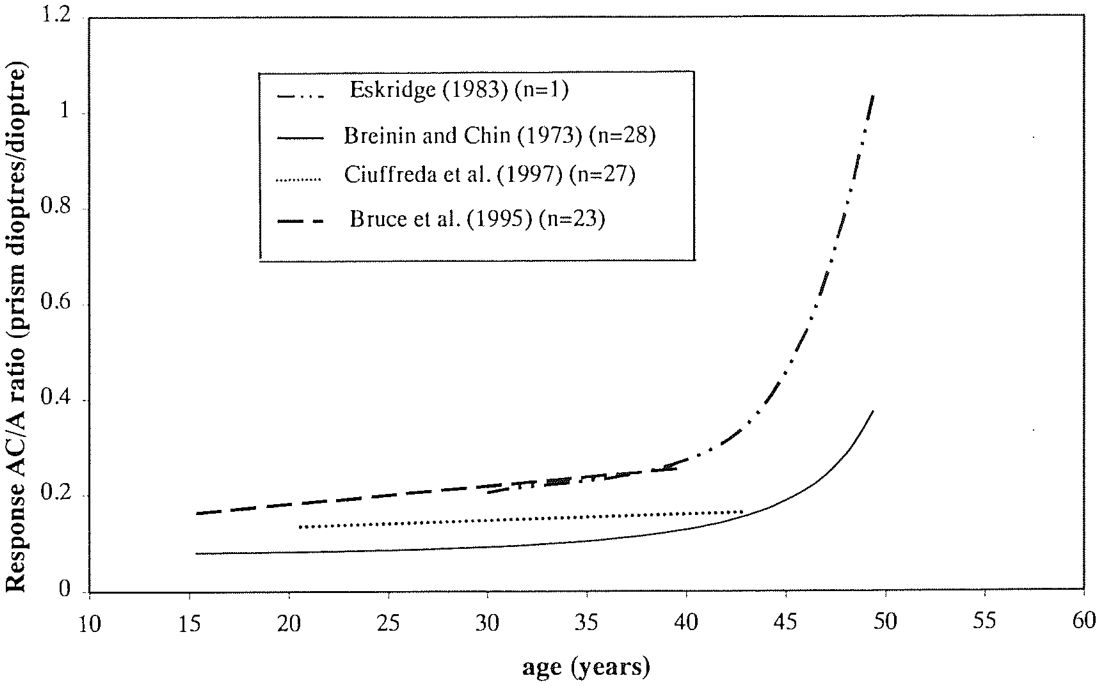

Figure 2.5 Graph of response AC/A ratio against age from earlier investigations.

Morgan and Peters (1951) assessed the stimulus AC/A ratio of 400 presbyopic subjects using the gradient technique and found a mean ratio of $3.8 \pm 2.6^{\Delta}/D$ (0.63 ± 0.43MA/D). Presbyopic subjects were defined as those who were aged over 45 years with an amplitude of accommodation of less than 4D. Morgan and Peters conclude that this mean AC/A ratio is not significantly different from that expected in a group of pre-presbyopes where the mean AC/A ratio is $3.1^{\Delta}/D$ (0.52MA/D) demonstrating that the AC/A ratio does not change significantly with age (this study is not represented in the figures).

It can therefore be seen that despite the various studies already undertaken to analyse how the AC/A ratio varies with age, the results are not conclusive. One of the main weaknesses of the studies outlined above is their cross-sectional nature. The studies of Fry (1959) and Eskridge (1983) were longitudinal but on single subjects only (the respective authors). Although an element of the Breinin and Chin study was longitudinal only a few subjects were aged between 40 and 45 years, the age where the change in AC/A ratio would be predicted to be at its greatest but still of an age where a sufficient amplitude of accommodation remains to allow an accurate determination of the ratio (Ciuffreda *et al.*, 1997).

2.7 OCULOMOTOR ADAPTATION IN INCIPIENT PRESBYOPIA

According to the Hess-Gullstrand theory of presbyopia (section 2.5.1) the effort to focus on a near object remains the same throughout life, despite the decline in accommodation that occurs. There exists however, a threshold level of accommodation beyond which no change in accommodation response occurs, despite an increase in accommodative stimulus. A gradual reduction in this threshold (amplitude of accommodation) occurs as the subject ages. If this theory of presbyopia holds true, the decline in accommodation with age would have no significant effect on the overall vergence response when viewing a near target since the same accommodative effort will be required to focus and the same convergence response will result. If a near target is brought to a point closer than the amplitude of accommodation there will be no further change in accommodation possible. At this closer distance, in order to prevent asthenopic symptoms due to a strain on fusional vergence (together with blur symptoms), there must be an increase in one of the components of vergence.

If the Hess-Gullstrand theory of presbyopia is incorrect, alternative theories of presbyopia predict that increasing innervation is required to produce a unit change in accommodation with age (section 2.5.1). According to these theories, maximum ciliary muscle effort is required to achieve a maximum accommodative response at all ages.

Thus if an older subject attempts to focus on a near target using the same effort to accommodate as when younger, there will be no change in the convergence response since the same synkinetic innervation to convergence will exist. There will however be a decline in the accommodative response and the target will appear to be blurred. Alternatively, if the stimulus is within the accommodative amplitude and additional effort is made to reduce the blurring of the target, there will be an increased convergence response due to the increase in synkinetic accommodative innervation. In this instance it is an increase in accommodative vergence that needs to be compensated for in order to maintain the overall vergence response. It could be that the subject does not use the additional accommodation to clear the target and instead only accommodates to the stage where there is no change in the overall vergence response. It may be that one of the other components of vergence declines with age allowing the additional accommodative convergence to be managed.

Thus, depending on which mechanism of presbyopia operates, there are two possible predicaments that may result from the decline in the amplitude of accommodation with age. Adopting the Hess-Gullstrand theory of presbyopia, the oculomotor challenge is a lack of convergence to a stimulus that is presented closer than the amplitude of accommodation. Alternative theories of presbyopia would instead result in increasing convergence as the amplitude declines.

2.7.1 Proximal vergence

A number of studies have investigated the relative contribution of proximal vergence to the overall vergence response and how this varies with age.

Schapero and Nadell reported a decrease in proximal vergence with age (Schapero and Nadell, 1957). The accommodation and vergence responses of 16 subjects aged between 30 and 74 years were assessed using a haploscope-optometer. The results showed that the magnitude of proximal vergence was greatest in the younger subjects and least in the absolute presbyopes. Although a relatively small number of subjects were used in this study

Schapero and Nadell conclude that proximal vergence appeared to be inversely related to age.

In contrast the study of Nuzzi *et al.* (Nuzzi *et al.*, 1982 cited by Hokoda *et al.*, 1991) found that proximal vergence played an increasing role in the overall vergence response with age. Nuzzi *et al.* calculated the stimulus AC/A ratios found using the gradient method at distances of 5m and at 0.33m. Two subject groups were assessed, the first had 35 subjects with a mean age of 59 years and the second had 25 subjects with a mean age of 27 years. The results showed that when using a distance target the mean AC/A ratio was markedly higher in the pre-presbyopic subjects but when using the near target the mean values were similar. The authors suggest that at near an increased proximal vergence response in the presbyopes compensated for the decline in accommodative convergence indicating that proximal vergence plays a more substantial role in presbyopic subjects. Hokoda *et al.* (1991) criticise this conclusion because the amplitude of accommodation of the presbyopic subject group will have been too low to allow accommodation to the near target, influencing the results found.

Wick (1985) assessed the proximal vergence response of 20 absolute presbyopes (mean age 61.6 years, range 50 to 76 years) and 20 pre-presbyopes (mean age 25.2, range 14-36 years). Wick used the formula given in section 1.5.2.a using values of both dissociated and associated heterophoria to give a measure of proximal vergence under both open- and closed-loop conditions respectively. Wick found that there was not a statistically significant difference between the mean value of proximal vergence found in each subject group under either condition. This result is similar to the findings of Sheedy and Saladin (1975) who used the same equation with the values of dissociated heterophoria in the distance and at 40 cm (with +2.50D lens) of 13 pre-presbyopes and 10 presbyopes. No significant difference in mean proximal vergence was found between each group, with values of 4.9^{Δ} (0.82MA) and 5.9^{Δ} (0.98MA) respectively.

A third study has also found that there is no variation in proximal vergence with age. Hokoda *et al.* (1991) measured the PC/T ratio (proximal convergence to test distance ratio; see section 1.5.2.a) of 106 subjects aged 6 to 47 years using measures of the AC/A ratio found with the gradient and heterophoria techniques. The results showed there was no significant correlation between the PC/T ratio and age.

Thus although not conclusive, the majority of experimental evidence indicates that there is no significant variation in proximal vergence with age.

2.7.2 Tonic vergence

Two studies have investigated the variation in tonic vergence with age. Ciuffreda *et al.* (1993) measured the tonic vergence position of 50 subjects aged between 20 and 68 years of age using a dual haploscope-optometer. After a period of 5 minutes in darkness, to allow the dissipation of any vergence bias, the subject observed two stigma (non-accommodative targets); the stigma were vertically separated by 5° to prevent fusion. The subject was instructed to align the stigma by rotating the haploscope arm and this alignment was repeated 6 times to calculate an average tonic vergence position. The subjects were split into 5 subject groups each representing a decade of age (20-29, 30-39 etc.) with 10 subjects in each group. When the mean tonic vergence positions for each age group were compared there were found to be no significant differences between the age groups. The results were then pooled into two groups representing clinical pre-presbyopes (20-39 years) and presbyopes (40-70 years). A small but significant difference was found between the mean of these two subject groups with means of 1.95° and 3.23° respectively. Ciuffeda *et al.* conclude that although the results indicate the absence of any progressive age-related change in tonic vergence position, there is a small convergent increase in tonic vergence after 40 years of age. However, this small increase in convergence, around 1.3° (approximately 2.2^{Δ} or 0.37MA), will have relatively little impact on the overall closed-loop vergence response.

Rosenfield *et al.* (1995b) assessed the tonic vergence of 41 subjects aged 20 to 70 years of age. The measurements were taken in darkness using a haploscope optometer. It was found that tonic vergence declined at a rate of 0.11deg/year (approximately 0.19^{Δ} or 0.03MA per year).

2.7.3 Fusional vergence

There are no studies that have assessed the change in fusional vergence with age, this is because it is a difficult component of vergence to measure directly. Most studies that have commented on the magnitude of fusional vergence rely on subtracting the measured values of the other three components to vergence (accommodative, proximal and tonic) from the overall vergence response to leave the fusional response.

Ciuffreda *et al.* (1997), who investigated the effect of age on accommodative convergence, suggested that fusional vergence must be the component of vergence that naturally and progressively increases with age to make up for a decline in the accommodative convergence component, since proximal and tonic vergence were known to remain stable. Similarly Hokoda *et al.* (1991) concluded that if proximal vergence remains fairly stable with age it must be that fusional vergence increases as accommodative convergence declines.

Measures of the positive and negative relative vergences (fusional reserves) of pre-presbyopes and presbyopes have been compared, that is the maximum prism through which single binocular vision can be maintained (Sheedy and Saladin, 1975). It was found that the pre-presbyopes were able to overcome larger prism deviations and although this may suggest that the fusional vergence of older subjects is reduced, it must be stressed that this is only a measure of the *potential* for fusion rather than the actual fusional vergence measured under closed-loop conditions.

Thus it can be seen that it is difficult to find direct evidence of a change in fusional vergence with age, conclusions instead depend on the variation in contribution to the overall vergence response of one of the other components and then by elimination, a variation in fusional vergence may be suggested.

2.7.4 Open- or closed loop vergence responses

A difficulty with using the four components of vergence in an additive way such as this is that it must be remembered that most of these measures of individual components of vergence are made under open-loop conditions. For example to measure accommodative convergence it is necessary to remove the cues to proximal and fusional vergence.

It may be that there is a difference between the magnitude and relative importance of each component when considered in the closed-loop conditions of natural viewing compared to the open-loop conditions under which the measurements were taken. Hokoda *et al.* (1991)

state such a caution in their discussion, suggesting that their measure of the PC/T ratio in presbyopes may reflect the *potential* proximal vergence and that in presbyopia under closed-loop conditions although the magnitude of this potential response may stay the same, the manifest proximal vergence may actually increase.

It is difficult to avoid the assumptions that the vergence responses are the same under open- and closed-loop conditions when undertaking quantitative analysis, since open-loop conditions are required to obtain such measures.

2.8 SUMMARY

During incipient presbyopia, the period where the decline in the amplitude of accommodation is at its most significant, changes in the oculomotor system must occur to maintain the overall vergence response of the eyes. The need to maintain clear single binocular vision during and beyond this period requires re-calibration of the correspondence between accommodation and vergence. The aim of this study is to identify the oculomotor changes that occur during this incipient phase of presbyopia.

Most critical to this analysis is the identification of any variation in the AC/A and CA/C ratios, since these measurements are a direct assessment of the accommodation-vergence interaction. These findings will help to establish the most valid theories of presbyopia and allow the determination of the nature of the re-calibration that must occur.

In order to analyse the complete oculomotor system measures of proximal vergence, tonic vergence and tonic accommodation are required along with an assessment of accommodative and vergence adaptation due to their significance when performing a sustained near-vision task.

A two-year longitudinal study has been undertaken to investigate various aspects of accommodation, vergence and their interaction. The following chapters will deal with different components of oculomotor function that have been measured over the experimental period.

Chapter 3 describes the instrumentation that has been used during this study with details of equipment and the reasons for it selection.

Chapter 4 gives details of the subjects that were used throughout the two-year study including information on their age and amplitude of accommodation. This chapter also investigates the long-term stability of tonic accommodation, which represents the intermediate resting position of the accommodation mechanism. An assessment is also made of accommodative adaptation, with the analysis of the time taken for the accommodative response to return to the baseline level following a near vision task. These parameters were analysed at regular intervals over the two-year study period.

Chapter 5 investigates how the interactions between the accommodation and vergence systems change with age. The subject groups are followed over the two-year period with measurements of the CA/C, stimulus AC/A and response AC/A ratios. In addition to providing evidence to explain how the relative contributions of the cross-link changes with time this data also allows conclusions to be drawn as to the validity of the theories of presbyopia outlined in section 2.5.

Chapter 6 describes the study of tonic vergence and proximal vergence over the two-year period in order to investigate whether there is a change in these components of the overall vergence response.

Chapter 7 is an investigation of the age-related changes in vergence adaptation. Changes in this post-task shift in vergence position may indicate a means by which the incipient presbyope is able to cope with a change in the accommodation and vergence relationship.

Chapter 8 utilises the results that have been found in the previous chapters to allow the manipulation of accommodation and vergence models in an attempt to mimic the changes in oculomotor function that occur during incipient presbyopia. The models have also allowed an assessment to be made of the impact that changes in the tonic accommodation or tonic vergence response of a subject would have on the overall vergence response as the amplitude of accommodation declines.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter gives details of the reasons for the choice of methodology used in the experimental chapters. Details are also given of the specifications of some of the basic apparatus and instrumentation.

3.2 MEASUREMENT OF ACCOMMODATION

An assessment of accommodation is an essential part of many of the experimental procedures undertaken in this study. The measurement of accommodation had to be objective, relatively quick and unobtrusive so as to prevent proximal cues to accommodation and facilitate the use of real-space stimuli.

3.2.1 Canon Autoref R-1 optometer

The Canon Autoref R-1 is an infra-red autorefractor that was first available in 1981 but is no longer manufactured. The use of infra-red light when measuring refraction has significant benefits. Firstly, it prevents the subject focusing on a visible target, which may lead to an increased accommodative response. There are dim red alignment lights that are visible to the subject, however these are displaced to either side of the visual axis and are very close to the subject and therefore should not influence the accommodative response. Secondly, the use of infra-red light allows the measurement of the accommodative response in conditions of complete darkness (tonic accommodation). This autorefractor also has the important benefit of an open field of view (18° by 50°), this allows the autorefractor to be used to measure the accommodative response to stimuli in real-space rather than internal to the instrument. This open-view also helps to minimise the proximal and cognitive stimuli to accommodation that may result in instrument myopia (Hennessy, 1975). The Canon Autoref R-1 also has an internal IR video camera supplying a magnified image (8.2x) to a TV screen facilitating the alignment of the instrument and allowing an assessment of subject fixation and pupil size if required.

The Canon Autoref R-1 has a measurement range of +15 to –15D sphere and +7 to –7D cylinder. Measurements are given in 0.12D increments with cylinder axes given to the nearest 1°. Each measurement of accommodation takes 0.2 seconds to complete and a measurement cycle can be completed approximately every 1 second. For all the experiments undertaken in this study individual static measurements of the accommodative response were sufficient but the Canon can be modified to allow the continuous measurement of the temporal accommodative response (Pugh and Winn, 1988; 1989).

The chromatic aberration of the eye results in the measurement of refraction given by infra-red optometers being more hypermetropic than found with optometers using visible light. To compensate for this, the manufacturers of infra-red optometers calibrate their instruments with reference to subjective measurements of refraction.

3.2.1.a Mode of operation

The Canon Autoref R-1 is aligned with the centre of the pupil with the help of an alignment ring and the corneal reflections of two light sources, the joystick button is then depressed. The Canon Autoref R-1 works on the grating focus principle (Henson, 1996). An infra-red beam is projected onto the retina through a mask, creating a grating image. The reflected image from the retina is then directed via a focusing lens through an identical mask onto a photodetector. The position of the focusing lens dictates the illumination incident on the photodetector and thus its voltage output. The maximum voltage output occurs when the lens is at the position corresponding to the refractive error of the eye (see figure 3.1). The focusing lens traverses the optical axis of the system at a known velocity; one measurement sweep is completed in 200ms. The refractive error is thus calculated from the time taken for the voltage output to reach its maximum.

Figure 3.1 Generation of the peak waveform during a single static autorefractor reading. Movement of the focusing lens produces a change in the voltage output from the photodetectors. (Reproduced from Davis *et al.*, 1993).

The refractive error is measured along three meridians simultaneously with infra-red beams directed through masks orientated at 30°, 150° and 270°. These measurements are then combined and the refraction is expressed in sphero-cylindrical form on the monitor screen.

If, during the 200ms that the lens is transversing the system, there is a movement of the eye, a blink or the autorefractor is incorrectly aligned, the peak of the voltage output may not be detected and an error reading will result.

3.2.1.b Pupil size

An error reading may also occur if the subject's pupil is too small, since the peak amplitude of the waveform will be reduced as less infra-red light will be reflected. Although the assessment of refraction is not based on the magnitude of the peak, it may become indistinguishable if the peak is flattened. The manufacturers of the instrument suggest a minimum pupil size of 2.9mm, which Winn *et al.* (1989) found to be the exit rather than the entrance pupil. Winn *et al.* showed that with pupils greater than 4mm the peak of the waveform could be easily distinguished and that above this pupil size there was no increase in sensitivity. Below 4mm it was found that there was a reduction in peak amplitude which made the detection of the peak position more difficult, initially evident as an increase in the cylindrical component of the refraction and subsequently as an error reading.

3.2.1.c Accuracy and repeatability

The accuracy and repeatability of the Canon Autoref R-1 was investigated by McBrien and Millodot (1985). Each of the 93 subjects underwent a routine subjective refraction of both eyes, followed by 6 measurements of refraction with the Canon Autoref R-1 while viewing a distance target. It was found that there was a high degree of precision between the successive measurements of refraction particularly in the myopic and emmetropic subjects with values of around 0.1D for the sphere and cylinder components and 6° for the axis precision. The hypermetropic subjects showed slightly more variability between measurements. The refractions of 50 eyes were measured again on a separate occasion and it was found that there was a high degree of repeatability between measurements. For the sphere component of refraction 96% of the readings showed a difference of ≤0.25D and for the spherical equivalent 94% had a difference of ≤0.25D.

When compared to the results found by subjective refraction, for the emmetropic and myopic subjects the Canon Autoref R-1 showed a mean difference in sphere component of 0.25D and a mean difference of 0.375D in cylinder power (0.30D difference in spherical equivalent). With the hypermetropic subjects the mean differences in the components of refraction were larger, which was suggested as being due to difficulties in controlling accommodation during auto-refraction. There is a tendency for the Canon Autoref R-1 to produce readings that are more negative in comparison to the subjective refraction. McBrien and Millodot comment that the endpoint of the subjective refraction is the maximum plus for best vision but if equality on the duochrome was the endpoint, an extra -0.25D would be found which would result in no significant difference between the subjective and autorefractor findings.

3.2.1.d Data collation

An interface unit (designed and distributed by Steve Spadafore, Franklin and Marshall College, Lancaster, PA 17604) that connected to the printer port of the auto-refractor allowed each measurement of accommodation to be relayed to a Macintosh Classic computer. The results were then saved in a format that allowed their manipulation within Microsoft Excel spreadsheets.

The Canon Autoref R-1 has been widely used as a research tool due to its accuracy, repeatability and ease of use and was without doubt the favoured method for measuring accommodation responses throughout this study.

3.3 MEASUREMENT OF VERGENCE

Ideally objective methods of assessing vergence would be used throughout this study however the use of eye trackers and eye movement monitors can be limited owing to the relatively poor resolution of the equipment when considering small changes in eye position. Instead vergence has been assessed using subjective techniques that have been widely used in previous research.

3.3.1 "Flashed" Maddox rod technique

A method of assessing tonic vergence and vergence during prism adaptation was required and this was achieved using the flashed Maddox Rod technique (Henson and North, 1980).

This technique has been described in section 1.10.4. The equipment is controlled by an Apple IIe computer linked to a CIL interface unit and is shown schematically in figure 3.2. The subject has their chin on the chin rest and head against the headrest and observes the test chart at 5m maintaining a clear focus on the letters. To measure the heterophoria the right eye is occluded by a *Blitz* electronic shutter for 15 seconds, after which the shutter is opened for 125ms to expose the Maddox rod placed behind the shutter, simultaneously the spotlight in the centre of the chart is illuminated and the chart switched off. The subject is asked to report to the nearest 0.25^{Δ} the position of the red Maddox Streak on the tangent scale that runs horizontally across the chart. The tangent scale was calibrated so that the distance between each number represented 1^{Δ} at 5m and thus the overall scale measured from 8^{Δ} esophoria to 8^{Δ} exophoria. There is then 15 seconds of binocular viewing (the examiner having removed the Maddox rod) followed by another 15 seconds of right eye occlusion prior to the next measurement.

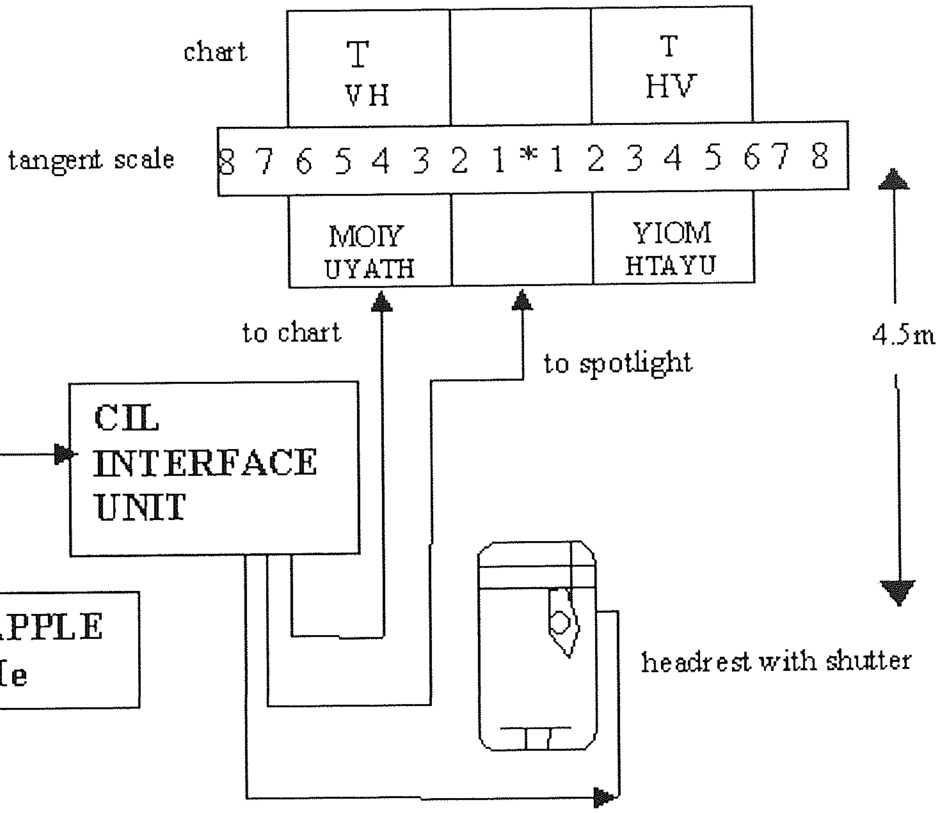

Figure 3.2 A schematic diagram showing the experimental set-up when measuring the prism adaptation of a subject

Prism adaptation

When assessing prism adaptation, baseline heterophoria values are taken first and then the adaptation to 6^{Δ} base-in or base-out prism is assessed over a period of 225 seconds of binocular viewing (15 readings). The recovery, after the removal of the prism, is then assessed over a further period of 135 seconds (10 readings).

Tonic vergence

To assess tonic vergence it was necessary to modify the programming of the Apple IIe (previously programmed by D.L. Sculfor, a final year elective student, Aston University, 1991) so that the time at which the “flash” occurred could be varied. It was also necessary to extinguish the chart light to allow conditions of complete darkness for a time before the assessment of vergence was made. Further details of the procedure used when measuring tonic vergence are given in section 6.2.

3.3.2 Haploscope

To assess the eye position during the measurement of the AC/A ratio a haploscope device was developed. Haploscopes have been used by other researchers when assessing vergence response (Morgan, 1954; Fincham and Walton, 1957; Flom, 1960a; Rosenfield *et al.*, 1995a; Ciuffreda *et al.*, 1997 and others).

The haploscope that was developed for use in this study needed to be incorporated into the optical bench set-up mounted around the autorefractor that was necessary for other measurements in the study. There was a limited space available between the subject and the semi-silvered mirror of the Canon R-1 autorefractor within which a device could be mounted and so it was decided to mount a mirror in this position that would allow the subject to view a target off-set to the side. Figure 3.3 shows the set-up used to assess changes in the vergence position of the left eye.

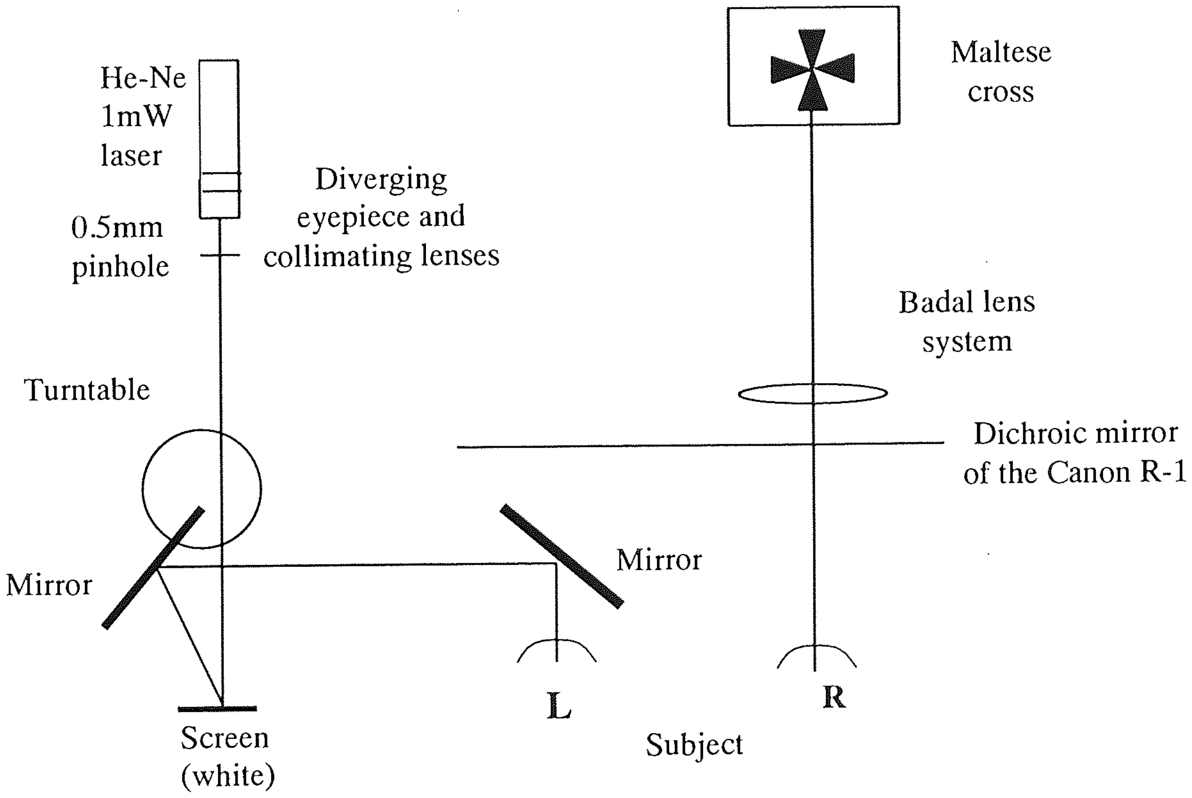

Figure 3.3 A schematic diagram showing the method of vergence assessment (shown from above).

The two front-surfaced aluminised mirrors (avoiding ghost images) allow the subject's left eye to view a 1mW He-Ne laser spot imaged on a blank screen. During the experiment as the subject's left eye converges, the laser spot will appear to move in relation to a fixed target (Maltese cross) being observed by the right eye, the images received by the two eyes being superimposed on each other. The subject is then asked to re-align the spot with this fixed target by rotating mirror 1 mounted on the turntable. The amount of rotation of the turntable is read directly from a vernier scale on the base of the optical turntable. More details about this method are given in section 5.2.

A computer program has been written in Microsoft Basic to convert the rotation of the turntable into the actual rotation of the eye (see Appendix 1). Appendix 2 shows the results of an assessment of the resolution of the haploscope.

3.4 OPENING THE ACCOMMODATIVE LOOP

For several of the investigations in this study it was necessary to measure accommodation under open-loop conditions. Section 1.3.3.a describes several methods of opening the accommodative loop.

When assessing the CA/C ratio a method of opening the accommodative loop was needed that still allowed a binocular target to be present, to ensure closed-loop vergence. It was therefore not possible to used bright empty field or dark field conditions to open the accommodative-loop.

The use of pinholes was considered, using a pinhole within a section of Kodak Wratten 87 filter that allowed IR to be transmitted, permitting the use of the infra-red auto-refractor through the natural pupil. The main disadvantage with using pinholes was that as the eyes converged or diverged to maintain single binocular vision, it was difficult to ensure that the pinholes were still in correct alignment with the visual axes of the eyes.

3.4.1 Difference of Gaussian target (DoG)

The Difference of Gaussian target has been described previously in section 1.3.3.1a. A DoG target with a spatial frequency of 0.1 c/deg has been shown to be a non-accommodative stimulus (Kotulak and Schor, 1987; Rosenfield, 1989b). An example is shown in figure 3.4.

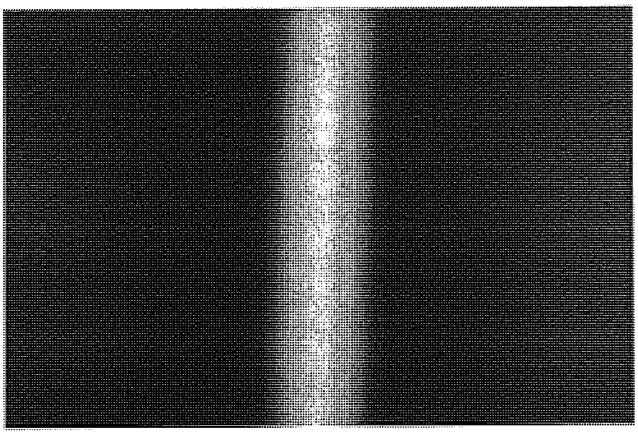

Figure 3.4 A Difference of Gaussian target

With the help of Dr Tim Meese, a 0.1c/deg DoG target was generated and displayed on a Macintosh LC475 computer and monitor using NIH Image 1.59.1 software. This software allows the manipulation of the spatial frequency, contrast and angular subtense of the image. In order to confirm that the accommodative loop was open when viewing the DoG target, the accommodative responses of 10 subjects (mean age 23.5 years) with supplementary lenses of varying powers (0 to – 4D) were measured using the Canon R-1 autorefractor. The results were compared to the responses found with the same lenses when viewing a computer generated Maltese cross as an accommodative target. The results showed that the accommodative loop was indeed open when viewing the DoG target (see Appendix 3). The DoG target was thus selected as the stimulus when measuring the CA/C ratio. Further details of the experimental procedure used are given in section 5.2.

3.5 MEASURING THE AMPLITUDE OF ACCOMMODATION

An accurate and repeatable method of assessing the amplitude of accommodation is of paramount importance to this study since it is the decline in this amplitude that is used to define presbyopia.

Objective methods of measuring the amplitude of accommodation have been described. Hokoda and Ciuffreda used dynamic retinoscopy when assessing the accommodative response of amblyopes (Hokoda and Ciuffreda, 1982). This retinoscopy technique involved finding the retinoscopic endpoint as a reduced Snellen reading card was moved towards the subject. The card was then held just within the subjective nearpoint (reported as just blurred) and the experimenter moved away from the card until the neutral point was found. The procedure was repeated three times and the average amplitude of accommodation was calculated.

Ramsdale and Charman (1989) used a laser optometer when assessing the accommodative response to increasing accommodative stimuli, with an allowance for the longitudinal chromatic aberration of the eye. The difference between the maximum and minimum accommodative responses was equal to the amplitude of accommodation. Laser optometers are described in section 1.3.3.c. Millodot and Newton (1981) assessed the amplitude of accommodation of 44 subjects by measuring the VEP response to negative lenses. It was found that there was a good correlation between the objective amplitude of accommodation measured with this technique and the amplitude measured by the subjective push-up method.

In this study however, a subjective method of assessment is satisfactory, since it is the subjective perception of blur that is the presenting symptom during incipient presbyopia.

There are 2 main subjective methods that can be employed to measure the amplitude of accommodation.

3.5.1 Minus lens technique

The minus lens method involves the subject observing a target at a fixed distance and then increasing power negative spheres are placed in front of the eye until the subject can no longer maintain the target in sharp focus. The maximum power of negative sphere through which a clear image can be seen added to the accommodative demand of the target distance will give the amplitude of accommodation. The main disadvantage of this technique is the unnatural viewing conditions it involves. There will be no proximal cues to accommodation since the target is at a fixed viewing distance and the lenses will cause the minification of the target as the negative power increases. It has been found that this method results in lower measurements of the amplitude of accommodation than the push-up technique (Hokoda and Ciuffreda, 1982; Kragha, 1986) which is likely to be due to the absence of the proximal cues.

3.5.2 Push-up technique

A reading target (letters, symbols or words) is brought towards the subject until blurring of the target is reported. The dioptric value of the distance at which blur is first noticed is taken to represent the amplitude of accommodation. Most frequently the RAF (Royal Air Force) rule is used to present the stimulus as this allows the rule to be rested on the patients cheeks and the target to be moved forward along the midline.

Target size

As the target is brought closer to the subject the angular subtense of the reading material will increase. The increase in target size may result in an overestimation of the amplitude of accommodation because as target size increases, the depth-of-focus of the eye increases and so a larger target may still appear clear where a smaller target may not (Tucker and Charman, 1975; Atchison *et al.*, 1994). Somers and Ford (1983) suggested that the increased separation of the target borders of a larger target may result in less overlap of the blurring of these edges; thus with a larger target, a greater degree of blurring will be necessary for the subject to actually report blur.

Rosenfield and Cohen (1995) and Atchison *et al.* (1994) both investigated how the target size influenced the measured amplitude of accommodation. Rosenfield and Cohen measured the amplitude of accommodation of 30 students (aged 22-27 years) and found that as target size increased the measurement of the amplitude of accommodation increased and thus the authors recommend the use of a small letter target (subtending around 5 min. arc) or a series of fine lines. The difficulty that may arise is that with young subjects to ensure that the target is sufficiently small the target may have to be a fraction of a millimetre in height, which can prove difficult to print and manufacture.

Atchison *et al.* (1994) investigated the use of a near-vision chart based on the Bailey-Lovie chart, so that as the target was moved closer, the subjects attention was drawn to a smaller line of letters ensuring that the angular subtense of the letters remained approximately the same. Sixty subjects were involved in the study, with 15 subjects in each of 4 age groups (25-29 years, 30-34 years, 35-39 years and 40-45 years). Comparing the results using the Bailey-Lovie style of chart to those with the standard N5 print size, the authors found that the N5 print significantly overestimated the amplitude of accommodation (by a mean of 2.2D in the subject group aged 25-29 years), although the mean difference in older subjects (aged 40-45 years) was smaller (0.8D).

Hokoda and Ciuffreda (1982) asked their subjects to focus on the smallest line of letters that they could resolve and as the target was brought closer the patient was encouraged to use the smallest line that could be distinguished. This is the protocol adopted for this experiment. Since the majority of the subjects in the current study are incipient presbyopes, with amplitudes of accommodation from around 2 to 7D, the range of letter sizes on the RAF rule allows for sufficiently small target sizes to prevent the overestimation of the amplitude, with a range from N5 to N12 print.

Push-up or push-down procedure

An alternative technique can be used whereby the target is taken further away, from a distance closer than the subject's nearpoint where it will be blurred, to the first point at which is reported as being clear (Bennett and Rabbetts, 1989). This is known as the push-down method and is usually performed by using the push-up technique until the target is blurred, taking the target slightly closer than the nearpoint and then moving it away until it is clear (Rosenfield and Cohen, 1996).

Several studies have reported differences between the amplitude of accommodation measured with the push-up and push-down techniques with the push-up technique resulting in consistently higher values (Fitch, 1971; Hokoda and Ciuffreda, 1982; Atchison *et al.*, 1994; Rosenfield and Cohen, 1996; Chen and O'Leary, 1998). Rosenfield and Cohen (1996) found the mean amplitude of accommodation of 13 subjects (mean age 24.3; SEM = ± 0.50 years) to be 10.11D (SEM = ± 0.49) using the push-up technique and 9.50D (SEM = ± 0.46) using the push-down technique. This difference in the estimation of amplitude between the push-up and push-down techniques may be due to a stronger proximal stimulus to accommodation when the target is moving towards the patient (Rosenfield and Gilmartin, 1990).

Repeatability

Rosenfield and Cohen (1996) assessed the repeatability of the push-up, push-down and minus lens techniques using 13 young subjects (mean age 24.3; SEM = ± 0.50 years). The amplitudes found by each technique were assessed on 5 separate occasions, the standard deviation for each technique was calculated for each subject and then the population mean was found. There was no significant difference between the mean standard deviations found for the three techniques. The 95% limits of agreement for the push-up, push-down and minus lens techniques were ±1.44, ±1.39 and ±1.43D respectively. This would imply that a change in the subjective amplitude of accommodation of at least ±1.50D is required to indicate a significant shift in amplitude.

Rosenfield and Cohen do stress that these results are from a young subject group and different repeatability statistics may be found in an older group. It may be that the results are more repeatable in an older subject group, particularly using the push-up and push-down techniques where the dioptric scale on the nearpoint rule is extended. Rosenfield and Cohen did try to overcome the collapsing of the dioptric scale by using additional negative lenses when the amplitude was greater than 8D, although no comment was made as to whether this interfered with the proximal accommodation cues.

3.5.3 Assessment procedure used in the present study

With the binocularly balanced (most positive) distance subjective refraction in place, the subject was instructed to observe a letter on the smallest line of letters resolvable when observing the letter chart of the RAF nearpoint rule. The target was brought forwards along the midline. If, as the target came closer, a smaller letter could be seen clearly, their attention was directed to this letter. The target was moved by the examiner, since it has been found that if the target is moved by the subject this may result in the overestimation of the amplitude (Fitch, 1971). The subject was asked to report the point at which the target first became blurred, the target was then taken slightly closer to the subject and then moved away until the letter first became clear. The dioptric stimulus distance was noted. This procedure was performed three times and the mean amplitude of accommodation calculated. An effort was made to use the same room when measuring the amplitude of accommodation to try and maintain the same room illumination (approximately 200cd/m^2).

In this study amplitude of accommodation was assessed binocularly since the study is investigating the decline in the amplitude of accommodation that is found under normal viewing conditions in incipient presbyopia. Binocular viewing will ensure closed-loop accommodation and vergence so that all the components of accommodation and vergence, such as fusional vergence, accommodative vergence and vergence accommodation are present as they would be in an everyday reading task.

CHAPTER 4

ACCOMMODATION DURING INCIPIENT PRESBYOPIA

4.1 INTRODUCTION

The primary objective of this study is to determine the nature and extent of the re-calibration of the oculomotor system that must occur during incipient presbyopia. This chapter investigates the characteristics of the change in the accommodative function with age with regard to amplitude of accommodation, tonic accommodation and accommodative adaptation. Knowledge of these functions is important since they are indices of the decline in accommodation that occurs.

Section 1.3.6 gives details of the research that has investigated the effect of age on tonic accommodation (TA). Four studies are described, all of which have reported a decline in TA with age (Simonelli, 1983; Ramsdale and Charman, 1989; Rosenfield *et al.*, 1995b; Mordi and Ciuffreda, 1998). A reduction in TA would place further demand on the other components of accommodation; proximal, blur-driven and convergence accommodation, a compensatory increase in any of these components would in turn have an influence on the composition of the overall vergence response.

Three of the studies of TA were cross-sectional in nature and are thus limited by the degree to which the sample reflects the total population. The longitudinal study of TA was limited due to the use of only one subject.

Following a near vision task the regression of the accommodative response back to the tonic accommodation level can be measured. This regression is thought to represent the decay of the tonic adaptive element of accommodation (Schor, 1986). It has been shown that the magnitude of adaptation is influenced by the magnitude of TA, with greater levels of adaptation as the target-to-TA position increases. Thus if TA does decline with age it would be expected that there would be less accommodative adaptation also.

The only study of the affect of age on accommodative adaptation assessed the open-loop accommodation response of 41 subjects aged 20 to 70 years of age (Rosenfield *et al.*, 1995b). Accommodative adaptation was found to decline with age at a rate of -0.034D/year. The mean zero level of adaptation was reached at 55 years of age.

4.2 SUBJECTS

Two subject groups were included in the longitudinal study and these same subjects were used for each of the studies described in the experimental chapters. The first group consisted of 28 incipient presbyopes aged 35 to 45 years of age (mean age 41.8 ± 2.9 years) at the commencement of the study. The second group comprised 10 young subjects aged 20 to 30 years of age (mean age 24.4 ± 2.7 years). All the subjects underwent a full eye examination prior to the first experimental session and were found to have no ocular pathology.

Visual acuity was equal between the two eyes and correctable to at least 6/6. The majority of subjects were emmetropes (defined here as spherical equivalent between –0.25DS and +0.75 DS with a cylinder no greater than 0.75 DC). Ametropic subjects wore corrective soft contact lenses (Bausch and Lomb, 70% water content, daily disposable) throughout the experimental sessions since the experimental viewing conditions did not allow for spectacle correction. The subjects were required to have no abnormalities of binocular vision with a maximum distance heterophoria of 3^{Δ} since if greater than this the heterophoria measured during the prism adaptation experiments (Chapter 7) may exceed the tangent scale limits. All subjects gave written informed consent before undertaking any aspect of the experiment (Appendix 4 contains copies of the consent forms and Ethical Committee application forms).

The subjects in the young subject group were all students within the Division of Optometry at Aston University. Seven of the subjects were emmetropes and 3 were myopes (spherical equivalent ≤ -3.00DS), 4 were female and 6 were male.

Eight subjects in the incipient presbyope subject group were staff or students at Aston University. The remaining 20 subjects were West Midlands Fire Service personnel. All 28 subjects were emmetropes, 24 were male and 4 female.

4.3 METHODS

Each of the 38 subjects attended an experimental session every 4 months for a total of 2 years, thus 7 sessions were completed in total. At each session a routine subjective refraction was performed to determine the distance refraction (most positive, binocularly balanced) and an assessment was made of the amplitude of accommodation, using the push-down technique described in section 3.5.3, with an average of three readings recorded.

Tonic accommodation

At each session, the subject was positioned with their chin on the chin rest and head against the forehead rest of the Canon Autoref R-1. Ten readings of distance refraction were taken, while the subject observed a letter target at 6m. The subject then sat in complete darkness for 3 minutes to allow the dissipation of any transient accommodative response (Wolf *et al.*, 1987) (see section 1.9). After this time, 10 readings of refraction were taken with the autorefractor over the following 20 seconds. The mean accommodative response in the dark was adjusted to take into account the mean pre-task distance refraction.

Simonelli (1983) describes this difference between the far-point of the eye (distance refraction) and the dark-focus position as the 'relative dark-focus'. An uncorrected hypermetrope will have a far-point beyond infinity and an uncorrected myope will have a far point that is proximal, thus if TA is determined without correction for this refractive error the measured TA position will appear to be far in the hypermetrope and close in the myope. Thus Simonelli suggested the use of the expression 'relative dark-focus' rather than the measured dark-focus. In this study however, the subjects were either corrected low myopes or emmetropes so there was only a small degree of uncorrected ametropia. The term tonic accommodation will continue to be used in this study although it should be noted that the value represents the difference between the far-point and focusing distance in darkness rather than the measure of the true dark focus position. The previous studies which have examined the change in tonic accommodation with age have also used this relative value (Simonelli, 1983; Ramsdale and Charman, 1989).

Accommodative adaptation

The subject was positioned at the autorefractor. Directly ahead of the right eye at a distance of 40cm was a computer monitor on which was displayed a Difference of Gaussian target (DoG). This target has been described in section 3.4.1. The DoG subtended an angle of 20° by 20° and thus opened the accommodative loop since any peripheral stimuli will not be cues to accommodation (Phillips, 1974 cited by Ciuffreda and Kenyon, 1983; Bullimore and Gilmartin, 1987). The subject was instructed to observe the centre of the target and to be unconcerned if the target appeared to be blurred. After 3 minutes of target observation 10 readings of the open-loop accommodative response of the right eye were taken to obtain a mean pre-task accommodative response.

A grid of high contrast, black on white, printed numbers, subtending an angle of 8° by 8° was affixed to the front of the monitor and front illuminated in order to provide an accommodative stimulus of 2.5D. In the centre of the numbers was a small cross. The subject was asked to read the numbers (not out loud) and then every ten seconds was asked to look at the cross while three readings of the accommodative response were taken. After the three-minute task the grid of numbers was removed from the screen and the subject was directed to look towards the centre of the DoG stimulus. A reading of accommodative response was then taken approximately every second over the next 90 seconds, to measure the regression of the accommodative response back to the tonic response level.

4.4 RESULTS

Amplitude of accommodation

The amplitude of accommodation of each incipient presbyope at the first experimental session is shown in figure 4.1. Using Statview software, a multiple stepwise regression analysis of the data included in this chapter and Chapter 5 showed that at each of the 7 experimental sessions a significant correlation was found between age and amplitude of accommodation ($p<0.001$) (see table 5.1). At 6 of the 7 sessions, age was shown to account for over 40% of the variability in the amplitude of accommodation (i.e. $r^2 \geq 0.40$). The need for a stepwise regression is further discussed in Chapter 5 and is due to the possible inter-correlation between the oculomotor functions assessed.

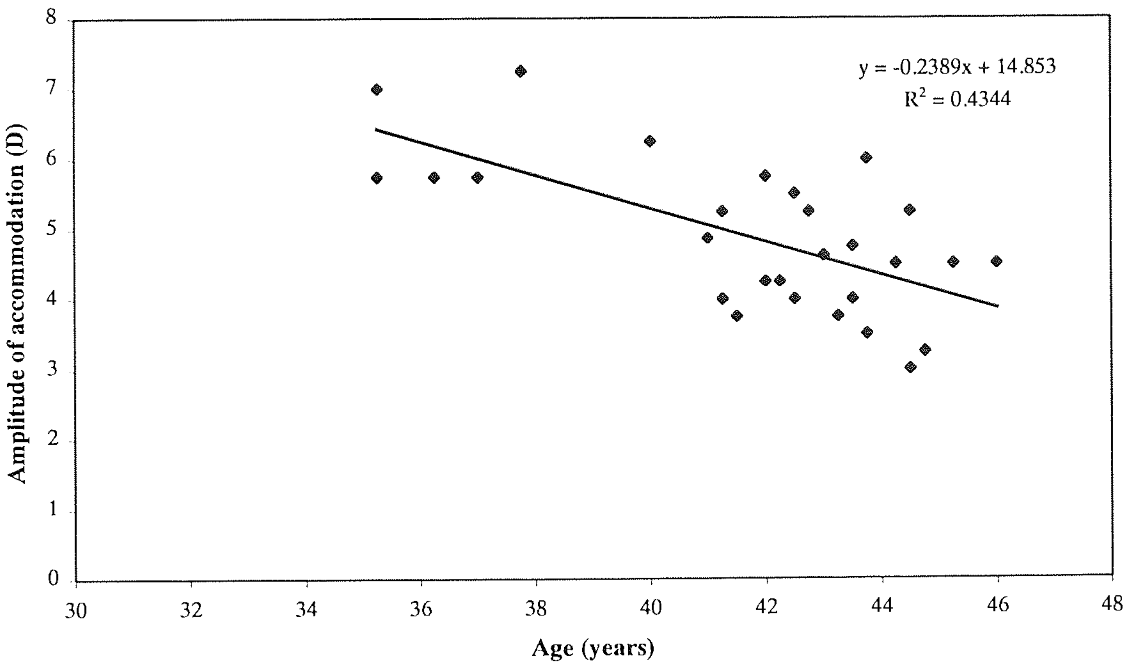

Figure 4.1 Amplitude of accommodation of incipient presbyopes at the first experimental session.

Over the two-year longitudinal study period, the mean decline in the amplitude of accommodation was 1.16D (±0.49D). Figure 4.2 shows the decline in the mean amplitude of accommodation over the 7 experimental sessions (p<0.001).

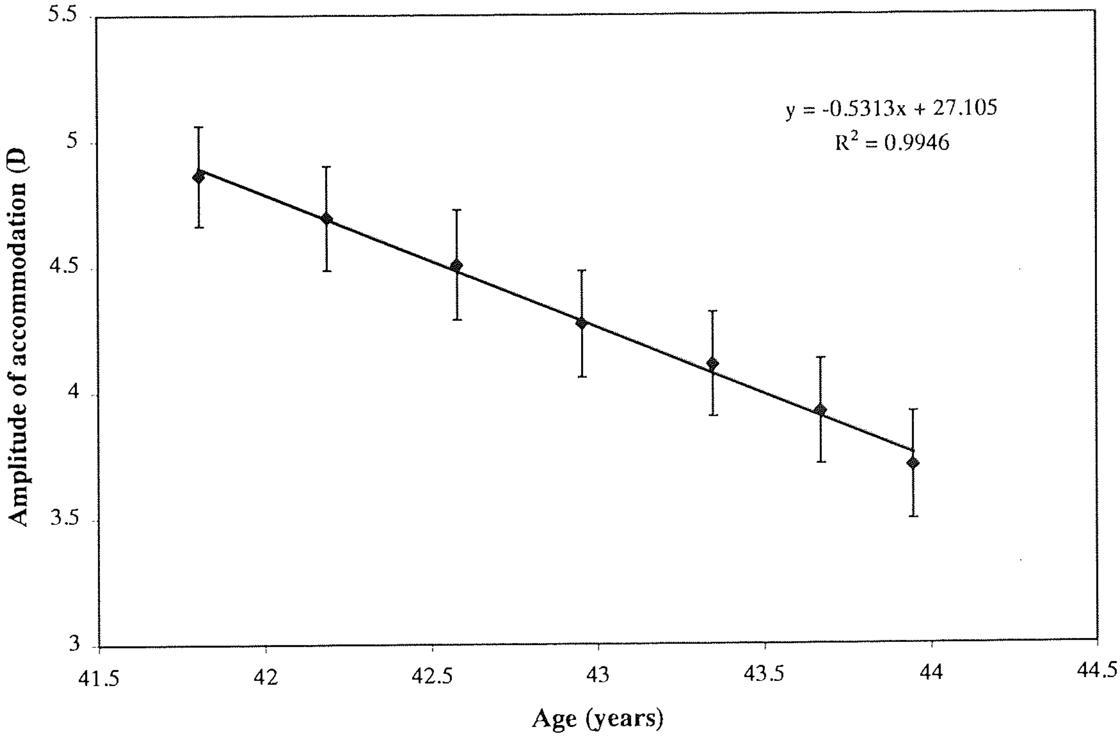

Figure 4.2 The mean amplitude of accommodation of incipient presbyopes measured over a two-year period (n=28). Error bars represent ±1SEM.

In the younger subject group a significant correlation between age and amplitude of accommodation was found at 4 of the 7 visits using the stepwise multiple regression analysis ($p<0.05$). Over the two-year period the mean decline in the amplitude of accommodation was 0.49D (±0.50D).

Tonic accommodation

There was found to be no significant correlation between the amplitude of accommodation and the TA of the subjects when analysed on either a cross-sectional or longitudinal basis using the stepwise multiple regression analysis.

The mean TA levels of each group at each session are shown in table 4.1.

Session	Mean TA in incipient presbyope subject group (D) (±SEM)	Mean TA in younger subject group (D) (±SEM)
1	0.63 (±0.10)	0.73 (±0.13)
2	0.87 (±0.12)	0.76 (±0.18)
3	0.83 (±0.11)	0.56 (±0.16)
4	0.80 (±0.10)	0.66 (±0.16)
5	0.76 (±0.12)	0.55 (±0.18)
6	0.77 (±0.07)	0.66 (±0.13)
7	0.85 (±0.12)	0.80 (±0.27)

Table 4.1 Mean TA on each assessment occasion for the two subject groups.

There was no significant difference between the mean TA measured in the two subject groups at any of the experimental sessions.

Accommodative adaptation

Accommodative adaptation was measured at the 4th, 5th and last experimental sessions. For each subject at each session the mean pre-task accommodative response was calculated and was subtracted from the within task and post-task accommodative responses. A graph was drawn of the post-task accommodative regression and from this the time for the accommodative response to return to the tonic level was calculated. Figure 4.3, 4.4 and 4.5

show three examples of accommodative post-task regression curves showing examples of subjects with significant adaptation, moderate adaptation and only slight adaptation, respectively.

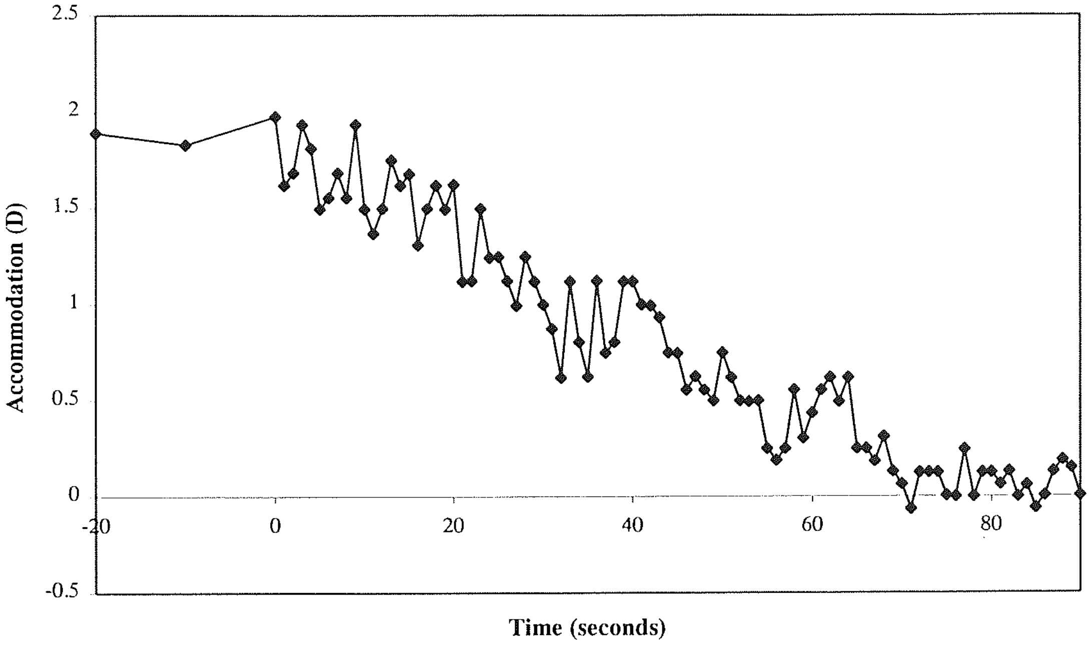

Figure 4.3 Accommodative regression for subject SB (aged 38 years) at the first experimental session. The plot is 20 seconds of the within task period and 90 seconds of the post-task period. (Regression complete in 70 seconds).

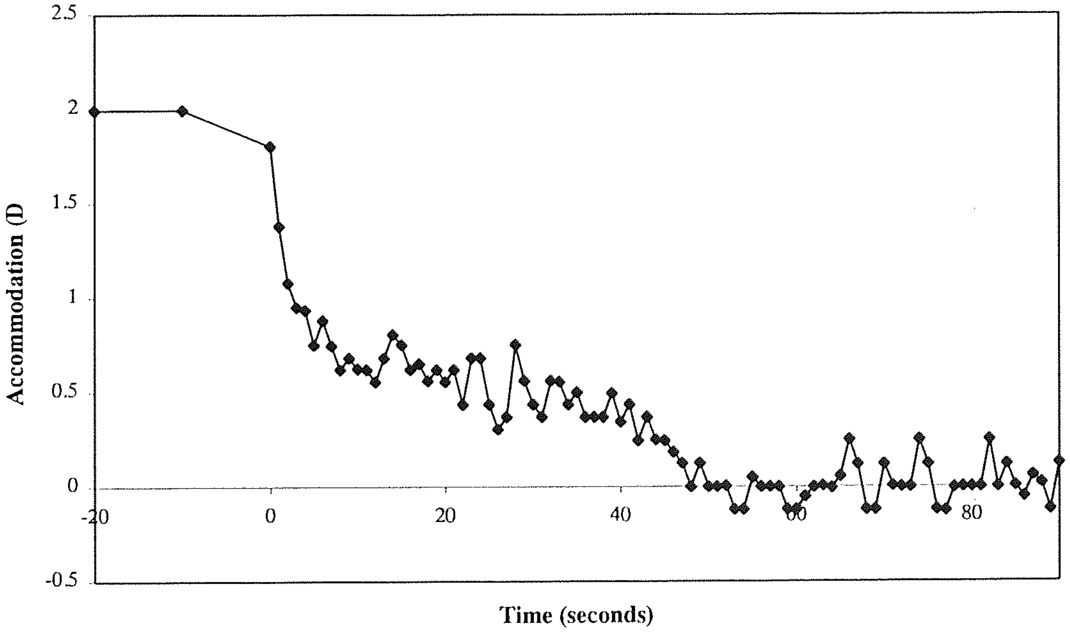

Figure 4.4 Accommodative regression for subject AA (aged 44 years) at the first experimental session. The plot is 20 seconds of the within task period and 90 seconds of the post-task period. (Regression complete in 50 seconds).

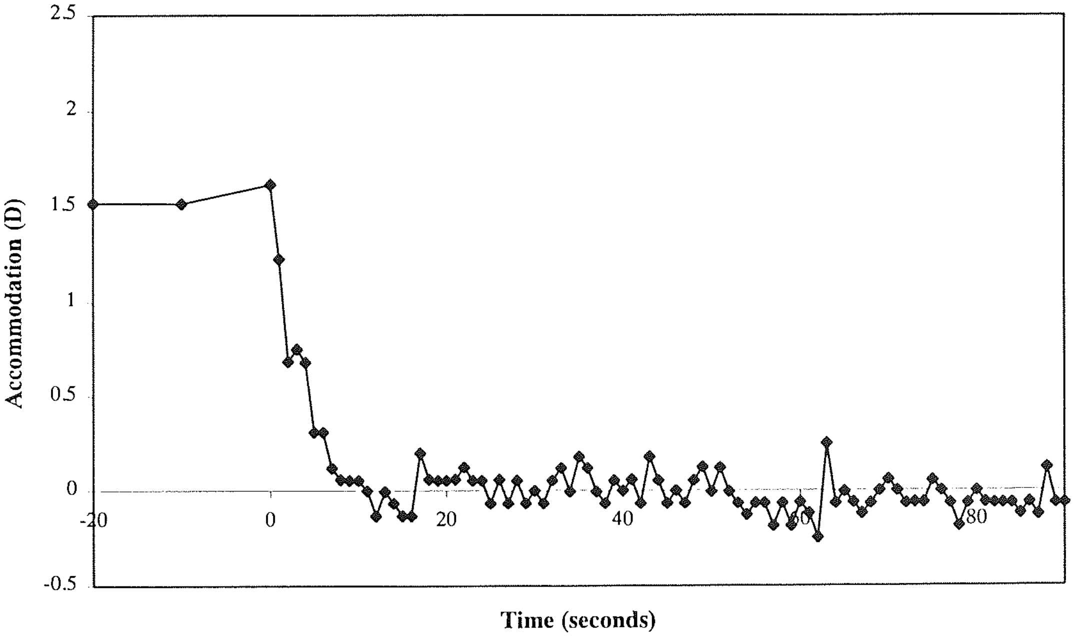

Figure 4.5 Accommodative regression for subject RT (aged 44 years) at the first experimental session. The plot is 20 seconds of the within task period and 90 seconds of the post-task period. (Regression complete in 10 seconds).

There was found to be a small but statistically significant positive correlation between the amplitude of accommodation and the time taken to reach the tonic accommodation level at the first time of assessment (4th session) as shown in figure 4.6 ($r=0.34$ $p<0.05$).

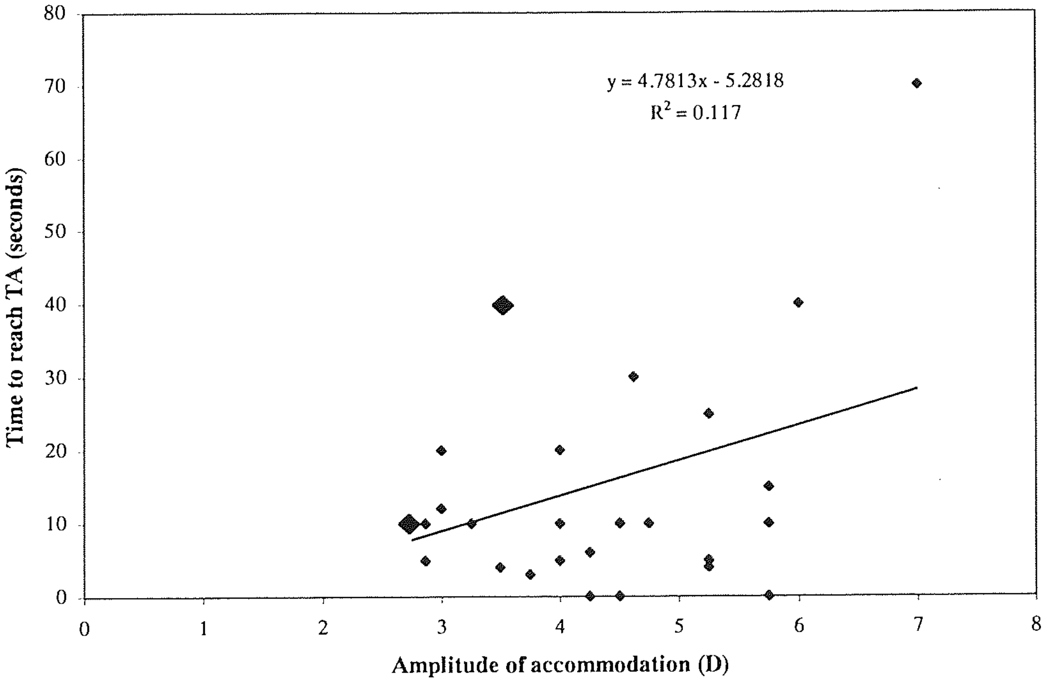

Figure 4.6 Time for accommodative regression to return to tonic accommodation level after near vision task (n=28). The larger filled diamonds represent two superimposed data points.

Thus as the amplitude of accommodation declines, the adaptation decreases. However, in figure 4.6 the data point for the subject with 7D of accommodation appears to be an out-lier and indeed with its removal there is no significant correlation between the amplitude of accommodation and the length of adaptation ($r=0.04$, $p>0.05$). This data point represents the subject shown in figure 4.3 where the data clearly shows a slow regression to the tonic level and thus the point has still been included in the analysis. It is however pertinent to note that without this single data point there is no significant correlation between amplitude and adaptation.

At the other two times of assessment (5th and 7th sessions) there was no statistically significant correlation between the two variables. Comparing the mean regression times of the older and younger subject groups there was found to be no significant difference between the group means at any of the experimental sessions and over the year of assessment there was no significant change in the group means.

The within-task accommodation responses were also used to assess the accommodative response to a 2.5D stimulus. The mean response over the first 30 seconds of viewing the accommodative stimulus was found for each of the incipient presbyopes. At each of the three times of assessment (4th, 5th and 7th sessions) there was found to be a statistically significant correlation between the amplitude of accommodation and the accommodative response ($r=0.38$, $p<0.02$; $r=0.38$, $p<0.02$; $r=0.57$; $p<0.002$ respectively). At each session there was a lower accommodative response to the 2.5D stimulus as the amplitude of accommodation declined.

4.4 DISCUSSION

The significant relationship between age and amplitude of accommodation found at each experimental session was as expected and confirms that this subject group is suitable for the longitudinal study of oculomotor function in incipient presbyopia. Of the 28 incipient presbyopes, 10 required their first reading addition during the study period although none were required during the first year and no subject required their glasses for all close-work, just for occasional use.

TA was found to be unrelated to the amplitude of accommodation which is not in agreement with previous research, where a decrease in TA with age was found (Simonelli, 1983; Ramsdale and Charman, 1989; Rosenfield *et al.*, 1995; Mordi and Ciuffreda, 1998). The level of TA found in the younger subject group in this study was significantly lower than that found by other researchers who have also used an infra-red optometer in darkroom conditions (Bullimore *et al.*, 1986; Rosenfield, 1989b). The TA of each of the subjects in the younger group is within the range found in other studies but it may be that with only 10 subjects in the group, the mean TA of the younger group is not representative of a younger population.

If a decrease in TA does occur with age this will place further demand on the blur-driven accommodative response to a near stimulus which may in turn lead to changes in the overall vergence response as a result of a change in accommodative convergence to a particular stimulus. The impact that a change in TA would have on the overall vergence response will be discussed further in Chapter 8 using computer simulations of the accommodation and vergence mechanisms and their interaction.

The study of accommodative adaptation showed little evidence of any correlation between amplitude of accommodation and the degree of adaptation. The study of accommodative adaptation in incipient presbyopes presents some difficulty because for many subjects the accommodative response during the task (stimulus of 2.5D) was only slightly higher than the TA level. It has already been stated that the extent of adaptation depends on the difference between the TA level and the stimulus distance. Thus if the within-task accommodative response were only slightly different from the tonic level there would be little adaptation and the time to return to the tonic level would be short. Therefore the significance of a comparison of the within-group correlation of accommodative adaptation and amplitude of accommodation will be weakened.

The finding of no significant difference in accommodative adaptation between the two groups agrees with the finding of no significant difference in TA between the two groups, since accommodative adaptation is related to TA level (Ebenholtz, 1985;1992).

CHAPTER 5

THE INTERACTION OF ACCOMMODATION AND VERGENCE DURING INCIPIENT PRESBYOPIA

5.1 INTRODUCTION

It is known that with increasing age there is no reduction in the overall vergence response to a particular stimulus, in fact fixation disparity (the steady state vergence error) has been found to decline with age (Sheedy and Saladin, 1975). Thus despite the reduction in the amplitude of accommodation the oculomotor system is able to maintain the same aggregate vergence response during incipient presbyopia.

Following the Hess-Gullstrand theory of presbyopia an adaptation in oculomotor function will be required when a subject is attempting to focus on a target closer than the amplitude of accommodation (see section 2.7). Within the amplitude of accommodation the accommodation and convergence interaction remains stable and it is only if an attempt is made to converge to a target closer than that amplitude that additional vergence is required.

Sheedy and Saladin (1975) suggest it is accommodative convergence that provides the increased vergence at distances closer than the accommodative amplitude, despite there being no further possible change in accommodative response. Both Fry and Jones, in personal communication with Sheedy and Saladin, agree that it is the ability to use the ciliary muscle effort that is left in reserve after the lens reaches the stage where it cannot respond, that allows a further synkinetic convergence response (Jones, 1975 cited by Sheedy and Saladin, 1975; Fry, 1975 cited by Sheedy and Saladin, 1975). The oculomotor system must attempt to accommodate in order to make use of the convergence that will result from this effort but without any further increase in accommodation. It is an analogous situation when considering a patient who has a reading addition. In order to satisfy the same vergence demand at near, the oculomotor system may still attempt to accommodate allowing the necessary synkinetic convergence response to operate.

If the Hess-Gullstrand theory of presbyopia proves to be incorrect the consequences of the decline in the amplitude of accommodation with age will be different. When an older subject attempts to focus on a near target there may be an increased convergence response due to the increase in accommodative effort required. This increase in the convergence response as a direct consequence of accommodation should be evident as an increase in the stimulus and response AC/A ratios with age.

Studying the interaction between accommodation and convergence as a subject reaches incipient presbyopia has two purposes. Firstly, changes in the AC/A and CA/C ratios with age will allow the differentiation between the theories of presbyopia, since the Hess-Gullstrand theory predicts no change in the AC/A or CA/C ratios with age but the other theories of presbyopia predict an increase in both stimulus and response AC/A ratios with a decrease in the CA/C ratio. Following on from this, the investigation of how the AC/A and CA/C ratios vary with the decline in the amplitude of accommodation may explain how the oculomotor system copes with the decline in the amplitude.

The affect of age on the AC/A ratio has been discussed in section 2.6 although the results of the previous studies have been inconclusive, with evidence of both static, increasing and decreasing stimulus and response AC/A ratios. There have been notably few longitudinal studies undertaken to analyse this relationship, presumably due to the difficulty in completing such a study and indeed the only longitudinal studies that have been completed are weakened by the small number of subjects included. Consequently a longitudinal study of the CA/C and stimulus and response AC/A ratios during incipient presbyopia was undertaken.

5.2 METHODS

The 38 subjects from the two subject groups (see section 4.2) attended experimental sessions approximately every 4 months over a two-year period. Assessments of the CA/C ratio, stimulus AC/A ratio and response AC/A ratio were made at each visit.

CA/C ratio

To open the accommodative loop when assessing the CA/C ratio the subject observed a Difference of Gaussian (DoG) stimulus on a computer monitor (see section 3.4.1) throughout the experiment. The subject was positioned in the chin and forehead rest of the Canon Autoref. R-1 and observed the DoG stimulus that was aligned with the left eye at a distance of 40cm. Kersten and Legge (1983) have shown that the CA/C ratio is not dependent on the angle of lateral gaze and thus off-setting the DoG, to be aligned with the left eye, will not affect the ratio measured. A schematic diagram of the experimental set-up is shown in figure 5.1.

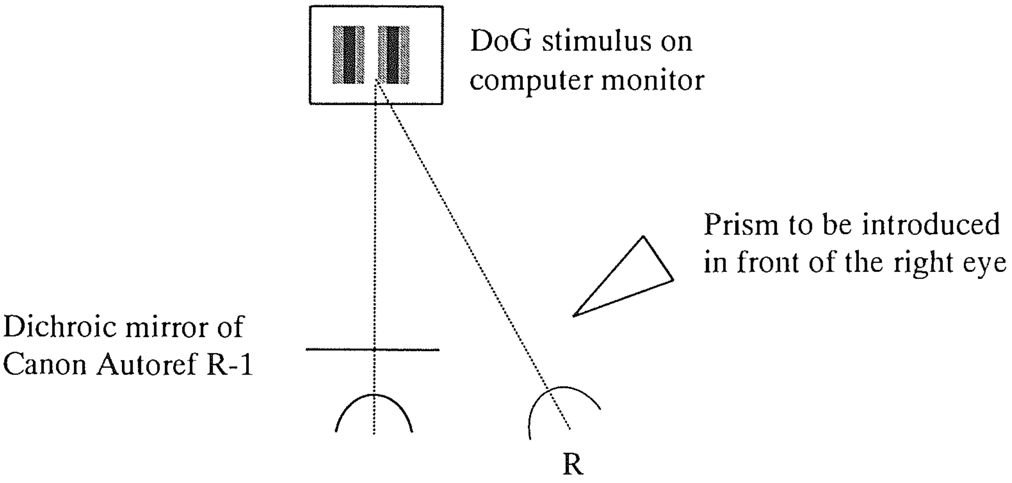

Figure 5.1 A schematic diagram showing the experimental set-up when measuring the CA/C ratio of a subject (shown from above).

The DoG target subtended an angle of 20° by 20° at 40cm so with the subject observing the centre of the target there were no peripheral cues to accommodation (Phillips, 1974 cited by Ciuffreda and Kenyon, 1983; Bullimore and Gilmartin, 1987). A thin (1mm diameter) vertical wire was located slightly in front of the subject's nose but within the field of view of both eyes. Throughout the experiment the subject was regularly questioned as to whether the wire appeared single or double whilst observing the DoG stimulus. If the wire appeared double it was known that there was not suppression of one eye. The wire represented an accommodative stimulus greater than 10D and as such did not influence the accommodative response.

A prism was introduced in front of the right eye and the patient was asked to keep the central white bar of the DoG target single but not to be concerned if the image appeared blurred. After 5 seconds, to ensure stable fusion of the image, 10 autorefractor readings were taken to assess the accommodative response. The procedure was repeated with prisms of 3, 6, 8, 12^{Δ} base-out and 3 and 6^{Δ} base-in. For each prism the average accommodative response was calculated and from this data the CA/C ratio was calculated.

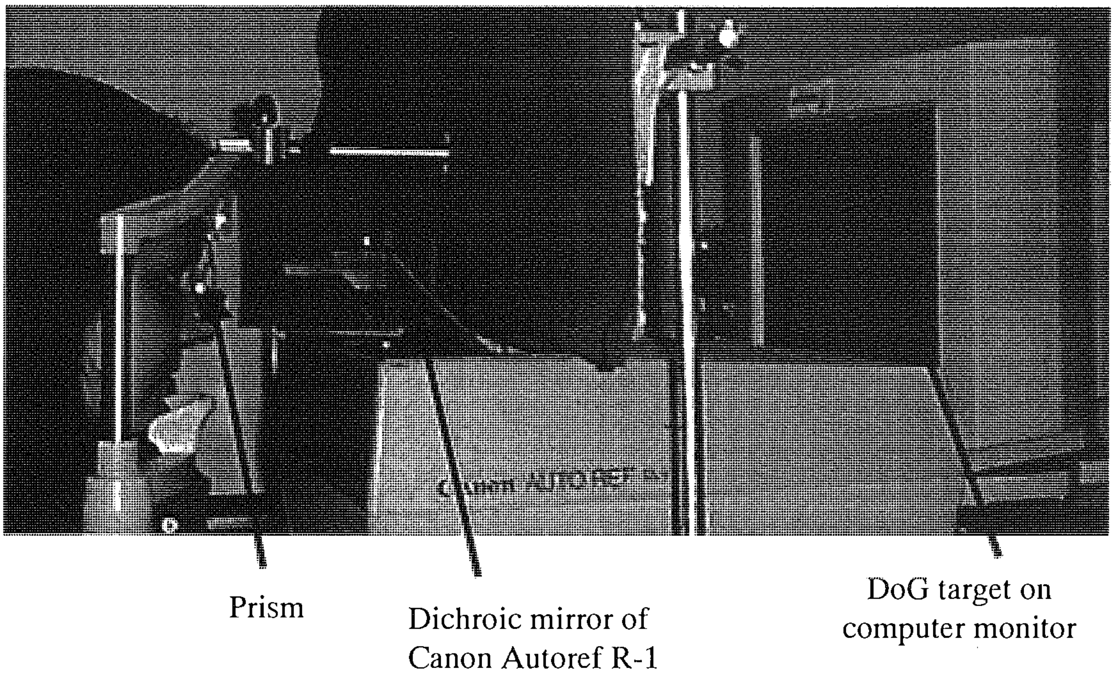

Figure 5.2 Experimental set-up when measuring the CA/C ratio

AC/A ratio

To measure the AC/A ratio is was necessary to open the vergence loop and close the accommodation loop. To open the vergence loop the eyes viewed dissimilar targets, preventing fusion.

The subject was positioned on the chin and forehead rest of the Canon R-1 with the right eye aligned with a front illuminated Maltese cross (angular subtense 10°) viewed through a +5.00D Badal lens system (70mm diameter). By varying the distance between the Maltese cross and the Badal lens the accommodative stimulus could be increased whilst maintaining constant stimulus size and illumination. Figure 5.3 shows the Badal lens system in front of the right eye.

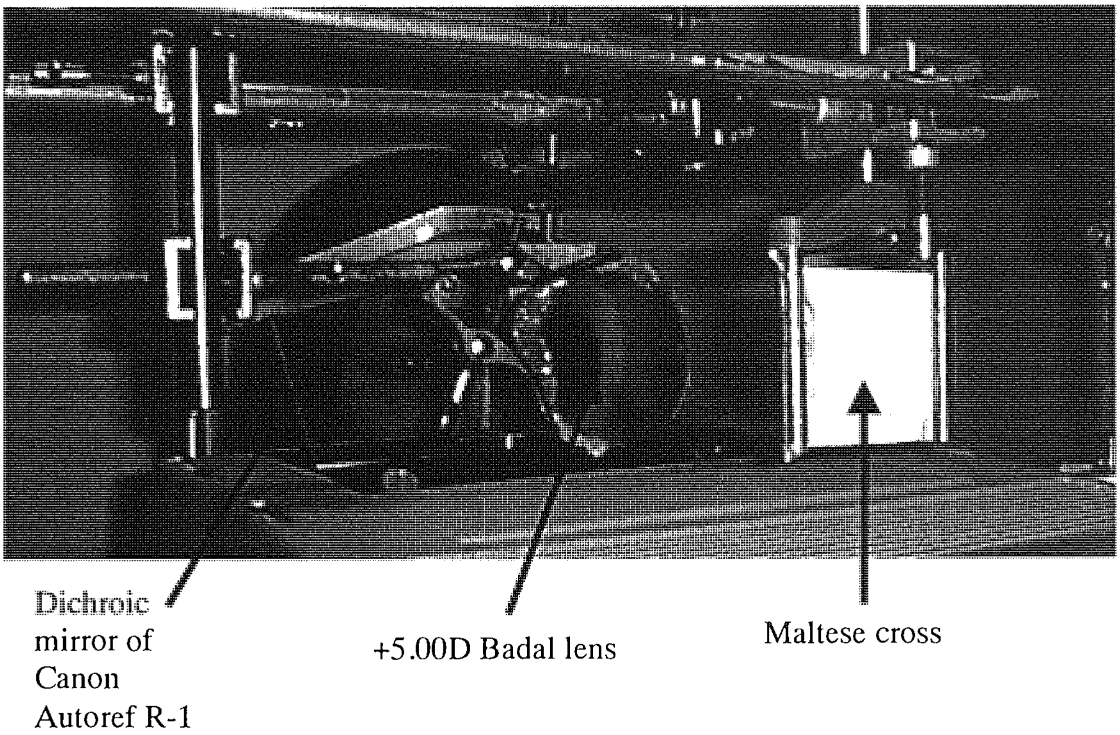

Figure 5.3 Badal lens system in front of right eye (mask that surrounds the Badal lens to prevent peripheral stimuli to accommodation has been removed for the photograph)

The left eye viewed the image of a laser spot through a series of front surface aluminised mirrors (see section 3.3.2 and figure 3.3). The subject was able to move the position of the laser spot by moving a handle on a vernier optical turntable that rotated one of the mirrors.

The subject was asked to keep the cross in clear focus and then to rotate the handle of the turntable to move the laser spot until it appeared to be in alignment with the centre of the cross. The position of the turntable was then read from a vernier scale on the base of the turntable. The subject was then asked to move the spot out of alignment and realign it. Three readings of this vergence position were taken for each level of accommodative stimuli. It was found that if more than three readings were taken the subject became fatigued towards the end of the experiment. For each accommodative stimulus, 10 readings of accommodative response were taken with the autorefractor. Accommodative stimuli from 0-4D were presented in 0.5D steps by varying the distance between the Maltese cross target and the Badal lens.

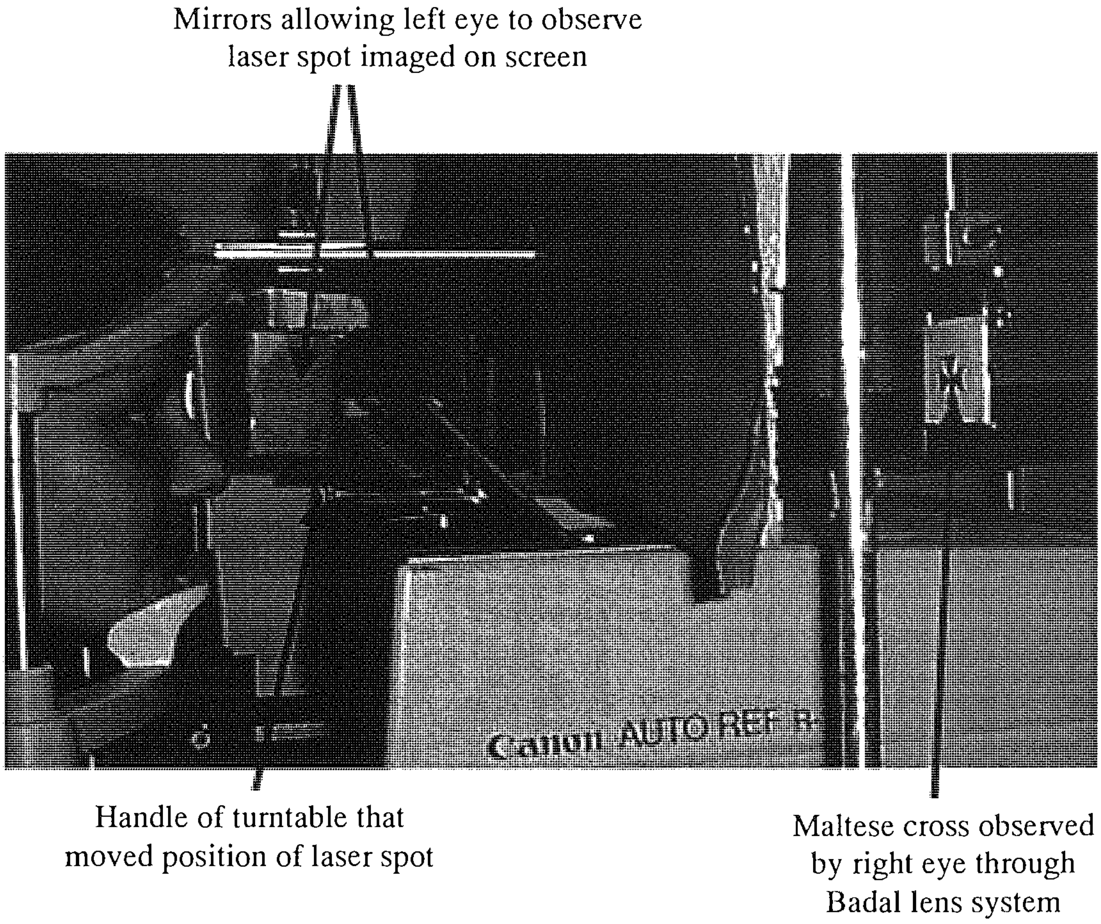

Figure 5.4 Experimental set-up when measuring the AC/A ratio.

A computer program was written in Microsoft Basic that converted the rotation of the turntable into the rotation of the left eye in prism dioptres (see Appendix 1), and from this and the measurements of accommodative response, the stimulus and response AC/A ratios were calculated.

5.3 RESULTS

To calculate the CA/C ratio a graph was drawn of the mean accommodative response to the various vergence stimuli. The CA/C ratio is the slope of the regression line that fits the data points. An example of such a graph is shown in figure 5.5. The ratio was then converted from D/$^{\Delta}$ to D/MA by multiplying by the subjects PD in cm.

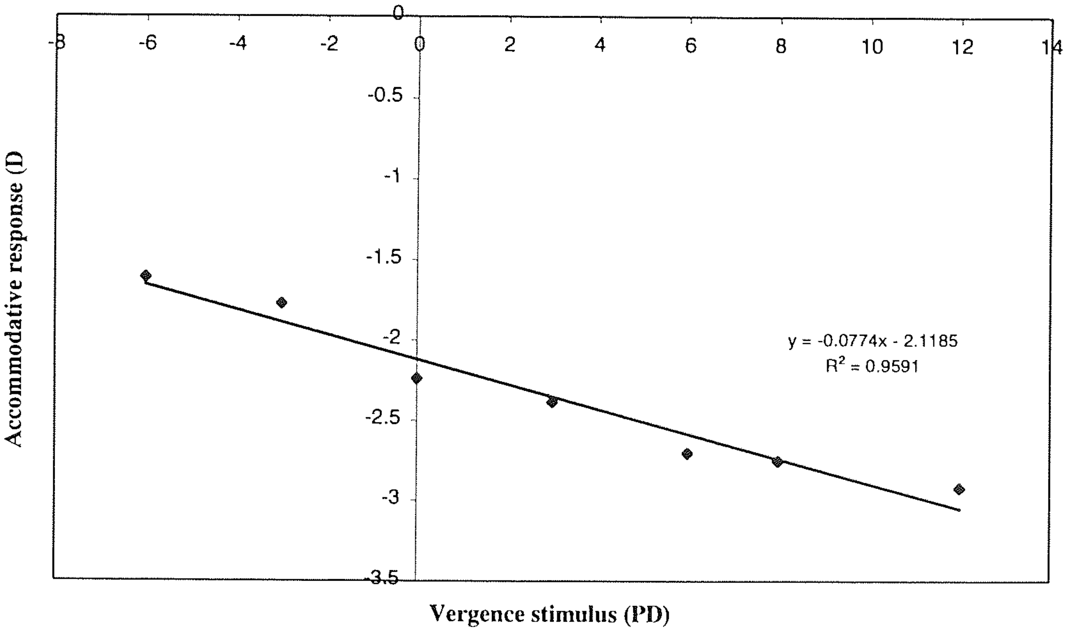

Figure 5.5 The mean accommodative response to a changing vergence stimulus for subject CH (age 43 years). The CA/C ratio is equal to the slope of the regression line, in this example 0.077 D/$^{\Delta}$ (0.53D/MA).

To calculate the stimulus and response AC/A ratios the mean accommodative response and vergence position (in prism dioptres) for each accommodative stimuli were calculated and graphs were drawn of the responses against the stimuli. Examples of the graphs drawn to calculate the stimulus and response AC/A ratios are shown in figures 5.6 and 5.7. The ratios were converted to MA/D by dividing the slopes of the graphs by the PD in cm.

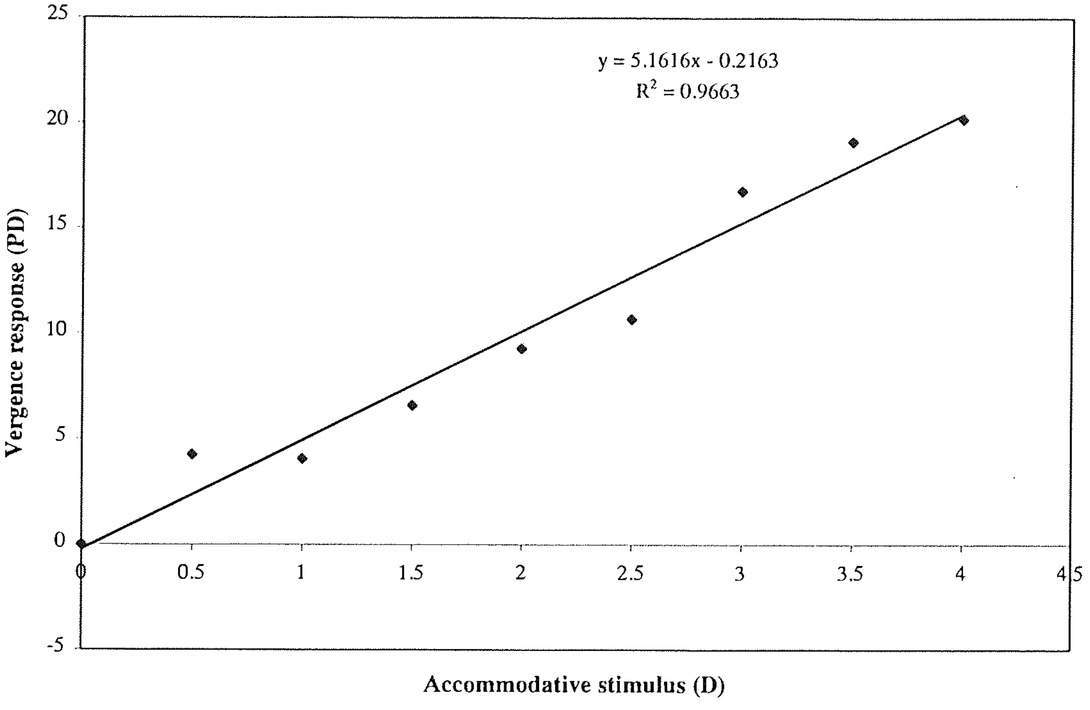

Figure 5.6 The mean vergence response to a changing accommodative stimulus for subject RG (age 41 years). The stimulus AC/A ratio is equal to the slope of the regression line, in this example 5.16$^{\Delta}$/D (0.85MA/D).

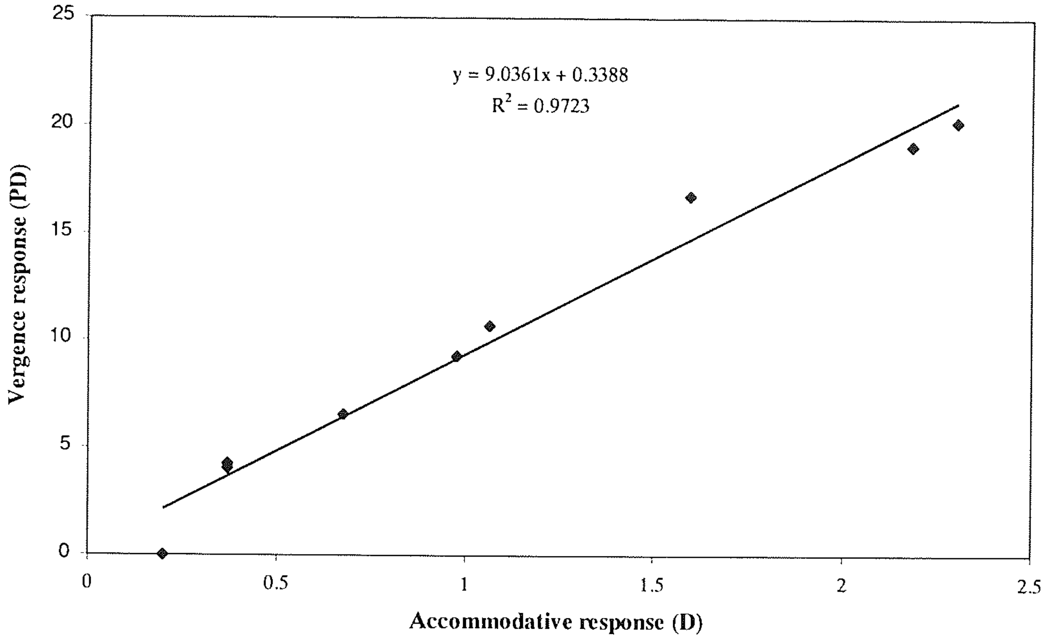

Figure 5.7 The mean vergence response and accommodative response to a changing accommodative stimulus for subject RG (age 41 years). The response AC/A ratio is equal to the slope of the regression line, in this example 9.04 $^{\Delta}$/D (1.48MA/D).

For each subject if the amplitude of accommodation was sufficiently low that any of the accommodative stimuli were within the last dioptre of accommodation, these stimuli were not used. For example if a subject had an amplitude of accommodation of 4.5D then only stimuli from 0 to 3.5D were included. These higher stimuli were excluded to ensure that there was not excessive effort being used to view the target (Ciuffreda *et al.*, 1997).

Various methods of analysing how the ratios have changed with the decline in the amplitude of accommodation can be considered.

For the incipient presbyopes, the mean CA/C ratio, stimulus AC/A ratio and response AC/A at each visit can be plotted against the mean amplitude of accommodation on these occasions. These graphs are shown in figures 5.8, 5.9 and 5.10 respectively.

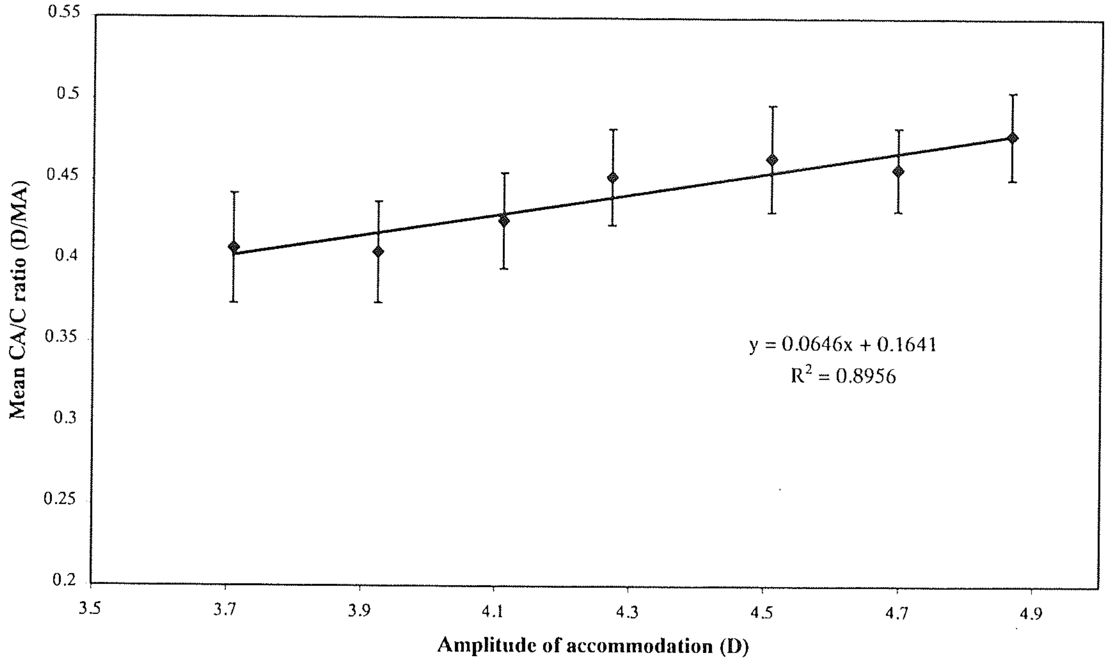

Figure 5.8 Graph showing the relationship between the mean CA/C ratio and the mean amplitude of accommodation over the two-year study period for the incipient presbyopes (n=28). Error bars represent ±1SEM.

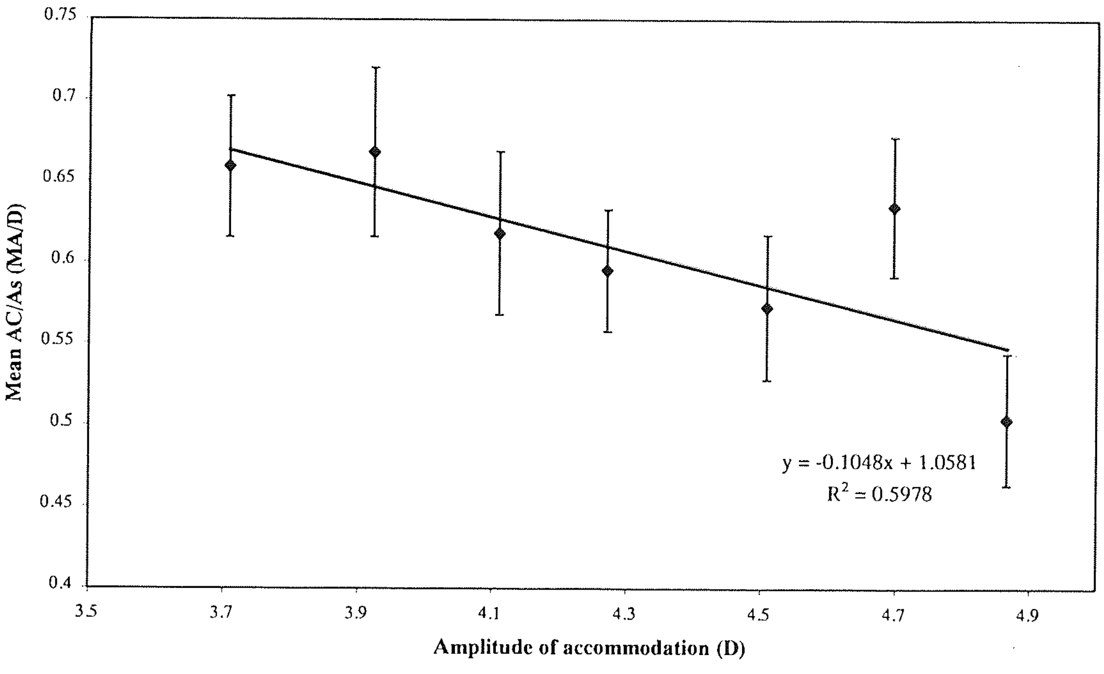

Figure 5.9 Graph showing the relationship between the mean stimulus AC/A ratio and the mean amplitude of accommodation over the two-year study period for the incipient presbyopes (n=28). Error bars represent ±1SEM.

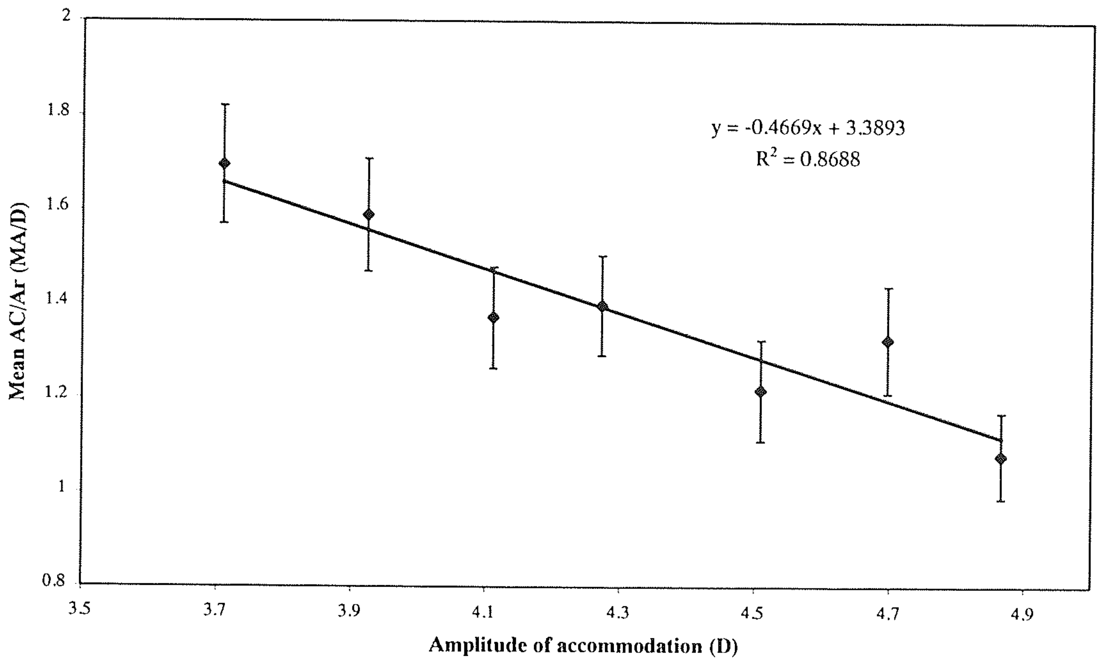

Figure 5.10 Graph showing the relationship between the mean response AC/A ratio and the mean amplitude of accommodation over the two-year study period for the incipient presbyopes (n=28). Error bars represent ±1SEM.

Caution should be exercised when attempting to draw conclusions from these graphs as to the longitudinal changes in the ratios. Although the correlation between the CA/C ratio and the amplitude of accommodation and the response AC/A ratio and amplitude of accommodation are statistically significant ($p<0.01$) it may be that due to the inter-correlation between the ratios themselves the strength of the individual relationships with amplitude is exaggerated. This method of analysis also does not take into account the variability of each mean data point, for example the size of the error bars (±1SEM) can be seen in the graphs plotted and in some graphs they are fairly large relative to the change in the variable over the study period.

In order to analyse the results in a longitudinal manner taking into account the inter-correlation between the various ratios a stepwise multiple regression analysis was performed on the data using Statview software. The analysis assessed the correlation between the change in amplitude of accommodation from the first to the last experimental session against the change in age, CA/C, AC/As, AC/Ar, TA and TV over that same period. This analysis found that none of the changes in the individual parameters were correlated with the magnitude of the change in the amplitude of accommodation.

Further analyses were undertaken using the same stepwise multiple regression analysis technique looking at each experimental session individually. For each experimental session the analysis selected which parameters were correlated with the amplitude of accommodation, taking into consideration inter-correlations. Table 5.1 shows which variables were selected as being correlated with amplitude of accommodation.

Session	Variable selected	r (cumulative)	r^2 (cumulative)	F ($p<0.001$ for all)	Variability in amplitude explained
1	Age	0.66	0.43	19.97	43%
	AC/Ar	0.77	0.59	18.09	16%
2	Age	0.68	0.46	21.86	46%
	AC/Ar	0.76	0.58	16.92	12%
3	Age	0.67	0.45	21.38	45%
	AC/Ar	0.75	0.56	15.72	11%
4	AC/Ar	0.72	0.52	27.81	52%
	Age	0.78	0.61	19.56	9%
5	Age	0.65	0.43	19.22	43%
	AC/Ar	0.74	0.55	15.54	12%
6	Age	0.69	0.47	23.21	47%
	CA/C	0.78	0.61	19.76	14%
	AC/Ar	0.84	0.70	18.43	9%
7	Age	0.70	0.48	24.29	48%
	CA/C	0.80	0.64	22.00	16%

Table 5.1 The results of a stepwise multiple regression analysis for each experimental session. The selected variables are those which correlate with the amplitude of accommodation.

The correlation between age and amplitude of accommodation has been discussed in chapter 4 and will not be discussed further here.

It can be seen from table 5.1 that at 6 of the 7 experimental sessions there was a significant correlation between amplitude of accommodation and AC/Ar. At each time of assessment the lower the amplitude of accommodation, the higher the response AC/A ratio. Figure 5.11 shows an example of the correlation found between amplitude of accommodation and AC/Ar. From the 7 sessions the mean increase in the response AC/A ratio with age was 0.33 MA/D (2.27^{Δ}/D) per dioptre of accommodation.

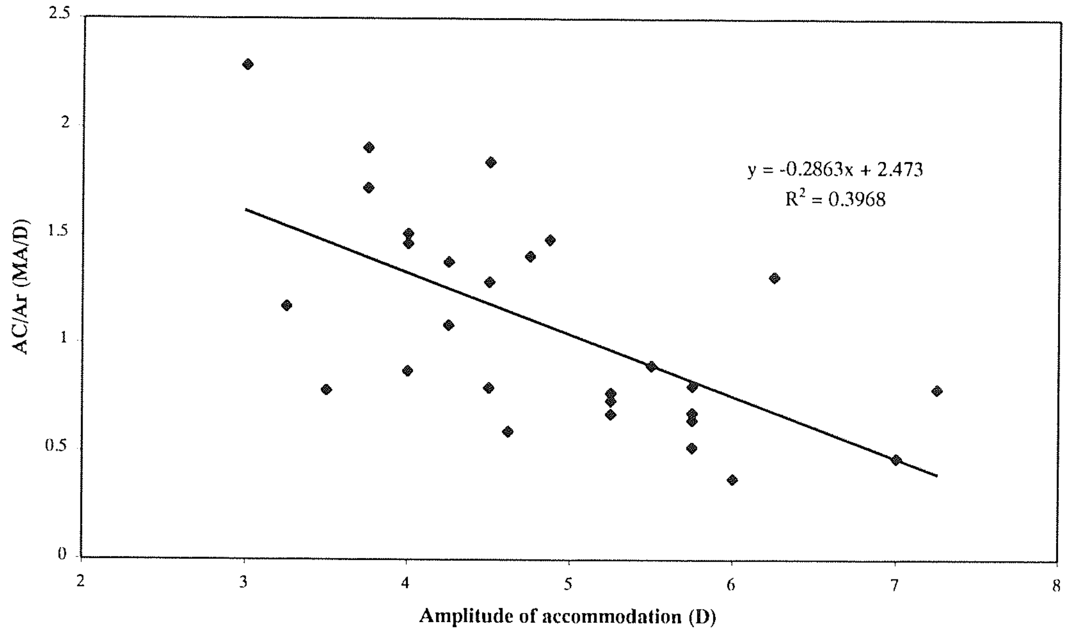

Figure 5.11 Graph showing the relationship between the response AC/A ratio and the amplitude of accommodation at the first experimental session for the incipient presbyopes (n=28).

Comparing the CA/C ratio to the amplitude of accommodation, there was a statistically significant correlation at each experimental session (figure 5.12 shows example).

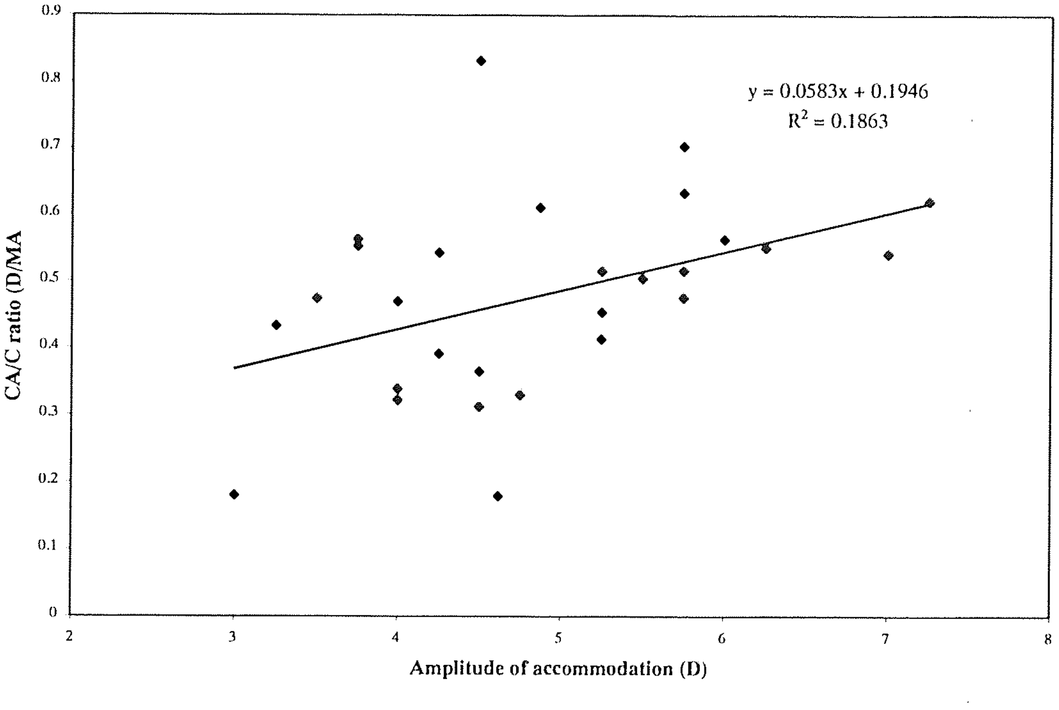

Figure 5.12 Graph showing the relationship between the CA/C ratio and the amplitude of accommodation at the first experimental session for the incipient presbyopes (r = 0.43 $p<0.05$) (n=28).

It is known however, that there is a relationship between the AC/A and CA/C ratios. Some researchers have reported that the two ratios are reciprocals (Fincham and Walton, 1957, Bruce *et al.*, 1995) whereas others have just reported that there is a trend for one to be high when the other is low (Rosenfield *et al.*, 1995a). Thus the significant correlations found between CA/C and amplitude of accommodation at each session, such as that in figure 5.12, may only appear significant because both are related to AC/Ar hence the need for the stepwise analysis. Using the stepwise multiple regression analysis the CA/C ratio was found to be correlated with the amplitude of accommodation at the last two experimental sessions only, with a mean decrease in the CA/C ratio of 0.097D/MA ($0.015D/^{\Delta}$) per dioptre of accommodation.

Using the stepwise multiple regression analysis there is no significant correlation between amplitude of accommodation and the stimulus AC/A ratio at any of the experimental sessions.

Reciprocal nature of CA/C and AC/A

It can be seen that as the response AC/A ratio increases with the reduction in the amplitude of accommodation there is a trend for the CA/C ratio to decline. In order to determine if there is any difference in the relationship between AC/Ar and CA/C as the amplitude of accommodation declines, an assessment was made of the relationship between the two parameters for each individual. The difference between the CA/C and the reciprocal of the AC/Ar was calculated, if the difference was zero the parameters were exact reciprocals. Figure 5.13 shows the difference in the ratios for each subject at the first experimental session against the amplitude of accommodation. The correlation was shown to be significant (Spearman Rho = -0.549, $p<0.01$) with the difference between the reciprocal of the AC/Ar ratio and the CA/C ratio becoming smaller with the decrease in the amplitude of accommodation. Negative values show that in the majority of cases the reciprocal of the AC/Ar exceeded the CA/C ratio.

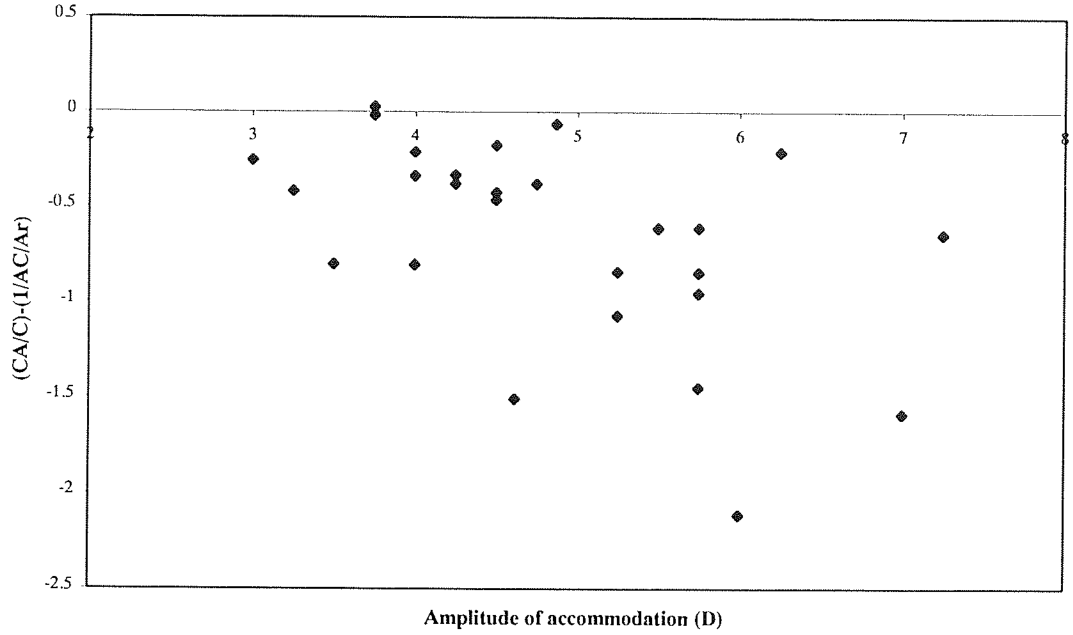

Figure 5.13 Graph showing the difference between the CA/C ratio and the reciprocal of the response AC/A ratio against amplitude of accommodation for the incipient presbyopes at the first experimental session (n=28).

Table 5.2 shows the mean difference in the ratios for the two subject groups at each experimental session.

Session	Mean difference in incipient presbyope group (±SEM)	Mean difference in younger subject group (±SEM)	t	p
1	-0.66 (±0.10)	-0.83 (±0.10)	0.99	0.33
2	-0.47 (±0.08)	-0.91 (±0.17)	2.65	<0.05
3	-0.53 (±0.06)	-0.67 (±0.09)	1.18	0.25
4	-0.45 (±0.12)	-1.34 (±0.32)	3.17	<0.01
5	-0.47 (±0.08)	-0.90 (±0.17)	2.49	<0.05
6	-0.37 (±0.08)	-0.82 (±0.20)	2.47	<0.05
7	-0.28 (±0.05)	-0.72 (±0.17)	3.41	<0.01

Table 5.2 Mean difference between the CA/C ratio and the reciprocal of the response AC/A ratio at each experimental session for the two subject groups.

It can be seen from table 5.2 that at 5 of the 7 experimental sessions there was a significant difference between the mean found for each group with the reciprocal of the AC/Ar exceeding the CA/C by more in the younger group. There also appears to be a trend in the incipient presbyope subject group for the value of the difference to become less with a variation from –0.66 at the first session to –0.28 at the last.

Gradient of the stimulus-response curve

The accommodative response measured for each accommodative stimulus, presented when assessing the AC/A ratio, can be used to analyse the gradient of the stimulus-response curve. It should be noted that these results were measured under conditions where the vergence loop was open. Table 5.3 shows the mean stimulus-response curve gradient found at each experimental session for each subject group. It can be seen that at every session there was a significant difference between the mean value in the two groups, with the gradient of the curve being substantially higher in the younger subject group.

Session	Mean gradient in incipient presbyope subject group (±SEM)	Mean gradient in younger subject group (±SEM)	t	p
1	0.51 (±0.04)	0.76 (±0.06)	-3.41	<0.01
2	0.53 (±0.04)	0.76 (±0.07)	-3.13	<0.01
3	0.52 (±0.04)	0.77 (±0.06)	-3.35	<0.01
4	0.49 (±0.04)	0.76 (±0.06)	-3.54	<0.01
5	0.50 (±0.04)	0.74 (±0.07)	-3.13	<0.01
6	0.47 (±0.04)	0.75 (±0.06)	-3.76	<0.001
7	0.43 (±0.03)	0.79 (±0.05)	-5.43	<0.001

Table 5.3 Mean gradient of the stimulus-response curve at each experimental session for the two subject groups.

It can be seen from table 5.3 that the mean gradient of the curve in the incipient presbyope group decreases slightly over the 7 experimental sessions although this trend is not statistically significant.

Analysing the gradient of the stimulus-response curve at each experimental session also shows a significant correlation with amplitude of accommodation. The correlation for the first session is shown in figure 5.14 and was shown to be significant (Spearman Rho = 0.498, p<0.01). Thus as the amplitude of accommodation declines the gradient of the stimulus-response curve under open-loop vergence conditions declines.

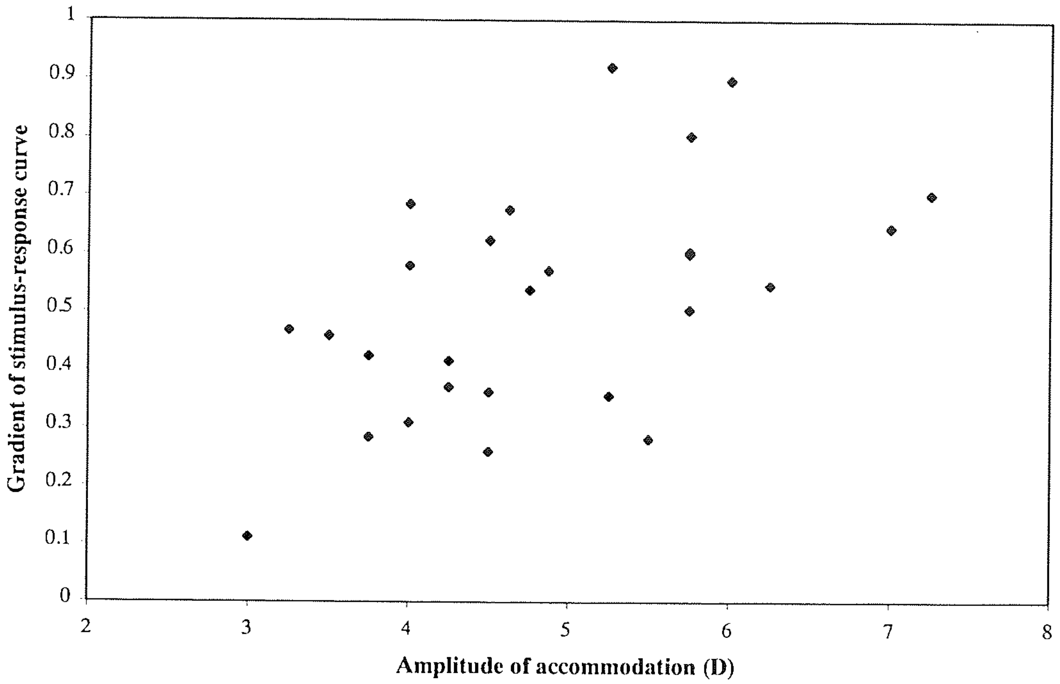

Figure 5.14 Graph showing the gradient of the stimulus-response curve against the amplitude of accommodation for the incipient presbyopes at the first experimental session (n=28).

5.4 DISCUSSION

The stimulus AC/A ratio has been found to be unrelated to the amplitude of accommodation. However, the stimulus AC/A ratio depends on the effort made by the subject to focus on the target and despite careful instruction this may vary between subjects and between experimental sessions. The response AC/A ratio however is a direct measure of the relationship between accommodation and vergence and thus will not be influenced by the effort that the subject makes. This may explain why, despite an increase in the response AC/A ratio, no increase was found in the stimulus AC/A as the amplitude of accommodation declined. The CA/C ratio has been shown to decline as the amplitude declines.

These changes with the decline in the amplitude of accommodation are evidence against the Hess-Gullstrand theory of presbyopia since they show that the innervation that produces convergence, no longer results in as much change in accommodation. These results thus support theories such as the Duane or Fincham theories where an increasing level of innervation is required to produce a change in accommodative response.

Thus when an older subject is presented with a near-target if the same effort is made to accommodate as when younger, a lower accommodative response will result and the target will appear blurred. With this same effort there will however be the same convergence response as before. If instead, additional effort is made in order to reduce the blurring of the target there will be an increase in the convergence response, since the additional innervation to accommodation will also cause a synkinetic increase in accommodative convergence. There are therefore several options that may allow the oculomotor system to achieve the least blurring of the target but without over-convergence.

It may be that there is a change in the relative contribution of the components of vergence with a decrease in proximal or tonic vergence. If one of these components gradually declined with age it would permit the use of additional accommodative effort to try to reduce the blur of a target because the resulting increase in accommodative convergence could still be managed. This will be investigated further in chapter 6.

It could be that instead, the additional accommodative convergence is compensated for by the fusional convergence component, with the ability to cope with a more convergent position. This may be evident as a change in the vergence adaptation ability of the oculomotor system as it may become better at handling more convergent disparities. Longitudinal variations in vergence adaptation will be investigated in chapter 7.

If there are no changes in any of the oculomotor components as the amplitude of accommodation declines, it may be that instead of over-converging the oculomotor system's response to a near-target becomes limited by the vergence position. The choice may be made to limit the convergence position in order to prevent diplopia or asthenopic symptoms, despite leaving an increasingly blurred target. This would be supported by the finding of a decreasing stimulus-response curve gradient with age, since to each accommodative stimulus there would be a decreasing accommodative response as the response was limited by the convergence that could be tolerated. A decrease in the stimulus-response curve gradient was reported by Ramsdale and Charman (1989) although Mordi and Ciuffreda (1998) found no change with age. The stimulus-response curves measured in this study were under open-loop vergence conditions and so are not directly comparable. The finding in Chapter 4 of a decreasing accommodative response to a 2.5D stimulus, during the reading task undertaken for the accommodative adaptation experiment, is evidence for a decreased accommodative response with age, even when the stimulus is within the amplitude of accommodation.

The rate of decline in the CA/C ratio appears to be slower than the rate of increase in the response AC/A with age, hence the finding of the ratios becoming more reciprocally related as the amplitude of accommodation declines. This could again suggest the increasing importance of the convergence accommodation cross-link in the oculomotor system rather than accommodative convergence. The CA/C ratio also became more correlated with the amplitude of accommodation at the later stages of the experimental study period which could again be indicative of convergence taking on a more critical role in managing the re-calibration of the oculomotor system caused by the decline in accommodative amplitude.

CHAPTER 6

PROXIMAL AND TONIC VERGENCE DURING INCIPIENT PRESBYOPIA

6.1 INTRODUCTION

The need for a re-calibration in the oculomotor response to a near target during incipient presbyopia has been described. Chapter 5 has described several ways in which this may be achieved. A decrease in proximal or tonic vergence response may assist the oculomotor system, since it will permit the increased accommodative convergence response that will accompany further accommodation.

Ciuffreda *et al.* (1993) and Rosenfield *et al.* (1995b) both undertook cross-sectional studies to investigate the effect of age on tonic vergence (TV) (see section 2.7.2). Although a small increase in TV was found (more convergent position) by Ciuffreda *et al.* when comparing the pre- and post-presbyopic subjects, no progressive age-related change in TV was identified. Rosenfield *et al.* found that tonic vergence declined significantly with age at a rate of 0.11deg/year (approximately 0.032MA/year). Both studies were limited due to their cross-sectional nature.

Section 2.7.1 describes several studies that have analysed the change in proximal vergence with age but the results are inconclusive. Studies have shown an increasing (Nuzzi *et al.*, 1982 cited by Hokoda *et al.*, 1991), decreasing (Schapero and Nadell, 1957) or unchanging proximal vergence contribution (Sheedy and Saladin, 1975; Wick, 1985; Hokoda *et al.*, 1991). However, all the studies were again of cross-sectional design.

This study assessed the tonic vergence, proximal vergence and distance heterophoria of the incipient presbyope and younger subject groups over the two-year study period.

6.2 METHODS

Tonic vergence

Tonic vergence was measured using an adaptation of the 'flashed' Maddox Rod technique described in section 3.3.1. Modifications were made to the program that was used for the prism adaptation experiments so that measurements of the vergence position of the eyes could be made after an 8-minute period in the dark.

The subject was required to place their chin in the chin rest and head against the forehead rest so that the *Blitz* electronic shutter was in front of the right eye. When illuminated the left eye was able to see a test chart at 5m, the right eye was able to see the Maddox streak when the shutter was opened (see figure 6.1). A spotlight was located in the centre of the chart either side of which was a tangent scale with numbers on that were visible when the spotlight was lit.

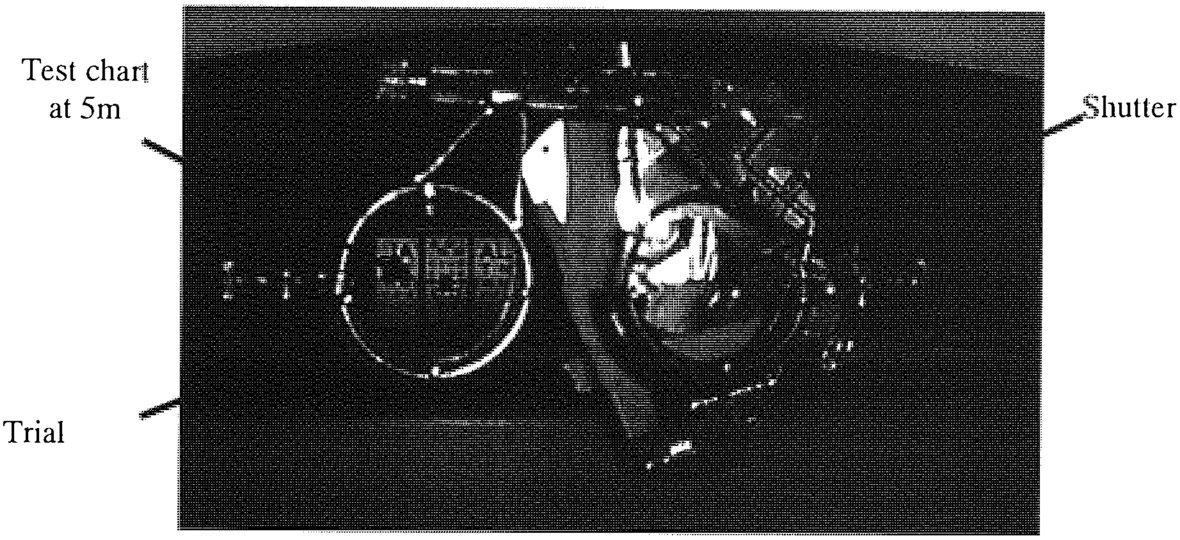

Figure 6.1 Experimental set-up when performing "flashed" Maddox Rod technique as seen by the subject. The right eye is positioned behind a shutter. The left eye is able to see the test chart at 5m.

After 8 minutes of dark viewing, to ensure there were no fusional, proximal or accommodative stimuli to vergence and that any slow fusional response had decayed, the subject was instructed to look straight ahead. The shutter was then opened for 125ms with the subject observing the Maddox Rod (positioned behind the shutter) as the spotlight was simultaneously lit. The subject was asked to report the position of the Maddox streak on the tangent scale and this was a direct measurement of the tonic vergence position of the eyes in prism dioptres. This measurement was then converted into metre angles.

Distance heterophoria

The 'flashed' Maddox Rod technique was also used to assess the distance heterophoria position of the eyes, in order to assess whether any change in this position occurred over the two-year study period. It is known that distance heterophoria is related to, although different from, the tonic vergence position (O'Shea *et al.*, 1988; Rosenfield and Ciuffreda, 1990a). To measure the heterophoria, three cycles of the presentation routine, with 15 seconds of binocular viewing followed by 15 seconds of occlusion and a subsequent Maddox Rod presentation, were undertaken (as described in section 3.3.1). The average distance heterophoria value was then calculated and converted to metre angles.

Proximal vergence (PC/T ratio)

The gradient AC/A ratio was measured at the first and last experimental sessions (0 months and 24 months). With the subject wearing their distance refraction (most positive, binocularly balanced) the near heterophoria was measured using the Maddox wing, the subject reported the position of the arrows to the nearest 0.5^{Δ}. The horizontal heterophoria was then measured after the introduction of +1.00DS and then +2.00DS in front of both eyes (see Appendix 5). At all times the subject was instructed to maintain focus on the numbers and arrows of the Maddox wing. The gradient AC/A ratio was then found by calculating the gradient of the slope when plotting heterophoria against accommodative stimulus.

At the first and last session the distance heterophoria was also measured using the Maddox Rod with the heterophoria recorded to the nearest 0.5^{Δ}. The inter-pupillary distance (PD) of the subject was measured using a millimetre rule in the routine manner (Bennett and Rabbetts, 1989).

The PC/T ratio (see section 1.5.2.a) was found by subtracting the gradient AC/A ratio from the AC/A ratio found by the calculation method using the measures of distance and near heterophoria recorded. The ratio was then converted into MA/D by dividing the ratio in $^{\Delta}$/D by the subjects PD in cm.

6.3 RESULTS

Tonic vergence

Tonic vergence was measured at the first experimental session and then at the second (4 months), fourth (12 months) and final (24 months) sessions. There was found to be no significant correlation between tonic vergence and the amplitude of accommodation at any experimental session in either subject group. Over the two-year period using the stepwise multiple analysis (as detailed in Chapter 5) there was also found to be no correlation between the change in tonic vergence and the decline in the amplitude of accommodation.

Table 6.1 shows the mean TV for each of the subject groups on each occasion of assessment. A significant difference was found between the mean tonic vergence position of the two groups at each of the experimental sessions.

Session	Mean TV in incipient presbyope subject group (MA) (±SEM)	Mean TV in younger subject group (MA) (±SEM)	t	p
0 months	0.13 (±0.04)	0.29 (±0.05)	-2.27	<0.05
4 months	0.15 (±0.05)	0.35 (±0.06)	-2.13	<0.05
12 months	0.15 (±0.05)	0.38 (±0.09)	-2.25	<0.05
24 months	0.14 (±0.04)	0.37 (±0.08)	-2.78	<0.05

Table 6.1 Mean TV on each assessment occasion for the two subject groups. All values are convergent positions.

Distance heterophoria

The distance heterophoria was assessed at the first experimental session and then at the second (4 months), fourth (12 months) and final (24 months) sessions. There was no correlation between the amplitude of accommodation and the distance heterophoria at any of the sessions for either subject group. The mean distance heterophoria was calculated for each subject group on each occasion and are shown in table 6.2.

Session	Mean distance heterophoria in incipient presbyope subject group (MA) (±SEM)	Mean distance heterophoria in younger subject group (MA) (±SEM)	t	p
0 months	-0.022 (±0.04)	0.132 (±0.05)	-2.21	<0.05
4 months	-0.036 (±0.04)	0.116 (±0.06)	-2.19	<0.05
12 months	-0.064 (±0.03)	0.163 (±0.06)	-3.38	<0.01
24 months	-0.014 (±0.03)	0.158 (±0.06)	-2.83	<0.01

Table 6.2 Mean distance heterophoria on each assessment occasion for the two subject groups. Negative values represent exophoric deviations; positive values are esophoric deviations.

It can be seen from table 6.2 that there was a significant difference in the mean distance heterophoria of the two subject groups at each assessment. The younger subject group had an overall mean distance heterophoria of 0.14MA (0.89^{Δ}) esophoria whereas the incipient presbyope group had an overall mean of 0.03MA (0.23^{Δ}) exophoria.

Proximal vergence

Table 6.3 shows the mean gradient AC/A, heterophoria AC/A and the proximal vergence calculated from the ratios.

Subject group	Visit	Gradient AC/A (MA/D) (±SEM)	Heterophoria AC/A (MA/D) (±SEM)	Proximal vergence (MA/D) (±SEM)
Incipient presbyopes	first	0.55 (±0.06)	0.93 (±0.02)	0.38 (±0.07)
	last	0.50 (±0.07)	0.91 (±0.04)	0.41 (±0.08)
Young	first	0.50 (±0.07)	0.95 (±0.04)	0.44 (±0.08)
	last	0.51 (±0.07)	0.97 (±0.04)	0.46 (±0.08)

Table 6.3 Mean gradient AC/A ratio, heterophoria AC/A ratio and proximal vergence of each subject group on the two occasions it was assessed.

There was no significant difference between the mean proximal vergence at the first and last sessions in either the incipient presbyopes or the younger subjects (t=-0.875, p>0.05 and t= -0.798, p>0.05 respectively).

There was also found to be no significant difference between the mean proximal vergence found in the younger group and the incipient presbyope group on either the first or last occasion (t=-0.755, p>0.05 and t=-0.507, p>0.05 respectively).

6.4 DISCUSSION

The finding of no age-related change in tonic vergence position with age is in agreement with the findings of Ciuffreda *et al.* (1993). However, when comparing the two subject groups, there was a significant difference between the two, with a less convergent tonic vergence position in the older subject group. This finding conflicts with that of Ciuffreda *et al.* who found a more convergent tonic vergence position in their presbyopic subject group when compared to the pre-presbyopes. However Rosenfield *et al.* (1995b) did find a progressive decrease in tonic vergence position with age.

The distance heterophoria has also been found to show no correlation with amplitude of accommodation. There was however a significant difference between the mean distance heterophoria of the two subject groups.

Although tonic vergence and distance heterophoria are not equivalent measures they are thought to be related (O'Shea *et al.*, 1988; Rosenfield and Ciuffreda, 1990a). O'Shea *et al.* approximate the difference between TV and distance heterophoria to be around 2^{Δ} (0.33MA), in this study the difference is around 1.3^{Δ} (0.22MA). Therefore the significant difference in distance heterophoria between the two groups supports the finding of a difference in tonic vergence between the two groups.

Previous studies have produced conflicting evidence as to the relationship between the distance heterophoria and age (Eames, 1933; Hirsch *et al.*, 1948; Scobee and Green, 1948). The studies also only show very slight increases or decreases in the deviation with age and are only just statistically significant.

The finding of a less convergent tonic vergence and distance heterophoria position in the older subject group is in agreement with the findings of Rosenfield *et al.* (1995b) that there is a decline in tonic vergence position with age. However, if a difference does exist Ciuffreda *et al.* (1993) calculate that even a change in position of the magnitude they found (approximately 0.37MA) would have relatively little influence on the overall vergence response. The impact that a change in tonic vergence position would have on the overall vergence response will be discussed further in Chapter 8 using computer simulations of the accommodation and vergence mechanisms.

The assessments of the PC/T ratio have shown that there is no age or amplitude of accommodation related change in proximal vergence. Thus with unchanging magnitudes of tonic and proximal vergence further investigation is required to determine the means by which the oculomotor system is able to cope with the decline in the amplitude of accommodation.

CHAPTER 7

THE AFFECT OF AGE ON VERGENCE ADAPTATION

7.1 INTRODUCTION

Chapter 5 demonstrated that with increasing age there was an increasing accommodative convergence response when attempting to maintain the same accommodative response to allow clear-focus on a near-vision target. It was proposed that this might be overcome by an increased fusional vergence response. For an increased fusional vergence response to be sustained it is the slow fusional response that would need to be augmented since the fast response is, by definition, short-lived.

Vergence adaptation represents slow, tonic vergence replacing the initial reflex vergence response. Thus if there is an increased demand on fusional vergence to cope with a change in the overall vergence response, it would be expected that there would be a change in the vergence adaptation ability of the oculomotor system. An increase in adaptation, particularly to vergence stimuli demanding a more divergent position would be expected, since the increase in accommodative convergence component of vergence will lead to an eso-deviation (over-convergence).

Previous studies have shown vergence adaptation to actually decline with age (Winn *et al.* 1994a; Rosenfield *et al.* 1995b) which means that as a subject gets older the rate and extent to which the oculomotor system can cope with changes in vergence demand reduces. Both studies were cross-sectional in nature and the study of Rosenfield *et al.* was only concerned with the adaptation that occurred when converging to a near-target so will not have considered disparities requiring divergence. The study of Winn *et al.* did look at adaptation to both base-in and base-out prism and so analysed the change in ability to cope with both convergent and divergent disparities and found a decrease in both.

This study was thus aimed at investigating vergence adaptation to both base-in and base-out prism, analysing subjects representing a cross-section of ages over a two-year longitudinal study period.

7.2 METHODS

The prism adaptation of the 28 incipient presbyopes and 10 younger subjects was assessed on 4 occasions over the 2-year study period. An assessment of adaptation to 6^{Δ} base-out and base-in was made at the 0, 4, 12 and 24 month visits.

The adaptation was assessed using the "Flashed" Maddox Rod technique as described in sections 1.10.4 and 3.3.1 and represented graphically in figure 7.1.

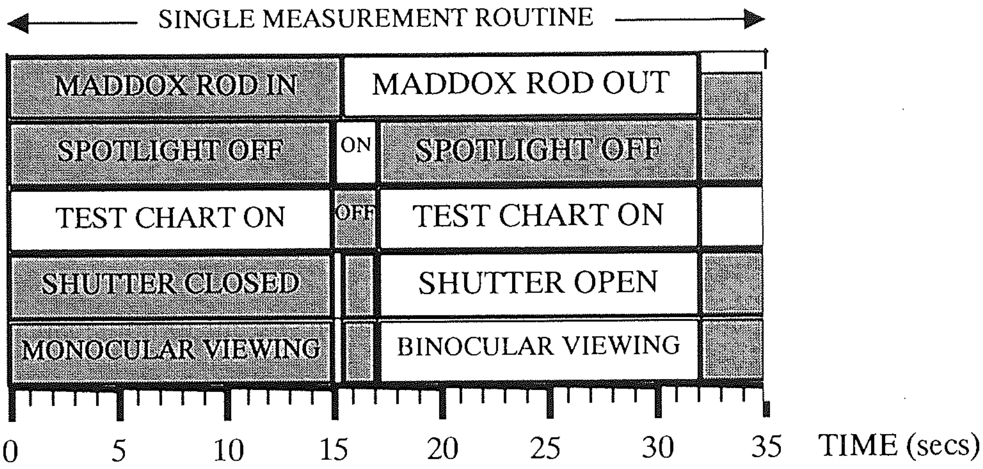

Figure 7.1 Diagram to show the experimental routine for one measurement of heterophoria.

Initially, three baseline heterophoria values were taken. For each there was 15 seconds of binocular viewing followed by 15 seconds of monocular occlusion and then an assessment of the Maddox streak position. At each presentation the subject reported the position of the Maddox streak to the nearest 0.25^{Δ}.

A 6^{Δ} prism was then inserted into the trial frame in front of the right eye either base-in or base-out. The next assessment of heterophoria followed 15 seconds of monocular occlusion and was thus prior to any binocular viewing and hence prior to any adaptation. A routine of 15 seconds of binocular viewing to allow adaptation followed by 15 seconds of monocular occlusion prior to the assessment of heterophoria then binocular viewing again continued for a total of 225 seconds of binocular viewing (15 readings). The prism was then removed and the routine continued for a further 135 seconds (10 readings), representing the recovery from the adaptation. The subject was constantly encouraged to read the letters of the test chart to the smallest line keeping the letters clear and single.

At each visit an assessment of both base-out and base-in prism adaptation was made, but the experiments were separated by a minimum of 15 minutes to ensure that the decay of the vergence adaptation from the first experiment was complete (Wolf *et al.*, 1987; Rosenfield *et al.*, 1995c). Figure 7.2 shows the experimental set-up used in the assessment of prism adaptation.

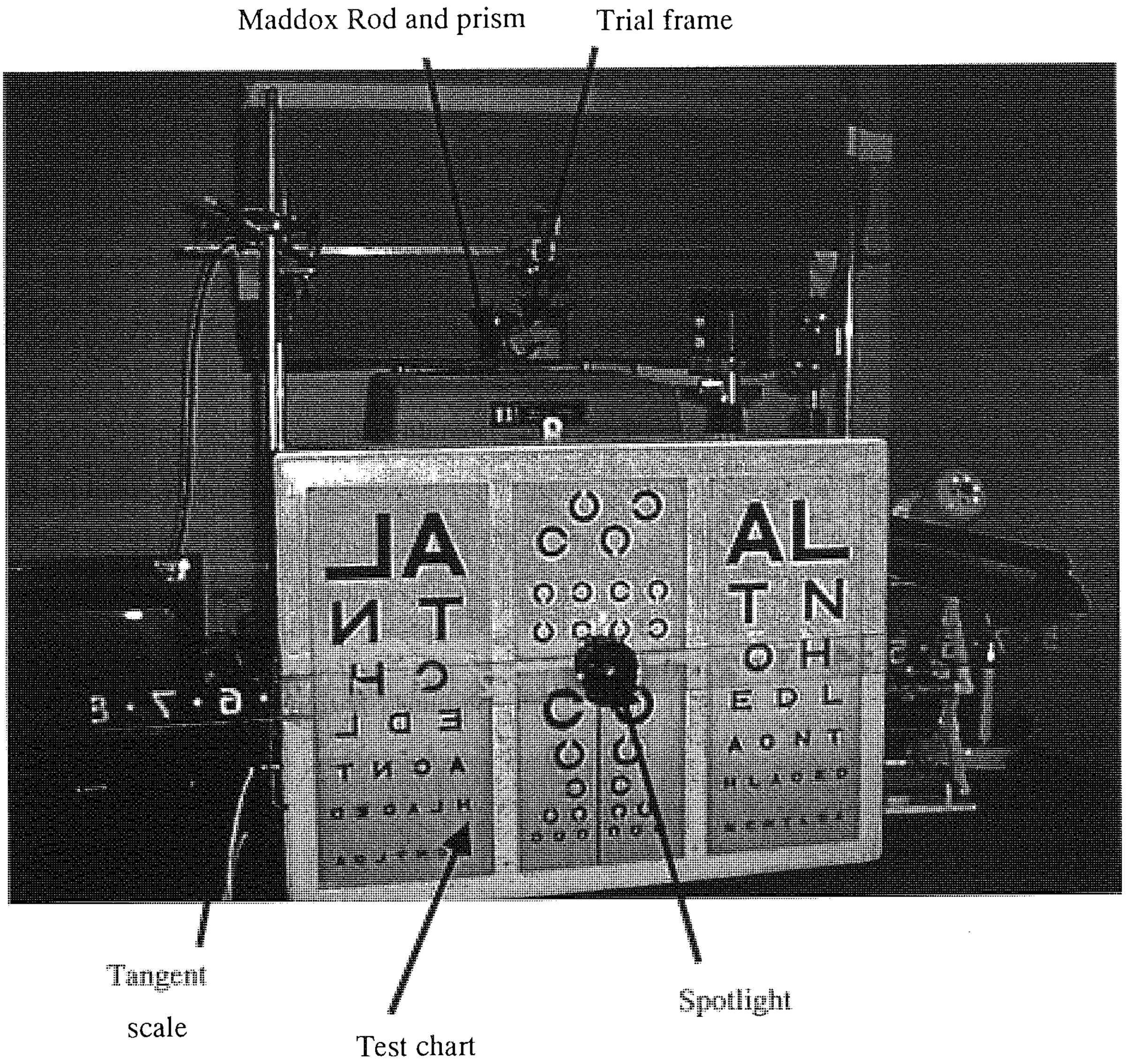

Figure 7.2 Experimental set-up for assessing prism adaptation. The subject sat behind the trial frame viewing the test chart via a mirror located 2.75m ahead.

7.3 RESULTS

The prism adaptation to 6^{Δ} base-out was assessed for all 28 subjects. However, for the base-in adaptation 6 subjects were unable to maintain single vision through the prism at every assessment occasion and thus only 22 subjects are included in the data analysis for base-in adaptation.

The heterophorias that were measured were converted from prism dioptres to metre angles by dividing the values by the subject's PD in cm. For each subject on each assessment occasion a graph could be drawn of the prism adaptation and a typical example is shown in figure 7.3.

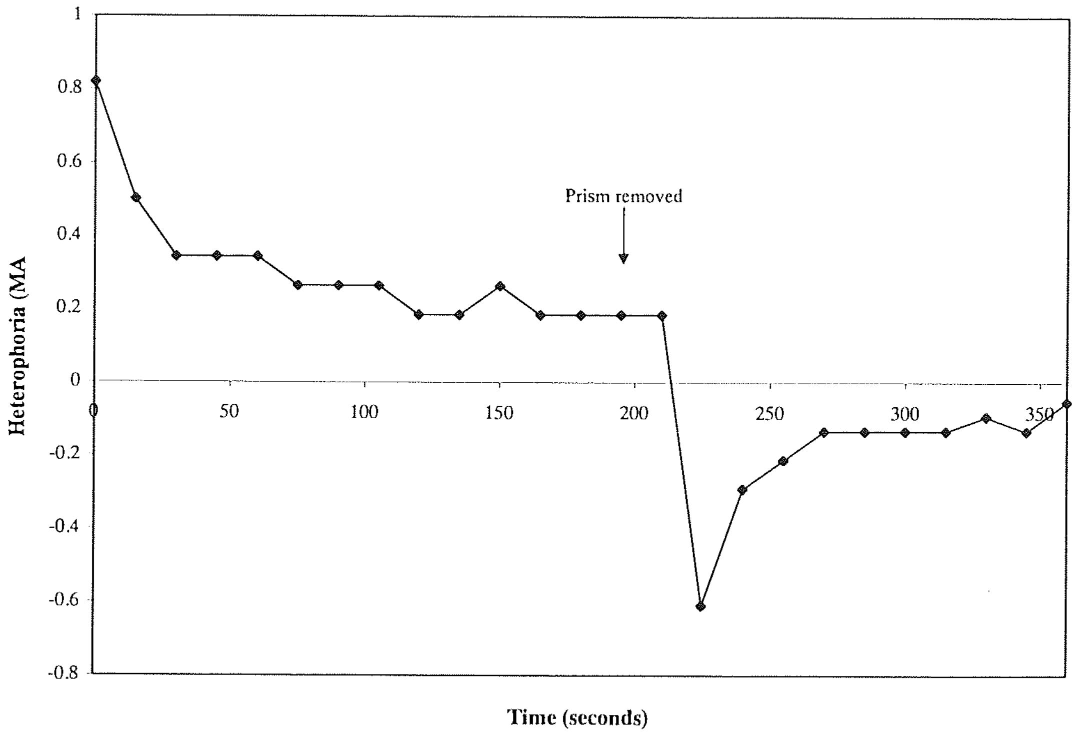

Figure 7.3 Adaptation and recovery for 6^{Δ} base-out prism for subject JS at first experimental session.

For each subject the heterophoria (in MA) at 15 seconds was subtracted from the induced heterophoria (due to the prism introduced) in order to calculate the degree of adaptation that had occurred after 15 seconds. This was repeated for the heterophoria after 210 seconds of binocular viewing. Thus the greater the magnitude of these values, the more the subject had adapted.

Cross-sectional analysis

In order to assess the change in the rate and extent of vergence adaptation with age a cross-sectional analysis of the incipient presbyopes was made. The relationship between amplitude of accommodation and the adaptation after the first 15 seconds of binocular viewing and after 210 seconds of adaptation was investigated.

At each experimental session, there was found to be no significant correlation between amplitude of accommodation and the adaptation after 15 seconds or 210 seconds for either base out or base in adaptation.

Longitudinal analysis

To analyse the data longitudinally, graphs were drawn of the mean heterophoria throughout the adaptation and recovery period for each experimental session. Figures 7.4 and 7.5 show the mean adaptation to 6^{Δ} base-out and base-in respectively. Error bars (SEMs of the order of ±0.01 to ±0.04 MA) have not been included on these graphs because they would prevent the data points from being distinguished from each other.

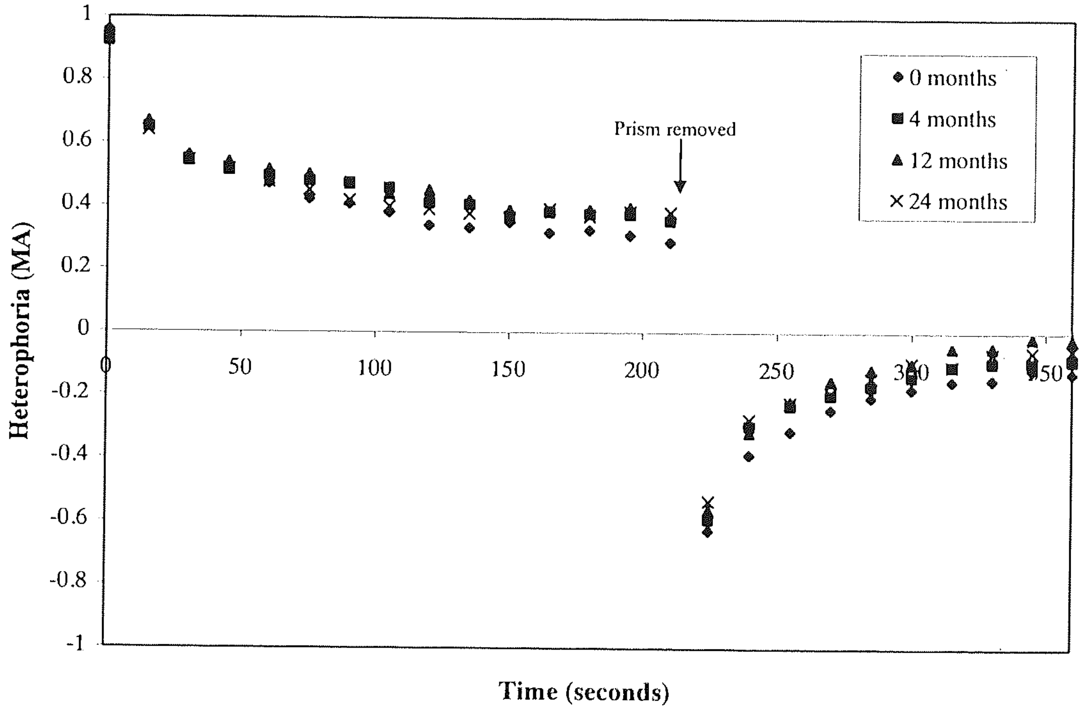

Figure 7.4 Mean prism adaptation to 6^{Δ} base-out for the incipient presbyope group (n=28).

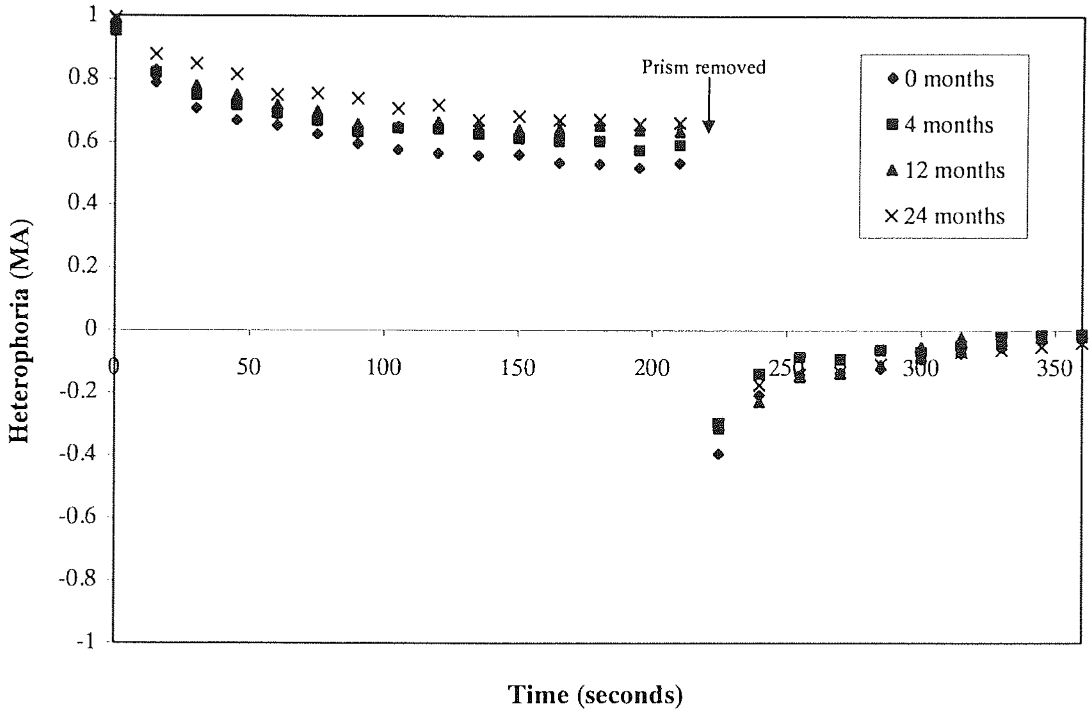

Figure 7.5 Mean prism adaptation to 6^{Δ} base-in for the incipient presbyope group (n=22).

From figure 7.4 it can be seen that there is a decrease in the adaptation to base-out prism over the two year-period and the difference between the adaptation at the first and last sessions was found to be statistically significant (t=2.925 $p<0.01$). The mean adaptation at the first and last sessions at 15 seconds was not found to be significantly different.

From figure 7.5 it can be seen that there was a gradual decrease in adaptation to base-in prism over the study period. The difference in mean adaptation at both 15 and 210 seconds was found to be significant (t=2.819 $p<0.01$, t=3.012, $p<0.01$) indicating that both the rate and final level of adaptation declines with age.

Figures 7.6 and 7.7 show the mean adaptation to the base-out and base-in prism for the younger subject group. Error bars (SEMs of the order of ±0.015 to ±0.05 MA) have not been included on these graphs because they would prevent the data points from being distinguished from each other.

It can be seen there was a difference in the rate and degree of adaptation over the two-year period for the base-out prism that was shown to be statistically significant (t=2.417 $p<0.05$). There was no significant difference in adaptation to the base-in prism.

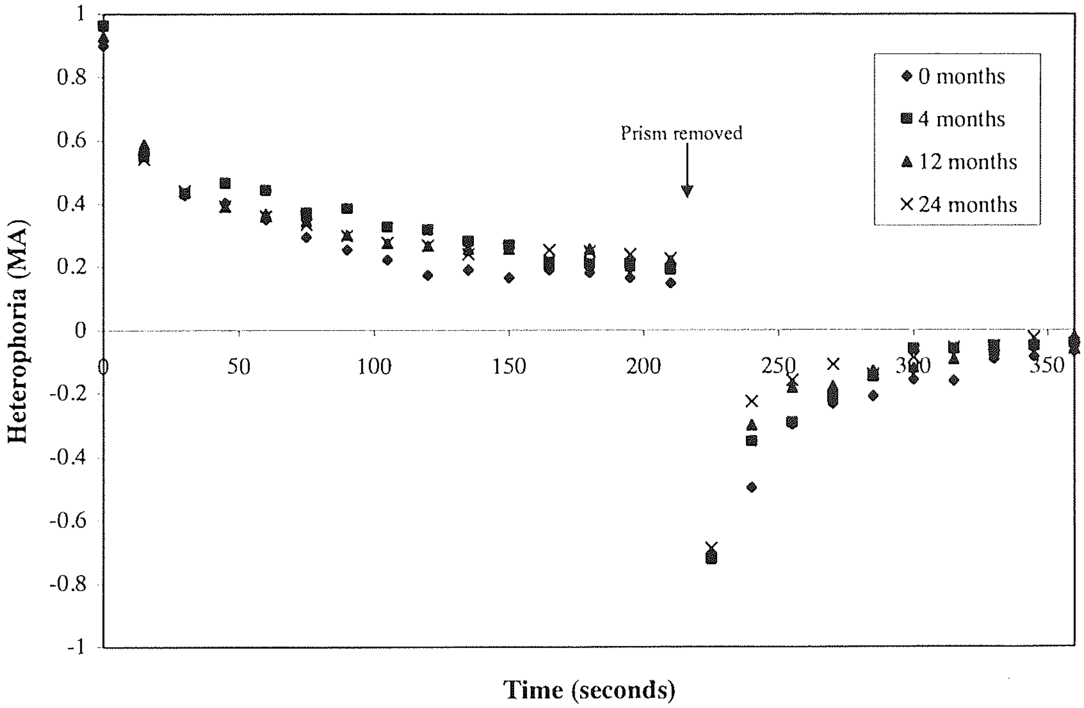

Figure 7.6 Mean prism adaptation to 6^{Δ} base-out for the younger subject group (n=10).

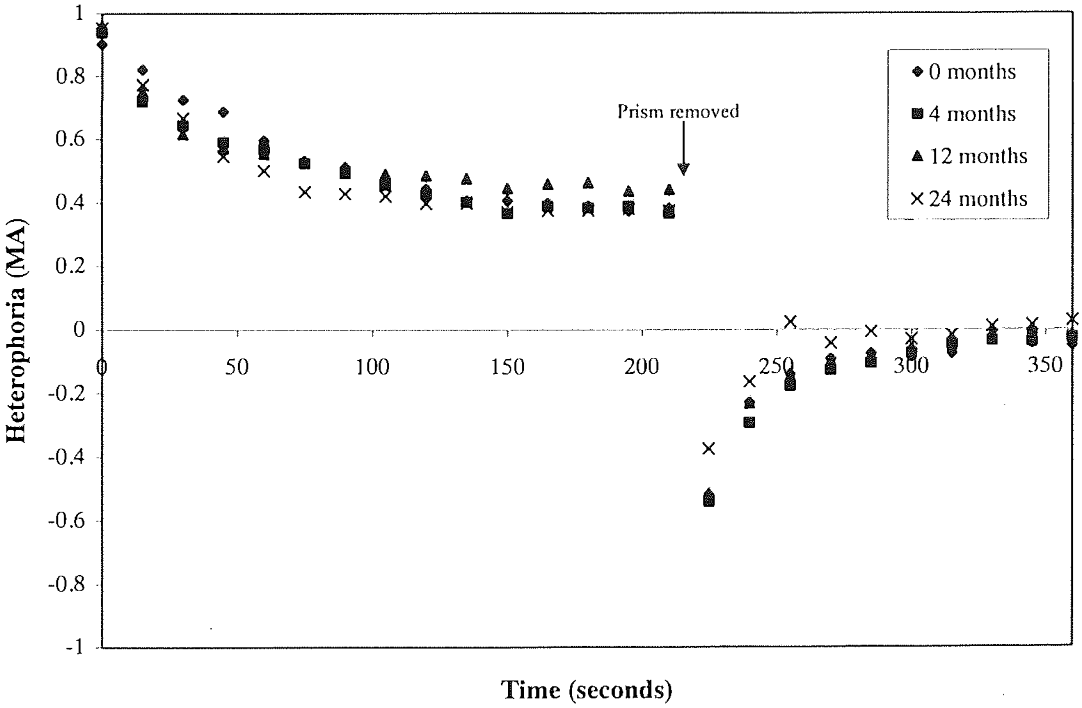

Figure 7.7 Mean prism adaptation to 6^{Δ} base-in for the younger subject group (n=10).

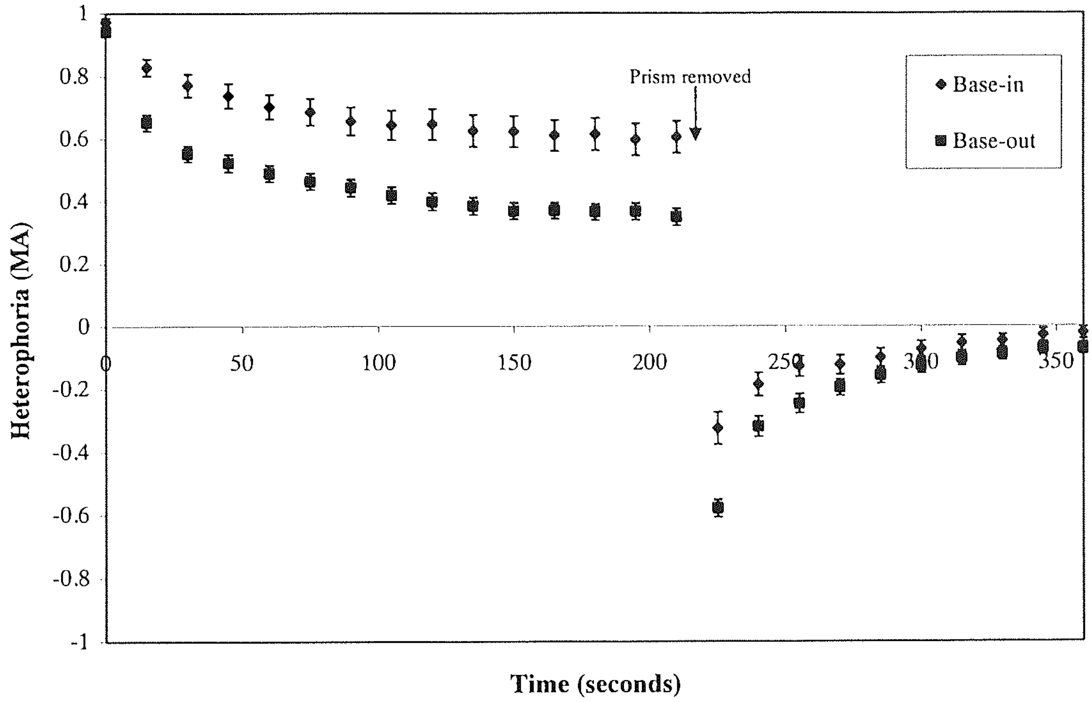

Figure 7.8 Mean prism adaptation for the incipient presbyope subject group (n=22). Error bars represent ±1SEM.

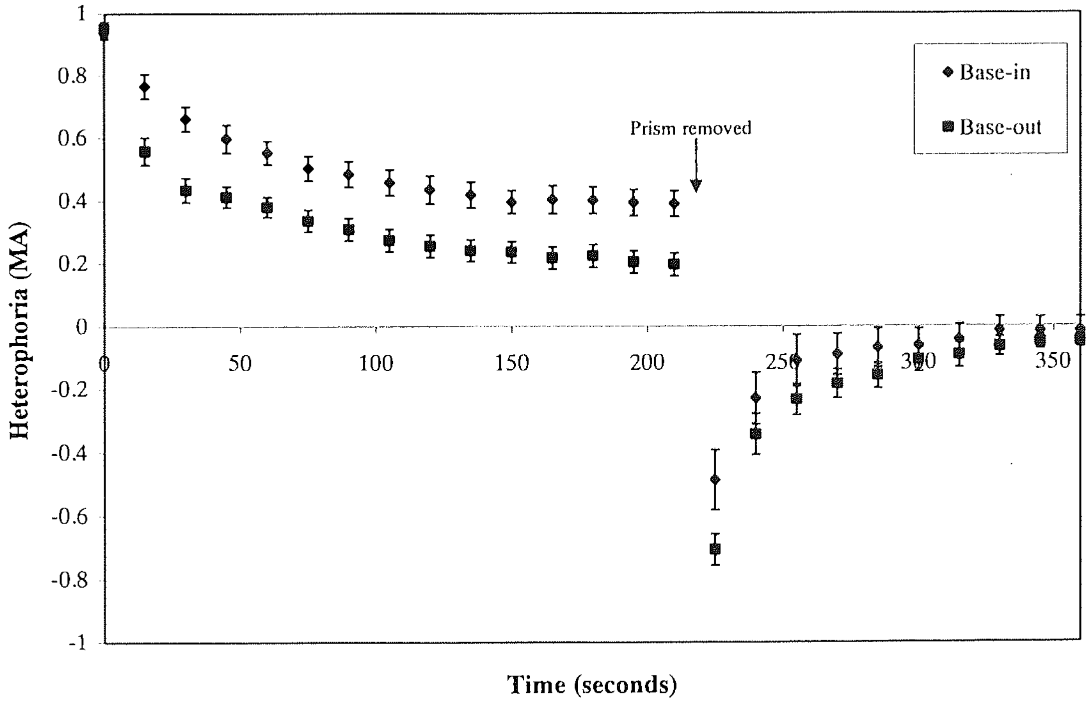

Figure 7.9 Mean prism adaptation for the younger subject group (n=10). Error bars represent ±1SEM.

Figures 7.8 and 7.9 show the mean adaptation to base-out and base-in prism for the incipient presbyope and young subject groups respectively. It was found that there was a significant difference in the rate and extent of adaptation to base-out and base-in prism at each experimental session for both subject groups.

Comparison between the two subject groups

Tables 7.1 to 7.4 show the mean adaptation found after 15 and 210 seconds of binocular viewing for each subject group at each experimental session for the two prism directions.

Session	Mean adaptation in incipient presbyope subject group (MA) (±SEM)	Mean adaptation in younger subject group (MA) (±SEM)	t	p
0 months	0.30 (±0.0.3)	0.41 (±0.05)	-1.889	0.07
4 months	0.31 (±0.0.3)	0.42 (±0.05)	-2.112	<0.05
12 months	0.28 (±0.02)	0.38 (±0.04)	-2.591	<0.05
24 months	0.31 (±0.03)	0.43 (±0.05)	-2.293	<0.05

Table 7.1 Mean adaptation after 15 seconds viewing through 6^{Δ} base-out and the significance of the difference in the group means.

Session	Mean adaptation in incipient presbyope subject group (MA) (±SEM)	Mean adaptation in younger subject group (MA) (±SEM)	t	p
0 months	0.64 (±0.03)	0.82 (±0.03)	-3.114	<0.01
4 months	0.58 (±0.03)	0.78 (±0.05)	-3.927	<0.001
12 months	0.56 (±0.02)	0.75 (±0.03)	-4.02	<0.001
24 months	0.55 (±0.03)	0.75 (±0.05)	-3.960	<0.001

Table 7.2 Mean adaptation after 210 seconds viewing through 6^{Δ} base-out and the significance of the difference in the group means.

Session	Mean adaptation in incipient presbyope subject group (MA) (±SEM)	Mean adaptation in younger subject group (MA) (±SEM)	t	p
0 months	0.17 (±0.02)	0.15 (±0.04)	0.498	0.62
4 months	0.15 (±0.03)	0.25 (±0.03)	-2.365	<0.05
12 months	0.13 (±0.02)	0.22 (±0.04)	-1.941	0.06
24 months	0.09 (±0.03)	0.20 (±0.05)	-1.945	0.06

Table 7.3 Mean adaptation after 15 seconds viewing through 6^{Δ} base-in and the significance of the difference in the group means.

Session	Mean adaptation in incipient presbyope subject group (MA) (±SEM)	Mean adaptation in younger subject group (MA) (±SEM)	T	p
0 months	0.41 (±0.05)	0.59 (±0.05)	-2.339	<0.05
4 months	0.36 (±0.05)	0.60 (±0.04)	-3.025	<0.01
12 months	0.31 (±0.04)	0.53 (±0.04)	-3.164	<0.01
24 months	0.30 (±0.04)	0.60 (±0.06)	-3.401	<0.01

Table 7.4 Mean adaptation after 210 seconds viewing through 6^{Δ} base-in and the significance of the difference in the group means.

It can be seen from table 7.2 and 7.4 that there was a significant difference between the two groups in the degree of adaptation that occurred to both base-in and base-out prism. The difference in adaptation at 15 seconds was statistically significant at 3 of the 4 experimental sessions for the base-out prism, but at only 1 session for the base-in prism. The rate of adaptation also appears to be different between the two groups when analysing graphs such as 7.10 and 7.11 which show the mean adaptation for the two groups to base-out and base-in prism respectively.

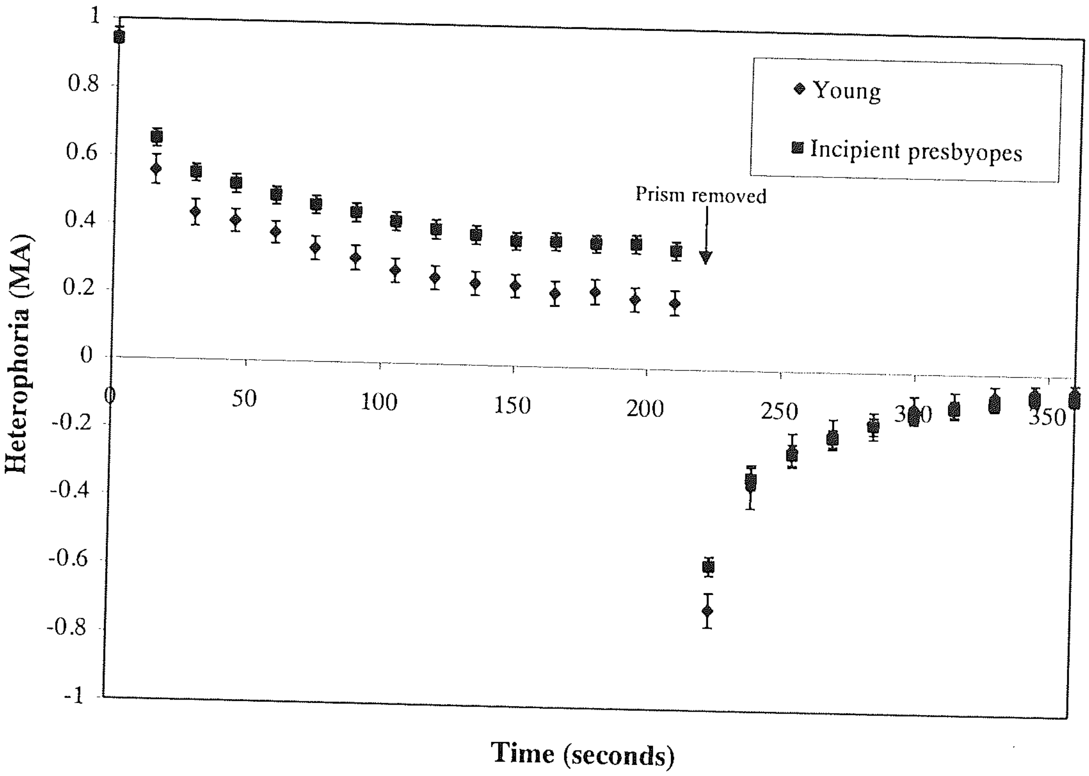

Figure 7.10 Mean adaptation to 6^{Δ} base-out for the two subject groups. Error bars represent ±1SEM.

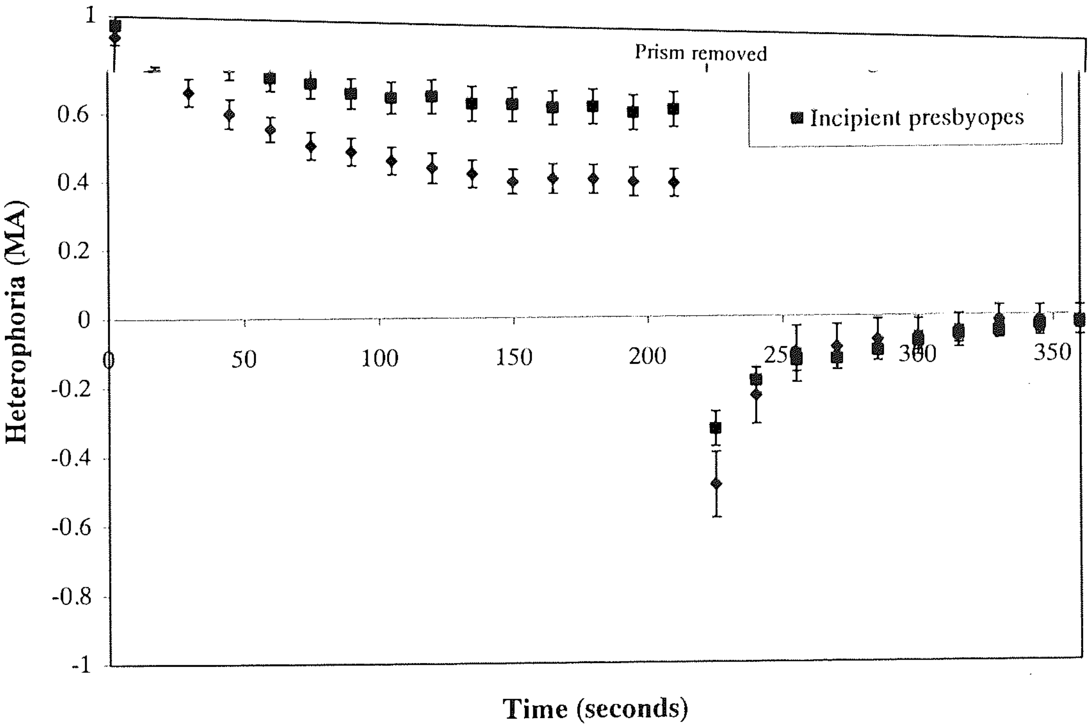

Figure 7.11 Mean adaptation to 6^{Δ} base-in for the two subject groups. Error bars represent ±1SEM.

7.4 DISCUSSION

The cross-sectional analysis did not show any statistically significant correlation between amplitude of accommodation and the degree of adaptation.

The results of the analysis did however show that there was a statistically significant decline in the degree of adaptation over the longitudinal study period. From graphical analysis there also appears to be a decrease in the rate of adaptation with age, although there was no statistically significant decrease.

There was also found to be a significant difference between the two subject groups in the magnitude of the prism adaptation that occurred to both base-out and base-in prism.

The results of this study are in agreement with the findings of Rosenfield *et al.* (1995b) and Winn *et al.* (1994a) who also found a decrease in vergence adaptation with age. The reduction in adaptation found is evidence that there is not an increase in the facility for the oculomotor system to overcome the more convergent disparities that may be predicted by the increase in accommodative convergence found in incipient presbyopia.

The finding that 6 subjects were not able to maintain single binocular vision through a 6^{Δ} base-in prism at the later sessions, when they could for the initial assessment, also indicates that the ageing oculomotor system is less able to deal with convergent disparities with age. This finding also indicates that there is a reduction in the divergent fusional reserves with age, which has also been found in previous research (Sheedy and Saladin, 1975). A decrease in the ability to diverge would add further strain on the oculomotor system, since the increase in accommodative convergence that occurs with age places an increased demand on the fusional reserves. Further investigation into the change in fusional reserves with age would thus be advantageous.

CHAPTER 8

MODELLING OCULOMOTOR FUNCTION IN INCIPIENT PRESBYOPIA

8.1 INTRODUCTION

Models of the accommodation and vergence mechanisms and their interaction are useful when attempting to explain the re-calibration of the oculomotor system that occurs as a subject ages. Model simulations of the oculomotor system can be useful in two ways. Firstly, existing models can be run with the values of the model parameters being changed to try and find a means by which the oculomotor system maintains the same overall vergence response. Secondly, changes can be made to the model components in an attempt to mimic the responses that were found by experimental investigations allowing the model to still reflect the accommodation and vergence mechanisms as the subject ages.

The impact that a change in tonic accommodation (TA) or tonic vergence (TV) would have on the overall vergence response can be demonstrated using model simulations of the oculomotor system. A change in the resting components of vergence and accommodation may prove sufficient to counteract the increase in accommodative convergence that has been found to be a consequence of the decline in accommodation during incipient presbyopia (see Chapter 5). The study described in Chapter 4 was unable to demonstrate an age-related trend in TA although previous research has shown a decline in TA with age. TV was shown to be significantly lower (less convergent) in the incipient presbyope subject group than in the younger subject group in the study detailed in Chapter 6, although again no significant correlation was found between TV and age.

Hung and Semmlow (Hung and Semmlow, 1980; Hung, 1998b) included a saturation element in their models, to represent the ageing crystalline lens, in their original static dual-feedback model of the accommodation and vergence mechanism. Figure 8.1 shows this model with the saturation element positioned prior to the feedback loop of the accommodative mechanism.

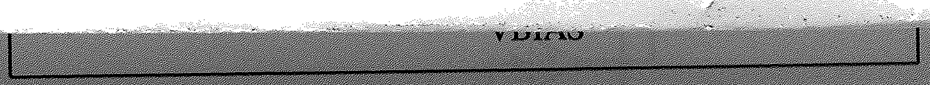

Figure 8.1 Block diagram model of the static interactive dual-feedback accommodation vergence system. Accommodative error (AE), or blur, is the difference between accommodative stimulus (AS) and accommodative response (AR). The dead space between + and – DSP reflects well-known dead space in accommodation. Output from dead space operator (AE1) goes into the accommodative controller which exhibits accommodative controller gain (ACG). Output from accommodative controller (ACC) is summed at a summing junction and is also cross-linked to the vergence system via gain AC (accommodative convergence). The accommodative bias under the no stimulus condition (ABIAS) is also summed at the summing junction along with the cross-link from the vergence controller output (VCC) via CA (convergence accommodation). The output from the summing junction goes through a saturation element, which reflects the plant saturation of the accommodative system, to give the accommodative response. Vergence error (VE), or fixation disparity, is the difference between vergence stimulus (CS) and vergence response (VR). Vergence error goes through a vergence controller with vergence controller gain (VCG) to give VCC. The vergence bias obtained under the no stimulus condition (VBIAS), VCC, and the cross link from the accommodative controller via AC all sum at the summing junction to give the vergence response (reproduced from Hung and Semmlow, 1980).

Using this model, the limit of the saturation element will be the amplitude of accommodation and will thus be reduced to mimic the ageing oculomotor system, resulting in a threshold cut-off point beyond which there is no accommodative response. The saturation element has been shown to reproduce successfully the experimental results but only where the Hess-Gullstrand theory has been found to hold (Hung, 1998b). The results of the study described in Chapter 5 have shown that the relationship between accommodation and vergence changes as the amplitude of accommodation declines, evidence against the Hess-Gullstrand theory of presbyopia. Thus in order for an oculomotor model to be valid for an older subject there needs to be amendments to the existing models that will reflect the changes in the accommodation-vergence interactions.

8.2 METHODS

In collaboration with Dr Andrew Eadie and Dr Lyle Gray of Glasgow Caledonian University a computer model based on the Hung and Semmlow (Hung and Semmlow,

1980) work has been developed using *MATLAB/SIMULINK* software (The MathWorks Inc.). A block diagram of this model is shown in figure 8.2.

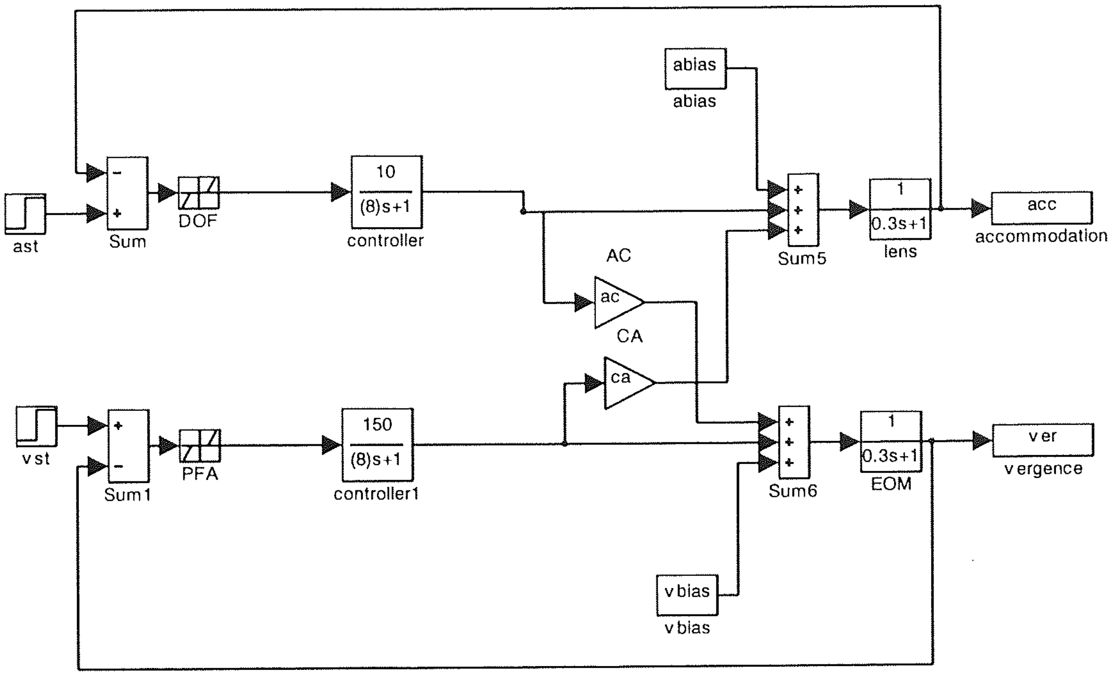

Figure 8.2 Block diagram of the model developed from the Hung and Semmlow (1980) model (shown in figure 8.1). The inputs '**ast**' and '**vst**' are step inputs, which are the changes in accommodative and vergence stimuli. **DOF** represents depth-of-focus and **PFA** represents Panums fusional area and both are dead-space operators, which only generate an output if the input is greater than the blur or disparity that **DOF** or **PFA** can tolerate without a change in accommodation or vergence response. The controllers are the accommodative and vergence controllers that are based on the values of controller gain found by Hung *et al.* (1996) and modify the input they receive. **AC**, **CA**, **ABIAS** and **VBIAS** are as described in figure 8.1. '**Sum**' represents a summing junction where the inputs are added to form the output. The '**lens**' and '**EOM**' controllers represent the actual responses of the crystalline lens and extra-ocular muscles to a certain input and the controller gains are again derived from work by Hung and co-workers. The outputs **acc** and **ver** are the accommodation and vergence responses to the original step inputs and will thus have been modified by all the model components.

This software allows the development of dynamic models in a block diagram format within a Windows setting allowing easy manipulation of the model parameters and alterations to the model structure. The model can be run either directly within the model window in the *SIMULINK* software, where outputs from the vergence and accommodation plants are displayed graphically on scopes, or a program can be written within *MATLAB* that runs the model for several values of input and collates the appropriate responses.

A program was written that allowed the model parameters TA (ABIAS), TV (VBIAS), AC and CA to be altered. The program calculated the accommodation and vergence responses to step changes in accommodation and vergence stimuli of 0 to 6D and 0 to 6MA respectively. Using this model several investigations were completed.

The impact of a change in TA or TV on the overall vergence response.

To investigate the affect of a change in TA on the overall vergence response a series of 11 runs of the model were performed with fixed values of TV, CA and AC but with varying values of TA. TA was varied between 0 and 2D in 0.2 D steps. The vergence response to a stimulus located at 33cm (3D and 3MA) was then found for each value of TA.

A similar investigation was then performed to find the affect of TV on the overall vergence response with fixed values of TA, CA and AC and a varying value of TV (0 to 2MA in 0.2MA steps).

With both of these investigations several series of the procedure were run in order to ensure that the effects noted were not due to the chosen values of CA and AC. Thus each investigation was run with the values of CA and AC shown in table 8.1 reflecting a range of normal values derived from the CA/C and AC/A ratios found in the current study. The 4th series had a lower value of CA gain and a higher value of AC gain since the cross-link gains are related to the CA/C and AC/A ratios and the study of incipient presbyopes found a decrease in CA/C ratio and an increase in AC/A ratio with age.

Series	CA	AC
1	0.8	0.8
2	0.6	0.6
3	1.0	1.0
4	0.4	1.2

Table 8.1 The values of CA and AC that were used for each series investigating the affect of TA and TV on the overall vergence response.

Modelling the change in the accommodation and vergence interaction that occurs with age.

The cross-link gains

The cross-links gains AC and CA in the closed-loop model shown in figure 8.2 are related to, but not identical to, the AC/A and CA/C ratios. Under open-loop vergence conditions however, AC is equal to the response AC/A ratio (AC/Ar). In the current study it was found that AC/Ar increased with age thus the gain AC would increase. The stimulus AC/A ratio (AC/As) was found to remain stable with age and from the equation

$$\frac{AC/Ar}{AC/As} = \frac{1+ACG}{ACG}$$

derived by Hung and Semmlow (Hung, 1992b), it can be seen that the ACG must decline to maintain the same AC/As with an increasing AC/Ar.

Under open-loop accommodation conditions, Hung and Semmlow (1980) show that

$$CA/C \cong \frac{VCG}{1+VCG} * CA$$

and since VCG is usually quite large, CA/C ≅ CA.

To show how the model could be adjusted to reflect the changes in the cross-link ratios found in Chapter 5, a series of model runs was performed. The model was run with a decreasing CA gain to represent the decrease in the CA/C ratio found experimentally. The gain AC was increased to reflect the increasing response AC/A ratio and the ACG ratio was also decreased appropriately to maintain a stable stimulus AC/A ratio. The accommodation and vergence responses to a 3D stimulus were analysed.

The series was also repeated with the increase in the AC gain and the decline in the CA gain but without an adjustment to the ACG. These simulations showed the responses that would occur if both the stimulus and response AC/A ratios increased with age.

Gain of the accommodative plant

Another possible method of altering the existing components of the model to represent the ageing oculomotor system is to adjust the gain of the accommodative plant, that is the lens, to produce a decline in accommodative response to a particular level of neural innervation.

To assess the impact that a decline in the gain would have on the AC/A ratio, the model was run with the vergence loop open (as shown in figure 8.3). The gain was reduced from 1 to 0.1 in 0.1 steps. For each value of the gain, the accommodation and vergence responses to accommodative stimuli ranging from 0 to 6D (1D steps) were found. From these responses the stimulus and response AC/A ratios and the gradient of the stimulus-response curve were calculated. The changes in the ratios and the stimulus-response gradient, found from the model as the gain was reduced, were compared to the changes with age found experimentally in Chapter 5.

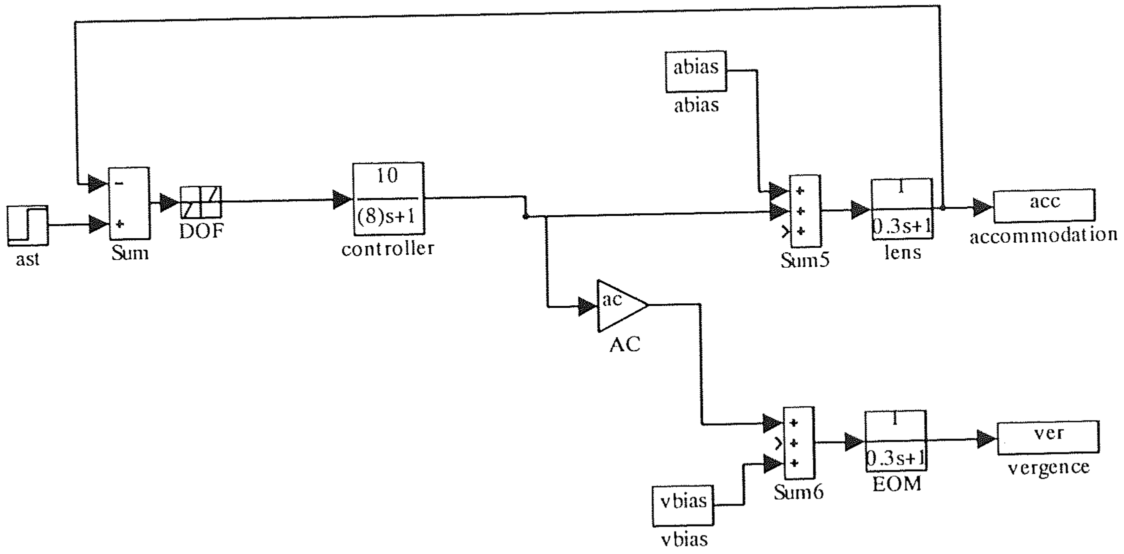

Figure 8.3 Block diagram showing the accommodation and vergence model with the vergence loop open.

An additional series of model runs were performed with the accommodation loop open (as shown in figure 8.4) with the gain declining from 1 to 0.1. The CA/C ratio was calculated from the model responses to vergence stimuli of 0 to 6MA (1MA steps). Changes in the CA/C ratio that resulted from the reduction in the gain of the accommodative plant were compared to the change in CA/C ratio found in Chapter 5.

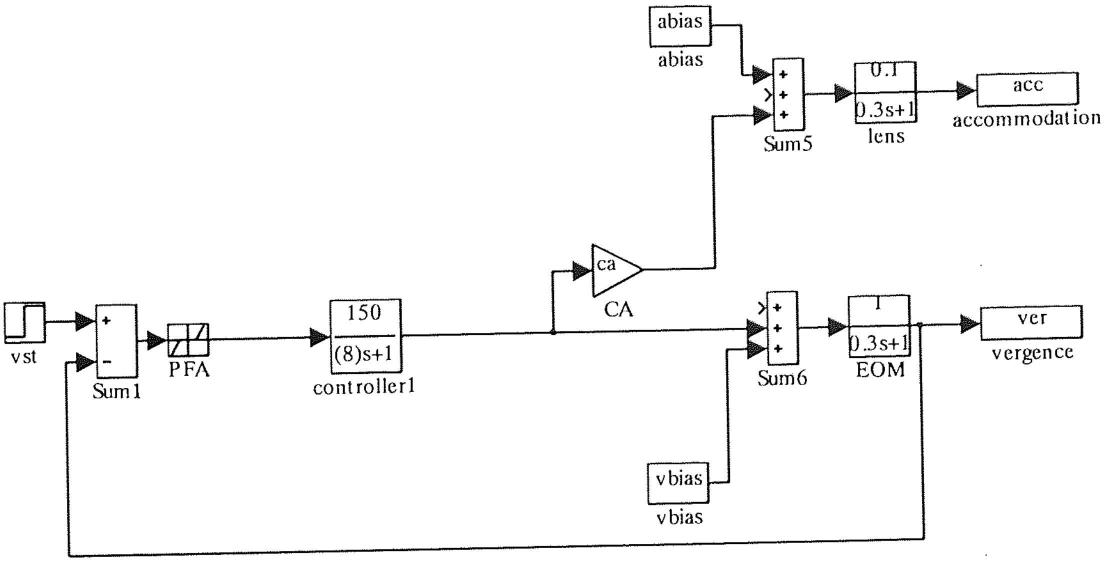

Figure 8.4 Block diagram showing the accommodation and vergence model with the accommodation loop open.

A final series of runs was performed using the closed-loop model as shown in figure 8.2. The accommodation and vergence responses to a 33cm stimulus were determined with the gain reduced from 1 to 0.1.

8.3 RESULTS

The impact of a change in TA or TV on the overall vergence response.

The vergence response of the model to a stimulus located at 33cm for each value of TA was found for the four sets of AC and CA values. Figure 8.5 shows the data obtained. It can be seen that as the magnitude of TA declines (i.e. becomes more distal) the vergence response increases. The rate of increase of the vergence response is dependent on the AC and CA gain values but in all cases there is a more rapid increase with values of TA below 1D.

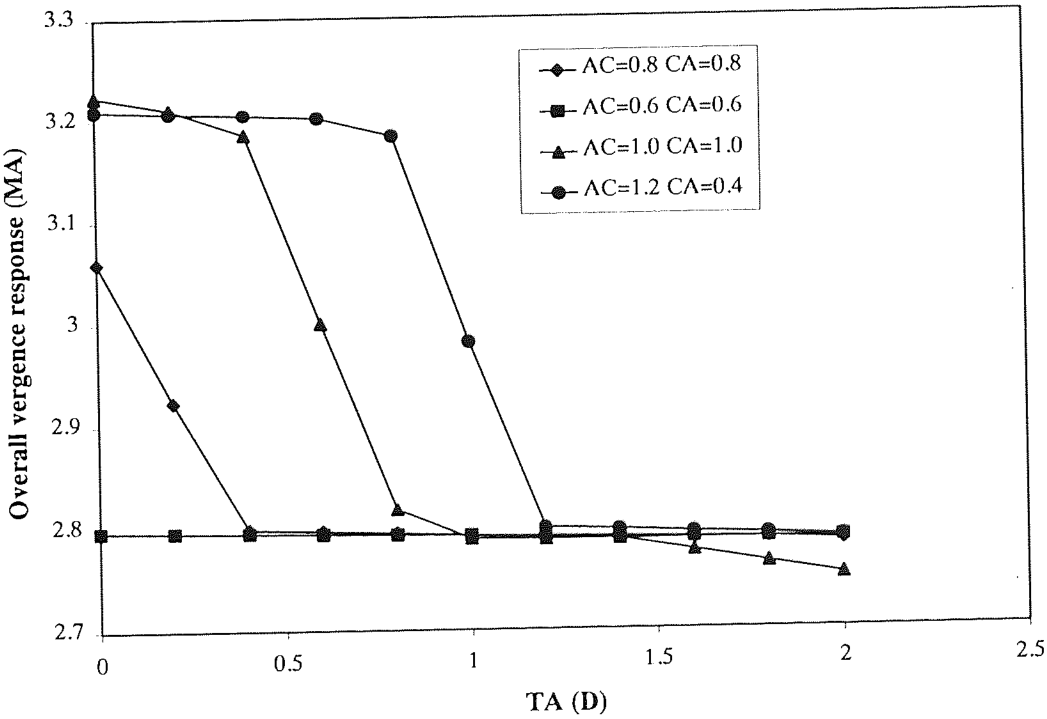

Figure 8.5 The change in the vergence response as the magnitude of TA changes, results for 4 sets of cross-link values.

The vergence response of the model to a target at 33cm with a changing TV position are shown in figure 8.6, for the 4 values of the cross-link gains.

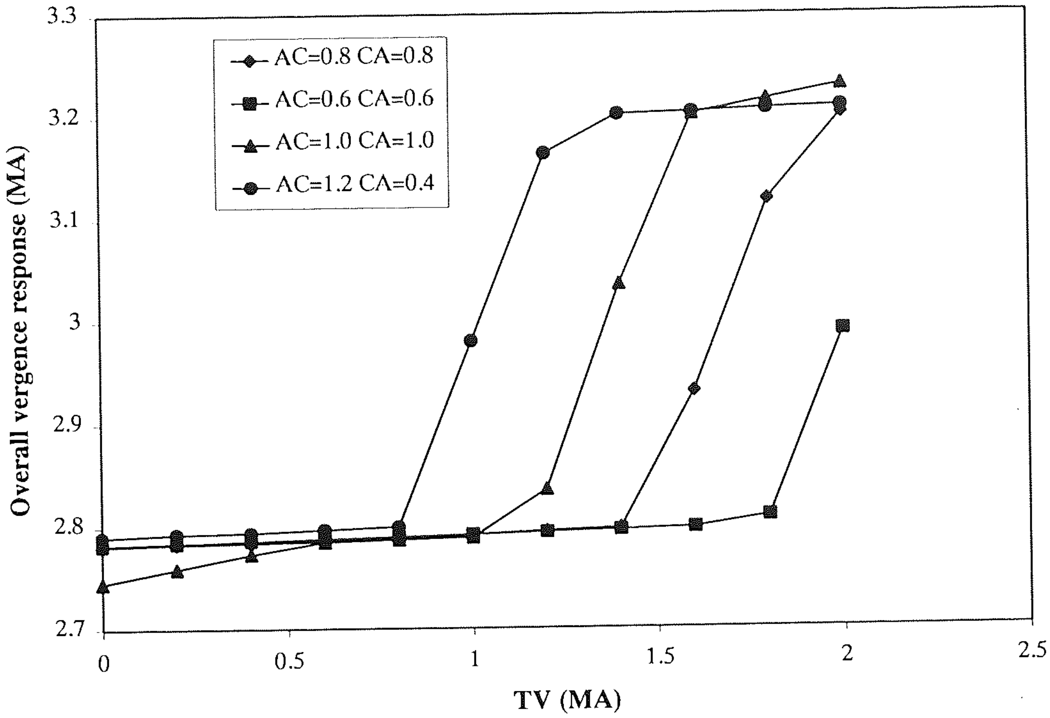

Figure 8.6 The change in the vergence response as the magnitude of TV changes, results for 4 sets of cross-link values.

It can be seen that as TV increases (becomes more convergent) the overall vergence response increases. As with the TA position, the rate at which the magnitude of the vergence response increases is dependent on the AC and CA gains but in all cases is greater for TV values greater than 1MA.

Modelling the change in the accommodation and vergence interaction that occurs with age.

The cross-link gains

Table 8.2 shows the stimulus-response curve gradient and vergence response to a stimulus at 33cm for each value of AC and CA used in the model. The value of ACG that was used for each level of AC ensured that the stimulus AC/A ratio remained the same, since this was what was found experimentally.

AC	CA	ACG	S-R gradient	Vergence response (MA)
0.8	0.8	15	0.968	2.793
0.9	0.7	5	0.894	2.794
1.0	0.6	3	0.817	2.795
1.1	0.5	2.1429	0.744	2.795
1.2	0.4	1.6667	0.676	2.796
1.3	0.3	1.3636	0.615	2.796
1.4	0.2	1.1538	0.560	2.797

Table 8.2 The vergence response to a stimulus at 33cm and the stimulus-response curve gradient for each pair of cross-link gains (TA=1, TV=1).

From table 8.2 it can be seen that by increasing the AC gain, reducing the ACG accordingly and decreasing the CA gain, only a very minimal increase in the overall vergence response occurred. This stable vergence response was predicted in Chapter 5 if the accommodative convergence response was limited to the position at which no diplopia would occur but with a decreased accommodative response.

If the accommodative response is not limited by the vergence position and instead further accommodative effort is made to minimise blurring of the stimulus the responses shown in table 8.3 would occur. As was expected there would be an increase in the vergence response to a particular stimulus if increased effort were made to focus on a stimulus.

AC	CA	ACG	S-R gradient	Vergence response (MA)
0.8	0.8	10	0.956	2.792
0.9	0.7	10	0.936	2.795
1.0	0.6	10	0.920	2.798
1.1	0.5	10	0.909	2.832
1.2	0.4	10	0.909	2.981
1.3	0.3	10	0.907	3.125
1.4	0.2	10	0.905	3.201

Table 8.3 The vergence response to a stimulus at 33cm and the stimulus-response curve gradient for each pair of cross-link gains (TA=1, TV=1).

The stimulus and response AC/A ratios derived from the open-loop vergence model are shown in table 8.4 for each value of the gain of the accommodation plant (lens).

Gain	AC/As (MA/D)	AC/Ar (MA/D)
1	0.727	0.800
0.9	0.800	0.889
0.8	0.889	1.000
0.7	1.000	1.143
0.6	1.143	1.333
0.5	1.333	1.600
0.4	1.600	2.000
0.3	2.000	2.667
0.2	2.667	4.000
0.1	3.976	8.000

Table 8.4 The stimulus and response AC/A ratios derived from the model simulation for each value of accommodative plant gain.

Both the stimulus and response AC/A ratios increased with the reduction in the gain of the plant. The relationship between the gain and the AC/A ratios is shown in figure 8.7 and can be seen to be non-linear; the rate of increase in the AC/A ratios increases as the gain reduces.

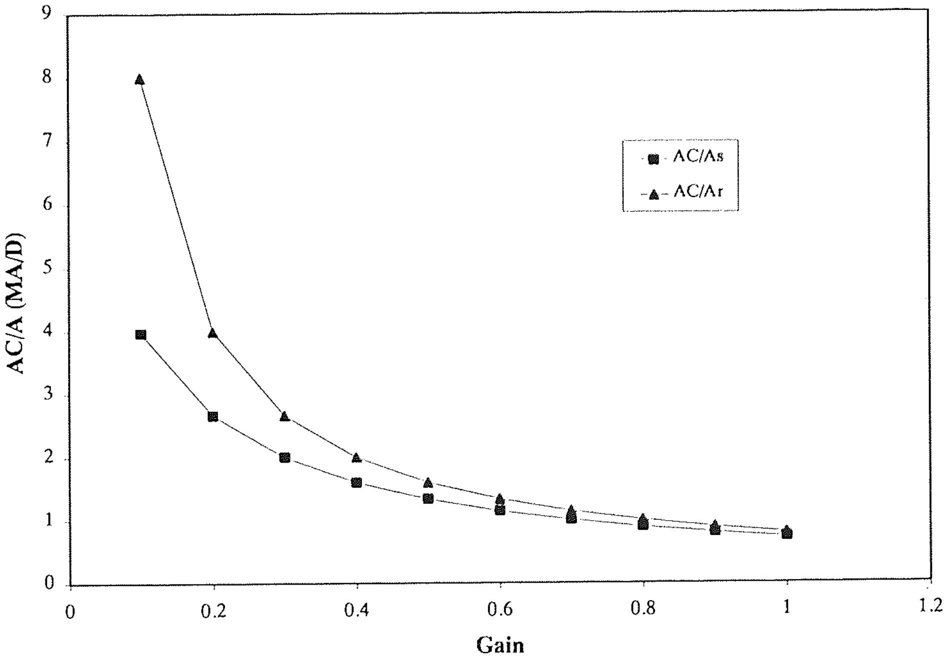

Figure 8.7 Model derived stimulus and response AC/A ratios for gain values of the accommodative plant.

The CA/C ratio derived from the open-loop accommodation model simulations are shown in table 8.5 for each value of the accommodative plant gain.

Gain	CA/C ratio (D/MA)
1	0.795
0.9	0.715
0.8	0.636
0.7	0.556
0.6	0.477
0.5	0.397
0.4	0.318
0.3	0.238
0.2	0.159
0.1	0.080

Table 8.5 The CA/C ratio derived from the model simulation for each value of accommodative plant gain.

The CA/C ratio declined linearly at a rate of 0.079 D/MA per 0.1 decrease in gain (0.013 D/$^{\Delta}$ per 0.1).

The accommodation and vergence responses to a stimulus at 33cm found under closed-loop conditions are shown in table 8.6.

Gain	Accommodative response (D)	Vergence response (MA)
1	2.720	2.792
0.9	2.657	2.796
0.8	2.578	2.817
0.7	2.538	3.120
0.6	2.439	3.205
0.5	2.294	3.212
0.4	2.106	3.222
0.3	1.851	3.236
0.2	1.486	3.255
0.1	0.927	3.285

Table 8.6 The accommodation and vergence responses to a stimulus at 33cm derived from the closed-loop model simulation for each value of accommodative plant gain.

It can be seen that reducing the gain of the accommodative plant results in a decrease in the accommodation response to a particular stimulus and an increase in the vergence response.

8.4 DISCUSSION

The results of Chapter 4 showed no age-related change in TA although this was not in agreement with previous research (Simonelli, 1983; Ramsdale and Charman, 1989; Rosenfield *et al.*, 1995b; Mordi and Ciuffreda, 1998). The magnitude of decline in TA found by previous research would predict a decline in TA from around 0.80D at age 20 to around 0.20D at age 60. From Figure 8.5 it can be seen that a change in TA of this magnitude although dependent on the magnitude of the cross-link gains could result in a significant increase in the overall vergence response.

Thus it seems that an isolated decrease in TA with age would lead to an increase in the overall vergence response. This is expected, since a reduction in TA will place further demand on blur-driven accommodation, which will in turn result in an increase in accommodative convergence. If a decrease in TA does occur with ageing this will thus add further to the strain on the oculomotor system caused by the increase in accommodative convergence.

In chapter 6 a significantly lower value of TV was found for the incipient presbyope subject group than for the younger subject group although no age-related change in TV was found. The mean TV in the younger group was 0.36MA and for the older group was 0.15MA. From figure 8.6 it can be seen that this decrease in TV will have very little affect on the overall vergence response with a slight decline in the response, depending on the AC and CA gains. Ciuffreda *et al.* (1993) found a mean TV of 0.57MA in a pre-presbyopic subject group increasing to a mean of 0.94MA in a presbyopic subject group and concluded that this would have little influence on the overall vergence response. However from figure 8.5 this increase may be of significance if the value of the AC gain has increased and the CA gain has deceased. Such changes in gain are found in this current study for older subjects and thus the changes found by Ciuffreda *et al.* may have significance.

It was proposed in chapter 5 that a gradual decrease in TV could compensate for a potential increase in accommodative convergence. It has been shown here that such a decrease in TV may compensate to some extent for the decrease in accommodative convergence but the data found from the model simulations also demonstrates the complexity of the relationship between the AC and CA gains and a decline in TV.

It was shown that the change in the accommodation and vergence cross-link ratios as the oculomotor system ages could be modelled by reducing the CA gain and increasing the AC gain. If the accommodation response is limited by the maximum accommodative convergence that prevents a strain on the vergence mechanism then the ACG must be reduced as the AC gain increases, in order to maintain the same stimulus AC/A ratio.

An alternative method of adjusting the model to reflect the decline in the amplitude of accommodation was attempted by reducing the gain of the accommodative plant function. The results showed that a linear reduction in the gain resulted in a linear reduction of the CA/C ratio but a non-linear increase in the AC/A ratios. Although the study described in chapter 5 shows an increase in the response AC/A ratio with age, because of the small age range included in the study it was not possible to comment on the linearity of the increase in the response AC/A that would occur over a larger age range. However, several previous studies have found that the rate of increase in the response AC/A ratio does increase with age (Breinin and Chin, 1973, Eskridge, 1983) as shown in figure 2.5. One longitudinal study (Fry, 1959) also found a similar trend in the increase of the stimulus AC/A ratio as shown in figure 2.4.

Reducing the gain of the accommodation plant function has produced measures of the CA/C ratio and stimulus and response AC/A ratios that have been found in previous research. The model simulations under closed loop conditions have shown that the parameter changes made would result in a significant decline in the accommodative response to a particular stimulus with a small increase in the overall vergence response.

CHAPTER 9

REVIEW OF EXPERIMENTAL WORK AND PROPOSALS FOR FUTURE WORK

9.1 INTRODUCTION

This study has consisted of a two-year longitudinal study involving two subject groups. The first group comprised of 28 incipient presbyopes aged 35 to 45 years at the commencement of the study and the second was a group of 10 younger subjects, aged 20 to 30 years. Data was collected approximately every 4 months, allowing the longitudinal analysis of changes in oculomotor parameters as the amplitude of accommodation declined. Cross-sectional analysis of the incipient presbyope group data collected at each session was also performed.

Each of the experimental chapters has contributed to an attempt to explain how the oculomotor system is able to cope with the decline in the amplitude of accommodation that occurs as an individual ages.

9.2 THE ACCOMMODATIVE RESPONSE

In order to ensure that a suitable subject group was chosen for the longitudinal study, Chapter 4 demonstrated the nature of the decline in the amplitude of accommodation that occurred across the study period. The significant correlation found between the amplitude of accommodation and the age of the subjects demonstrated that the incipient presbyope subject group was suitable for the longitudinal analyses performed in subsequent chapters.

As the amplitude of accommodation declines with age the composition of the accommodative response may vary. If there is a greater decline in one element of the accommodative response there may be a compensatory increase in a different component. Any change in the composition of the accommodative response will also have repercussions on the vergence mechanism due to the cross-links between accommodation and vergence. The magnitude of convergence accommodation was investigated in Chapter 5 where it was found to decrease linearly with the decline in the amplitude of accommodation. The longitudinal analysis of tonic accommodation (TA) in Chapter 4 found no significant decline in the TA of the subjects as their amplitude of accommodation declined, which was contrary to the findings of previous research. There was also shown to be no significant difference between the TA of the two subject groups although it may be that the smaller number of subjects in the younger subject group was not a true representation of a younger population. The impact that a change in TA would have on the overall accommodation and vergence response was discussed further in Chapter 8 using model simulations. It was found that an isolated decrease in the level of TA could lead to an significant increase in the overall vergence response to a particular stimulus since it would place greater demand on the blur-driven accommodative response, leading to increased accommodative convergence.

Chapter 4 also investigated whether there was any change in accommodative adaptation with age. After a sustained near-vision task the accommodative response does not immediately return to the pre-task resting level (TA) but regresses to this level after a period of time. The study investigated whether there was any correlation between amplitude of accommodation and the time taken to reach the resting level after a 3-minute reading task at 40 cm. It was found that there was no significant difference in the regression times between the two subject groups and no significant correlation between the amplitude and the regression time. This finding was in agreement with the finding of no correlation between TA and amplitude, since accommodative adaptation is related to the magnitude of TA. However, the study of adaptation was weakened due to the low within-task accommodative response of many of the incipient presbyopes where the response was only slightly greater than TA and hence little adaptation will have occurred in these cases.

9.3 THEORIES OF PRESBYOPIA

A distinguishing factor between the Hess-Gullstrand theory of presbyopia and the alternative theories such as the Duane or Fincham theories is whether the neural innervation to produce a unit change in accommodation increases with age. The Hess-Gullstrand theory of presbyopia predicts that with increasing age there is no change in the innervation required to achieve a unit change in accommodation. In contrast, the alternative theories of presbyopia predict that with increasing age an increasing effort is required to produce a unit change in accommodation, with maximum effort being required for maximum accommodation.

Due to the synkinetic link in innervation between accommodation and vergence, studying the relationship between the two responses allows for a differentiation between the theories of presbyopia.

From the two-year study of the cross-link ratios CA/C and AC/A described in Chapter 5 it was found that there was a significant increase in the response AC/A ratio and a significant decrease in the CA/C ratio with age. These findings are not consistent with the Hess-Gullstrand theory of presbyopia but are evidence in support of the alternative theories.

9.4 COMPONENTS OF THE VERGENCE RESPONSE

The finding of an increase in the accommodative convergence response with age if the same accommodative response was maintained led to the study described in Chapter 6 which assessed tonic vergence and proximal vergence. The increase in the response AC/A ratio means that when a subject focuses accurately on a stimulus, the resulting accommodative vergence increases as the subject ages. To compensate for an increase in this component of vergence a reduction in tonic vergence (TV) or proximal vergence was suggested. The study did not find any difference in the magnitude of proximal vergence from the first to the last experimental session. There was also no significant difference between the mean proximal vergence of the younger and older subject group.

There was also found to be no correlation between TV and amplitude of accommodation at any of the experimental sessions. A statistically significant difference was found between the mean TV of the older subject group compared to the younger subject group with a less convergent position in the older group. This reduction in TV was also supported by the finding of a less esophoric mean distance heterophoria in the older subject group.

The impact that a change in TV would have on the overall vergence position was investigated in Chapter 8 using *MATLAB/SIMULINK* computer simulations. It was found that a change in TV of the magnitude found in this study would have a minimal effect on the overall vergence response under closed-loop conditions. However, the model simulations did show that the impact of a change in TV was dependent on the value of the AC and CA gains. Chapter 5 showed a decrease in the CA/C ratio and an increase in the response AC/A ratio, which Chapter 8 showed, could be represented by a decrease in the

CA gain and an increase in the AC gain respectively. As the difference in CA and AC became larger it was seen that there was a shift in the range of TV within which a change in magnitude would influence the overall vergence response. There is therefore a complex relationship between TV and the AC and CA gains, which may mean that as a subject ages the changes in the cross-link gains found in this study can be partially compensated for by a decrease in TV. This study did not however find an age-related decrease in TV but the finding of a difference between the mean of the two groups indicates that a relationship may exist. Further study of a larger cross-sectional population or a longitudinal study for a longer period of time may provide stronger evidence as to whether such a decline in TV with age does exist.

With no clear evidence that a change in tonic or proximal vergence is able to compensate for a potential increase in accommodative convergence a change in the fusional vergence response of the oculomotor system may be significant. The longitudinal study of the vergence adaptation to base-in and base-out prism undertaken in Chapter 7 showed that there was a decline in the adaptation to both prism directions as the amplitude of accommodation declined. There was also a significantly lower level of adaptation in the older subject group than the younger group to both convergent and divergent disparities. Several patients also developed difficulty in maintaining fusion with the base-in prism indicating that with age there is a reduction in the fusional reserves dealing with convergent disparities.

Vergence adaptation occurs as the slow fusional vergence response replaces the initial fast fusional response. The finding of no increase in vergence adaptation, particularly to base-in prism where divergence is required, provides no evidence for a change in the fusional vergence contribution to the overall vergence response. With the increase in accommodative vergence that has been predicted to occur during the development of presbyopia an increase in the ability of fusional vergence to overcome a more convergent position would have been beneficial.

9.5 THE COMPROMISE BETWEEN ACCOMMODATION AND VERGENCE

There has not been conclusive evidence that changes in the components of the vergence response are able to cope with the increase in accommodative convergence that must occur for each unit of accommodative response. Instead it is proposed that the accommodative response is limited to a response that will not lead to excessive convergence. The vergence response will thus become the limiting parameter in the near response in order to prevent asthenopic symptoms due to over-convergence. As a subject ages, no increase in the effort made to focus on a target would result in an unchanging vergence response but a lower accommodative response and thus the image may appear blurred. The finding of a more accurate vergence response to a stimulus with age (Sheedy and Saladin, 1975) supports the finding that the vergence response takes control of the near response with age. It is interesting to note that in clinical practice my observation is that subjects who require their first reading addition typically present complaining of symptoms of blur rather than asthenopic symptoms due to strain on fusional vergence, although this may be due to 'blur' being used as a broad description for a range of symptoms.

A function that might demonstrate whether there is an accurate accommodative response to a stimulus is the accommodative stimulus-response function. The stimulus-response curve data gathered in Chapter 5 was measured under open-loop conditions and is therefore not directly comparable. Ramsdale and Charman (1989) found that the stimulus-response curve gradient declined with age. Within the amplitude of accommodation a decrease in the gradient indicates that the accommodative response to a stimulus reduces with age, implying that there is a factor limiting the accommodative response proposed here to be the vergence response.

Mordi and Ciuffreda (1998) found that the gradient did not change with age. It was concluded that this was support for the Hess-Gullstrand theory but it could instead indicate that there is a sufficient means of compensation by the oculomotor system, such as the decrease in TV, to allow the additional effort required to maintain the same accommodative response (i.e. Duane or Fincham theories could still hold).

Further study of the closed-loop accommodative stimulus-response function would assist in explaining whether the subject makes additional effort to focus on a near stimulus, despite this leading to an increase in accommodative vergence, or whether the vergence response limits the accommodation response, leading to an increase in blur.

The increase in the response AC/A ratio found in Chapter 5 was found to be faster than the decrease in the CA/C ratio that occurred. These results led to the observation that the ratios became more reciprocally related as the amplitude of accommodation declined. This finding would seem to indicate that convergence accommodation becomes more significant with age. It was also found that towards the end of the study period the CA/C ratio became more closely related to the amplitude of accommodation than the response AC/A ratio, further indication of the increasing importance of convergence accommodation.

9.6 DEPTH-OF-FOCUS

This study has not considered the influence of pupil size on the near response. The affect of age on the pupil size could be of significance, since a decrease in pupil size and thus an increase in depth-of-focus, may be of assistance with the compromised accommodation response that is being proposed. An increase in depth-of-focus may enable the subject to maintain focus on a stimulus that would have appeared blurred due to the limit placed on accommodation by the vergence response.

Previous investigation has found that there is a decrease in the pupil size with age (Schafer and Weale, 1970; Weale, 1982; Charlier and Hache, 1987; Winn *et al.*, 1994b,). Mordi and Ciuffreda (1998) found no increase in the objective depth-of-focus with age (mean of ±0.38D) but a significant increase in the subjective depth-of-focus (from ±0.40D age 20 to ±0.90D age 50). Mordi and Ciuffreda conclude that this increase in depth-of-focus could not be solely due to a decrease in pupil size but also may be due to the subject's increased tolerance of blur with age. This increase in the subjective depth-of-focus and increased toleration of blur could contribute to the ability to cope with the decline in the accommodative response.

9.6 MODELLING THE AGEING ACCOMMODATION AND VERGENCE MECHANISMS

The finding of evidence against the Hess-Gullstrand theory of presbyopia led to the observation that the inclusion of a saturation element in the accommodative loop of model simulations was not appropriate. Instead two methods of modelling the ageing oculomotor system were investigated using *MATLAB/SIMULINK* software.

Firstly the cross-link gains AC and CA were varied in accordance with the findings of Chapter 5 with a gradual increase in AC and decrease in CA. It was found that these changes resulted in the accommodation and vergence that were expected but were dependent on the value of the accommodative controller gain (ACG). If the effort that a subject makes to focus on a stimulus does not increase with age, then the ACG must be reduced as the AC increases in order to maintain the same overall stimulus AC/A ratio. If an increased effort is made to focus on the stimulus then the ACG remains the same, resulting in an increased vergence response.

An alternative method of modelling the ageing response was to alter the gain of the accommodative controller function with a decline in the gain representing a decrease in accommodative amplitude. This reduction in gain did result in a decrease in the CA/C ratio and an increase in the AC/A ratio in agreement with the experimental findings of Chapter 5. The decline in the CA/C was linearly related to the reduction in gain but there was a rise in the rate of increase in the AC/A ratio. The exact nature of the rate of increase in the AC/A ratio can not be determined from this current study but an increase in the rate of increase as the amplitude of accommodation declines has been found previously (Breinin and Chin, 1973; Eskridge, 1983). Thus two methods by which the dual-feedback accommodation and vergence mechanism can be altered have been found.

9.7 CONCLUSIONS

Evidence has been found against the Hess-Gullstrand theory of presbyopia. As the amplitude of accommodation declines, an increase in the AC/A ratio has been found which requires a re-calibration of the oculomotor response to a near stimulus.

Some evidence has been found to support an age-related decrease in tonic vergence, which may compensate for an increased accommodative vergence response when maintaining an accurate response to a near vision stimulus (within the amplitude of accommodation). If this decline in tonic vergence is not sufficient or if there are in fact no compensatory changes in the components of the vergence response, there is a choice between a focused accommodative response with over-convergence, or fusion (no diplopia or strain on fusional vergence) with under-accommodation. It may be that a compromise is made between the correct accommodation response and an accurate vergence response, with the use of the maximum accommodative vergence that can be tolerated despite this resulting in a lower accommodative response. In this way it seems that as the amplitude of accommodation declines, the vergence response becomes more critical in the control of the near response.

Thus it is proposed that as the amplitude of accommodation initially declines the gradual increase in the accommodative convergence response is compensated for by a decrease in tonic vergence and an increase in the subjective depth-of-focus allowing a lesser accommodative response. When the amplitude of accommodation has reached a stage where the accommodative response is not sufficient to allow a satisfactory focus on a near target, a reading addition will be required. When using a reading addition the effort to accommodate and converge will be unchanged (unless compensating for a decrease in TV) and the reduced level of synkinetic accommodative response will no longer be significant. As the power of the reading addition is increased that same effort to vergence and accommodation can be maintained.

Throughout the experimental chapters reference is frequently made to an increase in the accommodative convergence response with age. This claim is only made assuming that the same accommodative response is maintained with age (response AC/A ratio was found to increase). It is not possible to assess directly the change in accommodative convergence that occurs with age since this would need to be measured under closed loop conditions, circumstances under which the accommodative convergence could not be isolated.

Consideration was given to an analysis of the accommodative convergence that results from a certain accommodative stimulus (e.g. 2.5D) during the assessment of the AC/A ratio. This will however show nothing more than that shown by the stimulus AC/A ratio (which was inconclusive) and is also dependent on whether the subjects decided to make additional effort to focus on the target; here they would have the freedom to exercise additional accommodation since the resulting convergence would not matter as the vergence loop would be open. The results would thus not be the same as under closed loop conditions.

The experimental Chapters 6-8 investigate whether, to overcome the potential increase in accommodative convergence that would result from the maintenance of the same accommodative response, the oculomotor system has a reduction in one of the other vergence components. Alternatively it was considered that additional accommodative convergence could not be tolerated, with instead a reduction in accommodative response.

The latter was found to be more strongly supported, which indicates that there will be no increase in accommodative convergence with age.

9.8 IMPLICATIONS OF THE CONCLUSIONS AND PROPOSALS FOR FUTURE WORK

The proposal that the near response is limited by the acceptable vergence response has implications when considering the development of a drug to counteract presbyopia. A drug that increased the central neural innervation (i.e. to both the accommodation and vergence mechanisms) would not increase the accommodative response since the synkinetic increase in convergence would not be tolerated. A locally acting drug however, could act on the specific structure, such as the ciliary body or the crystalline lens that has weakened with age, allowing an increase in the accommodation response with the convergence response remaining unchanged.

The use of base-out prisms to increase the accommodative response needs to be investigated. With the accommodative response limited by the vergence response, a near target may appear blurred despite it being within the amplitude of accommodation. The use of a base-out prism might permit an increased accommodative convergence response and thus an increased accommodative response, allowing the use of a larger proportion of the accommodative amplitude.

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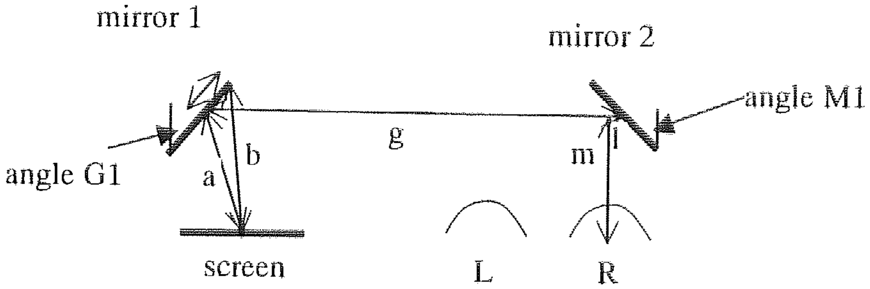
APPENDIX 1: COMPUTER PROGRAM

The computer program listed below is written in Microsoft Basic. The program converts the rotation of the turntable read from the vernier scale (in degrees and minutes) into the actual rotation of the eye around its centre of rotation (in prism dioptres). The diagram below shows the distances required in the initial steps of the program, a diagram showing the full experimental set-up is shown in figure 3.3.



Program

```
10 CLS
20 INPUT "enter distance a from laser spot on screen to fixed point on mirror 1(cm)",a
30 INPUT "enter distance b from laser spot on screen to centre of rotation of mirror
1(cm)",b
40 INPUT "enter distance c from point on mirror 1 to centre of rotation of mirror 1(cm)",c
50 INPUT "enter angle G1 between mirror 1 and vertical(deg)",G1
60 INPUT "enter distance g from point on mirror 1 to point on mirror 2(cm)",g
70 INPUT "enter angle M1 between mirror 2 and vertical(deg)",M1
80 INPUT "enter horizontal distance l from cornea to point on mirror 2(cm)",l
90 INPUT "enter vertical distance m from cornea to point on mirror 2(cm)",m
100 INPUT "enter number of trials",z
110 LET p=3.141592653589#
120 FOR n=1 TO z
130 INPUT "enter known rotation of turntable (deg)",A1
135 LET A2=(A1*p)/180
140 LET B1=((c*c)+(a*a)-(b*b))/(2*c*a)
150 LET B2=ATN((SQR(1-(B1*B1)))/B1)
155 LET B3=B2+p
160 LET D1=p-B3-A2
170 LET d=(c*SIN(A2))/SIN(D1)
180 LET Y1=p-(2*(p-B3))
190 LET E1=p-Y1-(2*D1)
200 LET f=d*SIN(2*D1)/SIN(E1)
210 LET e=d*SIN(Y1)/SIN(E1)
220 LET h=a-d+e
230 LET i=g-f
240 LET j=SQR((h*h)+(i*i)-(2*h*i*COS(p-E1)))
250 LET F1= h*(SIN(p-E1))/j
260 LET F2=ATN(F1/(SQR(1-(F1*F1))))
```

```
270 LET k=SQR(((g+a)*(g+a))+(j*j)-(2*(g+a)*j*COS(F2)))
280 LET n1=SQR((l*l)+((m+1.35)*(m+1.35)))
290 LET O1 =ATN((m+1.35)/l)
291 REM 1.35 is to account for centre of rotation of eye being 1.35cm behind corneal pole
295 LET G2=(G1*p)/180
300 LET H1=p-G2-(p-B3)
305 LET M2=(M1*p)/180
310 LET N2=p-M2-(p-H1)
320 LET P1=O1+((p/2)-M2)+N2
330 LET Q1=O1+((p/2)-M2)+N2+F2
340 LET q=SQR(((g+a)*(g+a))+(n1*n1)-(2*(g+a)*n1*COS (P1)))
350 LET r1=((g+a)*SIN(P1))/q
360 LET r2=ATN(r1/(SQR(1-(r1*r1))))
370 LET r=SQR((j*j)+(n1*n1)-(2*j*n1*COS(Q1)))
380 LET S1=(j*SIN(Q1))/r
390 LET S2=ATN(S1/(SQR(1-(S1*S1))))
400 LET U1=r2-S2
410 LET U2=100*TAN(U1)
410 PRINT"rotation of eye= "U2" prism dioptres"
420 NEXT n
490 INPUT" do you wish to do any more calculations? type 1 for yes, 2 for no:",r1
495 IF r1=1 THEN GOTO 510
500 IF r1=2 THEN GOTO 550
504 BEEP
505 GOTO 490
510 INPUT "do you wish to use the same location measurements? type 1 for yes , 2 for
no",r2
520 IF r2=1 THEN GOTO 100
530 IF r2=2 THEN GOTO 20
535 BEEP
540 GOTO 510
550 STOP
```

APPENDIX 2: MEASUREMENTS OF THE VERGENCE RESPONSE USING THE OPTICAL TURNTABLE

An assessment was made of the resolution of the turntable using the experimental set-up described in section 3.3.2. The accommodative stimulus was fixed at 3D and the subject was asked to align the image of the red laser spot with the centre of the Maltese cross while keeping the cross in focus. A reading of the turntable position was read directly from the vernier scale on the side of the turntable and then the subject was asked to move the spot out of alignment and then to realign it. This was repeated for a total of 10 readings and the complete procedure was performed with 4 subjects.

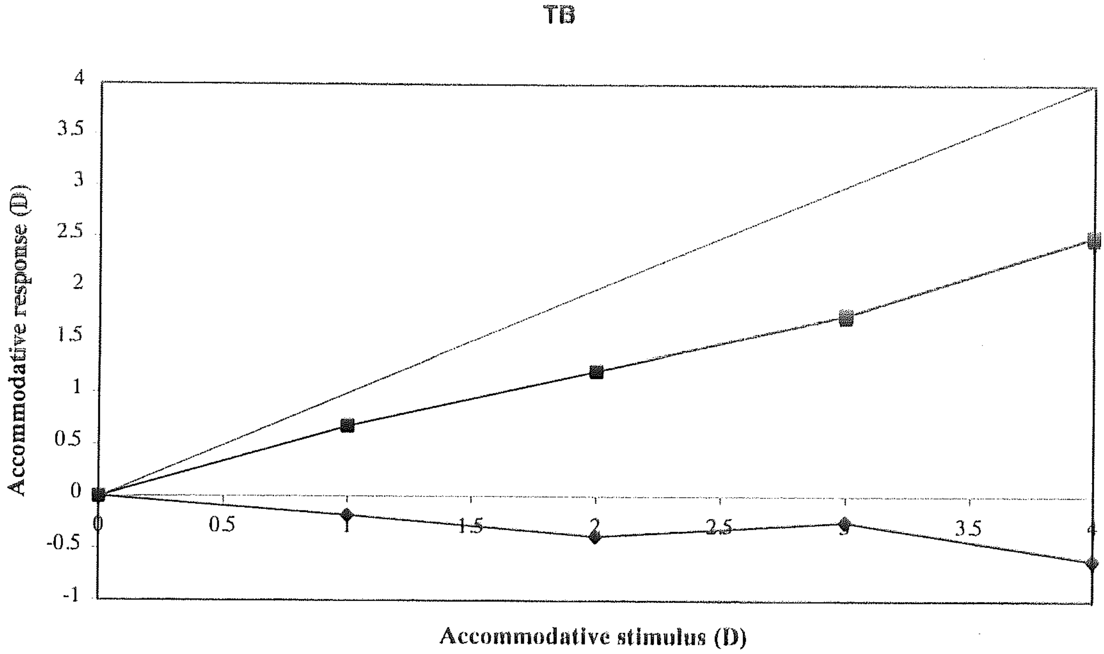
The mean vergence response and standard deviation for each subject are shown below in both prism dioptres and metre angles.

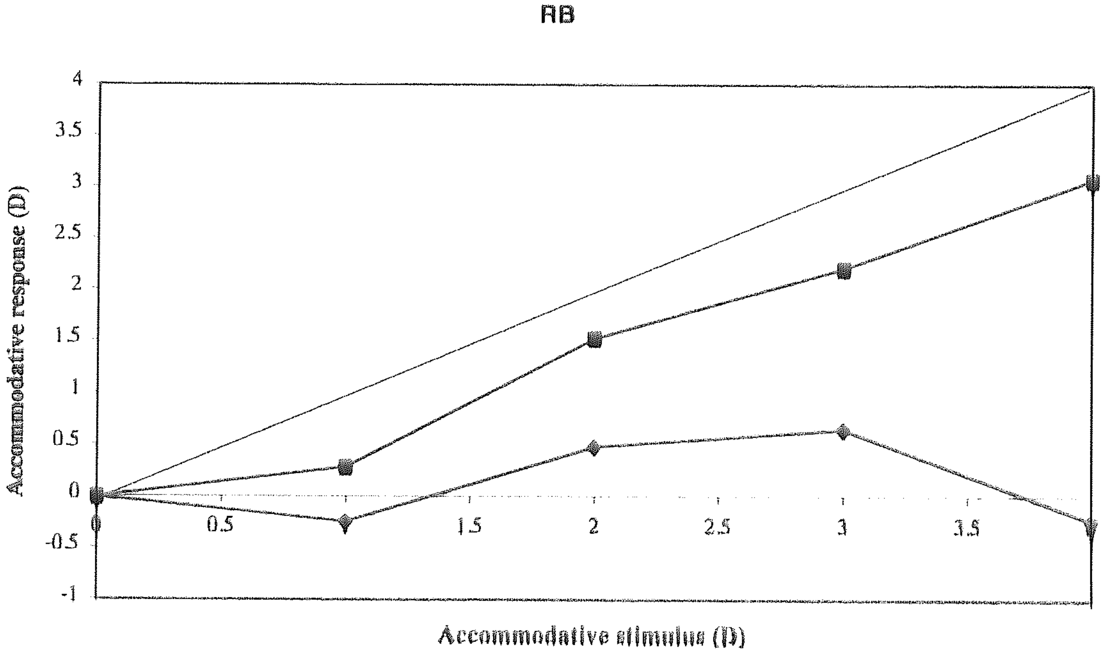
Subject	Mean vergence response ($^{\Delta}$)	Standard deviation ($^{\Delta}$)	Mean vergence response (MA)	Standard deviation (MA)
1	6.21	0.099	1.02	0.016
2	8.12	0.110	1.33	0.018
3	7.15	0.102	1.15	0.016
4	9.45	0.086	1.55	0.014

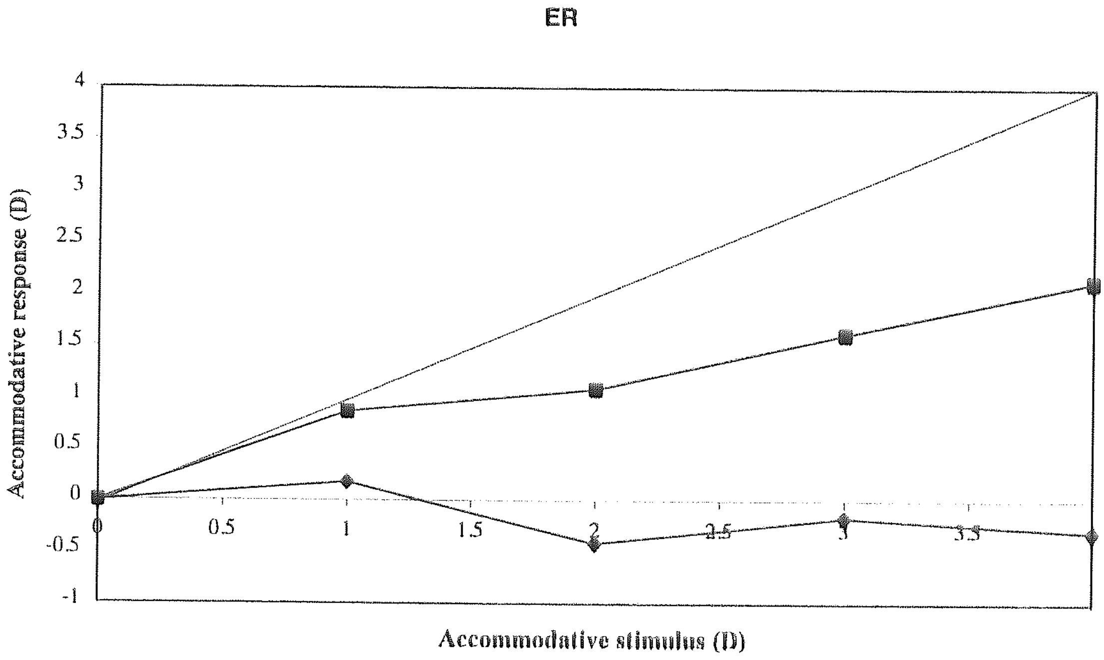
It can be seen that the haploscope allowed a precise measurement of the vergence response.

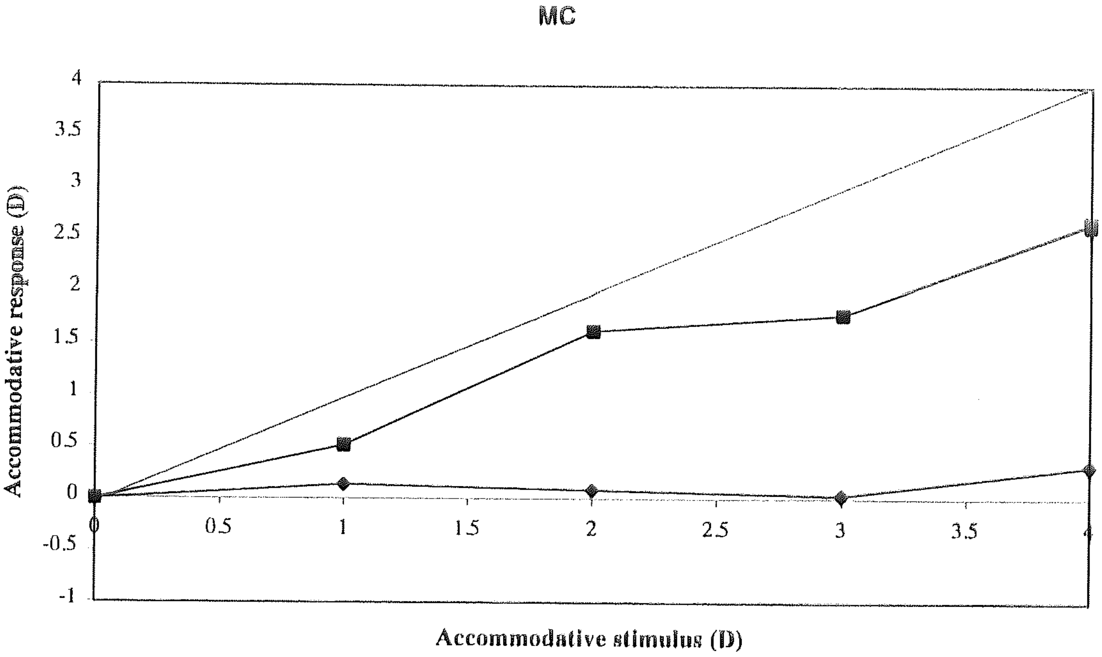
APPENDIX 3: OPENING THE ACCOMMODATIVE LOOP

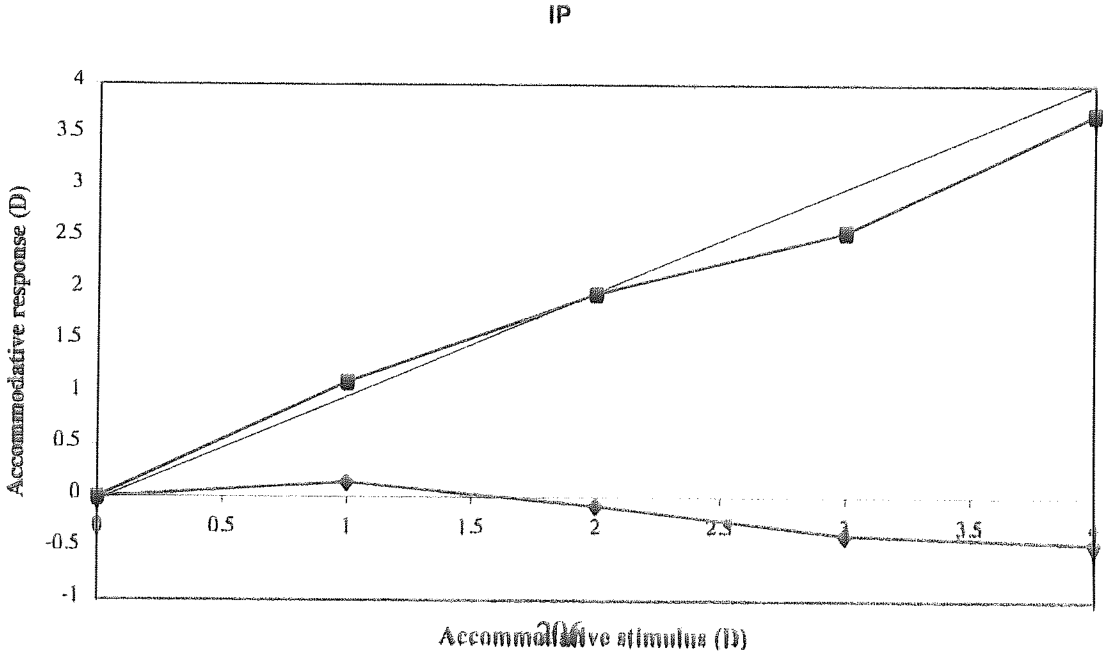
An investigation was undertaken to show that the 0.1 c/deg DoG (Difference of Gaussian) stimulus used when measuring the CA/C ratio did not provide a stimulus to accommodation. Ten subjects were used (mean age 23.5: range 20-26). The subject was asked to observe the DoG stimulus generated on a Macintosh LC475 computer monitor. Negative spheres (0 to -4D) were placed in front of both eyes and 10 measurements of the accommodative response were taken with the Canon R1 IR autorefractor. The experiment was repeated with a computer generated Maltese cross (95% contrast) as a target. All subjects were emmetropes or soft contact lens wearers and had an amplitude of accommodation that was normal for their age. The mean accommodative responses were normalised and are shown in the graphs below. The response to the DoG stimulus is shown with the filled-diamonds and the response to the Maltese cross is shown by the filled squares. The solid diagonal line in each graph represents the 1:1 ratio between the accommodative stimulus and response.

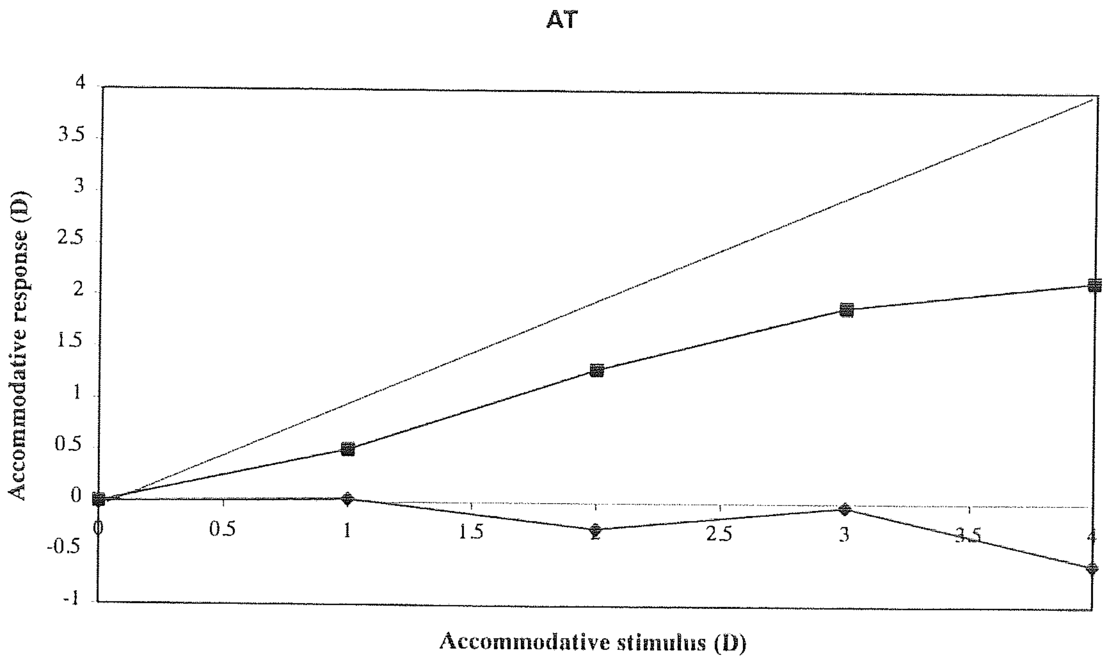





ER
Accommodative response (D)
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5
Accommodative stimulus (D)

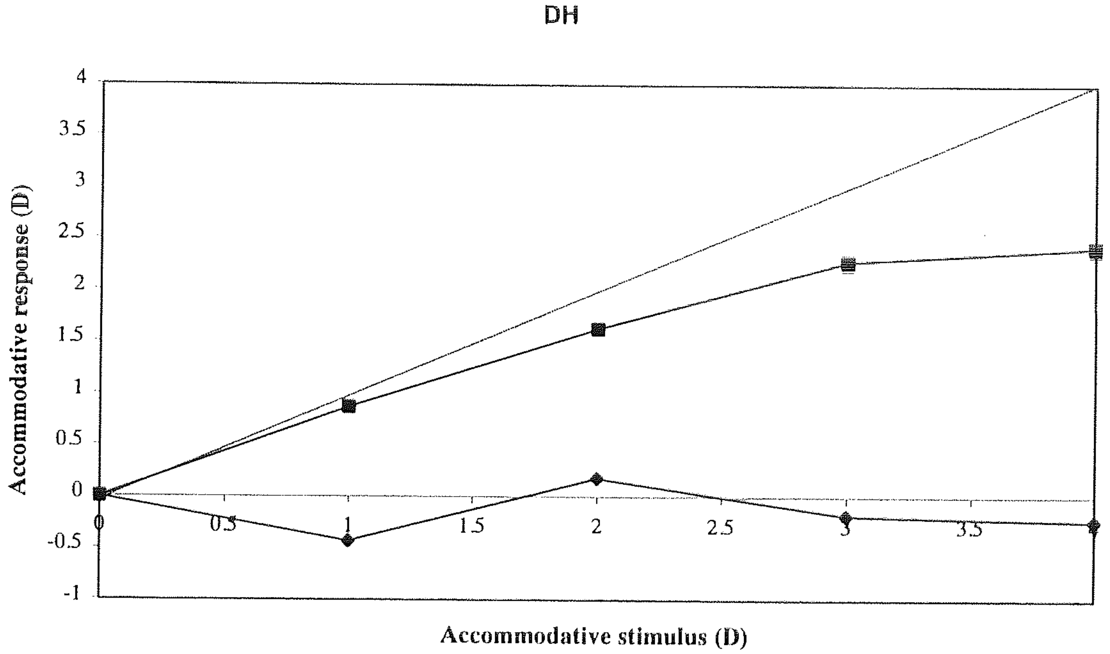

MC
Accommodative response (D)
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
Accommodative stimulus (D)


IP
Accommodative response (D)
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
Accommodative stimulus (D)



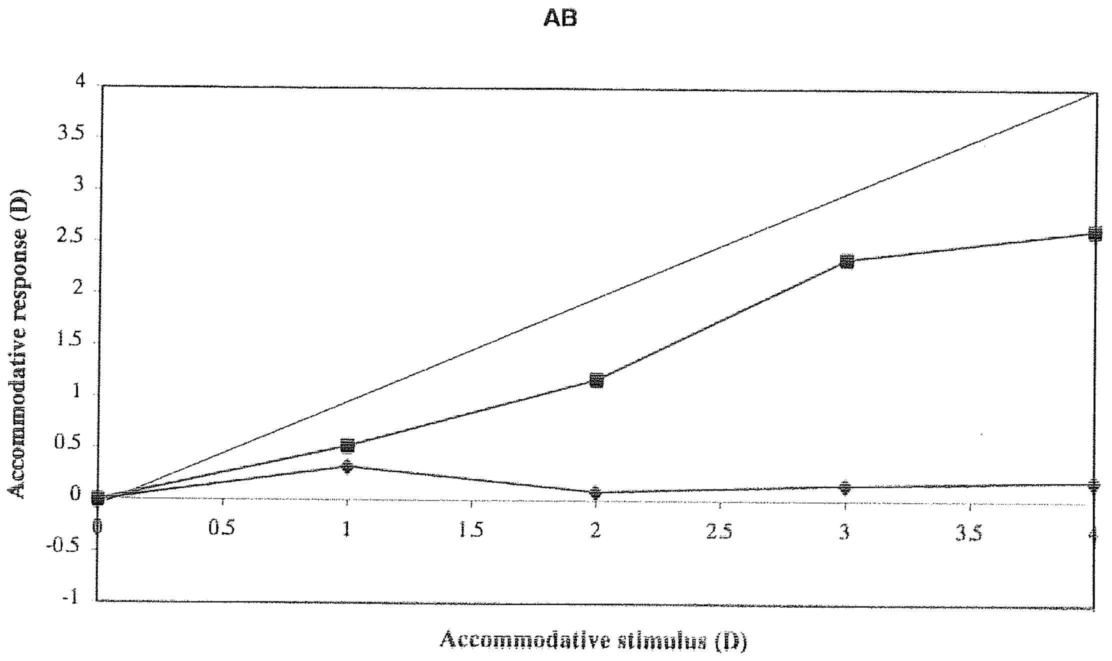
AT

Accommodative response (D)
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
Accommodative stimulus (D)



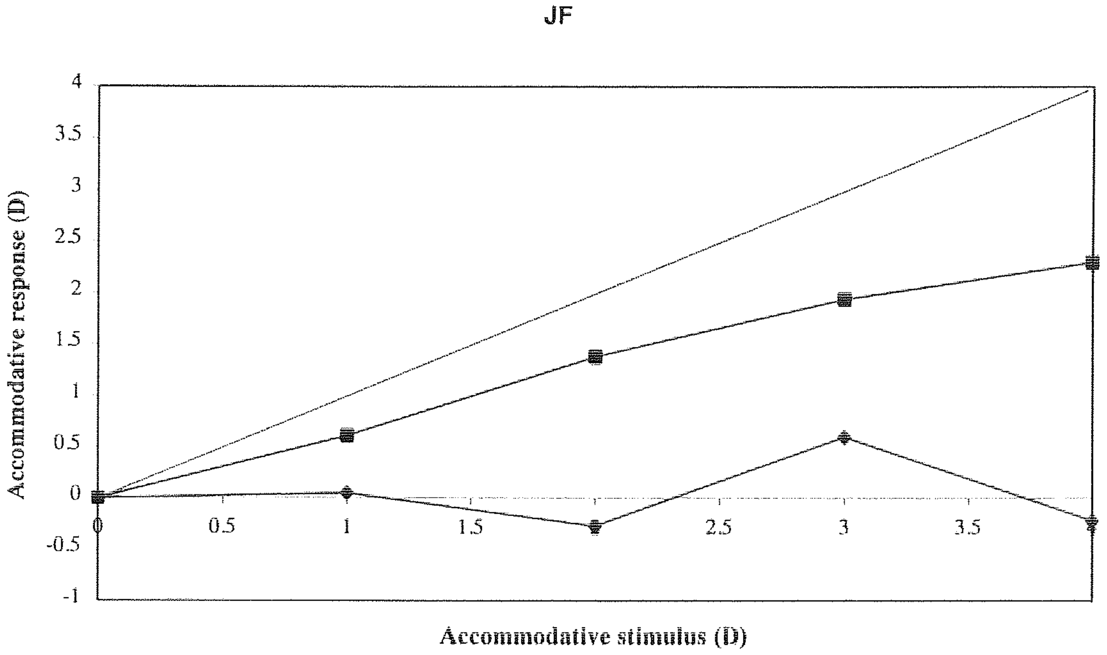
DH

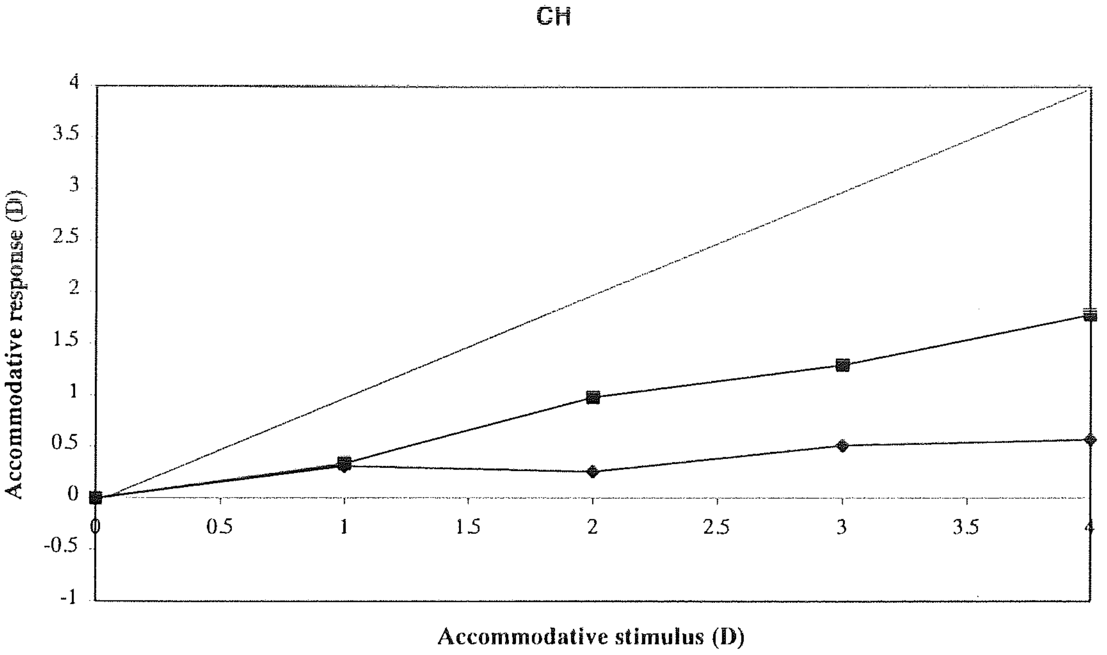
Accommodative response (D)
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5
Accommodative stimulus (D)



AB

Accommodative response (D)
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
Accommodative stimulus (D)





It can be seen from the graphs that the DoG stimulus did not act as a stimulus to accommodation and thus could be used to create open-loop accommodation conditions.

APPENDIX 4: ETHICAL COMMITTEE SUBMISSION

The following pages show duplicates of the forms submitted to the Human Science Ethical Committee at Aston University as an application for approval of the research project.

ASTON UNIVERSITY **PROJECT NO...........**

THE SENATE **REG/97/130**

HUMAN SCIENCE ETHICAL COMMITTEE

Application for approval of a research project involving human volunteers

Please read the enclosed guidelines before completing this form - in typescript or black ink - and return the form to: The Secretary of the Human Science Ethical Committee, Registry. If you intend to administer or expose subjects to a physical procedure other than simple venepuncture **you must also submit an experimental protocol.**

Project title:

Incipient presbyopia: An investigation of oculomotor, refractive and biometric parameters.

Investigators: **Department /address:**

Aston University

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....

A
Details of sponsoring/collaborating organisation (if any)

1. Name: N/A

2. Does the sponsoring/collaborating organisation provide insurance? YES/NO

3. If drugs are used, do any require a clinical trials certificate or clinical trials exemption certificate? YES/NO

B
Summary of project

1. Starting date: January 1998

2. Duration: 2½ years

3. Location: Vision Sciences Dept., Aston University

4. Physical procedures:

Amplitude of accommodation reduces with age; the symptoms during close work that this reduction causes tend to appear between 35 and 45 years of age. Crosslinks exist between accommodation and the vergence of the eyes. Variations in the oculomotor functions of the eyes that may occur alongside the reduction in accommodative amplitude are thus being investigated in a longitudinal and cross-sectional study.

The longitudinal study will involve a subject group aged 35 to 45 and a control group aged 25 to 35 with experimental measures taken every 4-5 months. The cross sectional study will involve subjects aged between 10 and 75 years of age and these subjects will only be required to attend for two experimental sessions.

1) A sight test will be performed that will include ophthalmoscopy, a subjective refraction, measurement of the subject's amplitude of accommodation using the RAF rule, an assessment of stereopsis and an assessment of distance heterophoria using the standard Maddox rod technique.

2) Stimulus and response AC/A (accommodative convergence/accommodation) ratios will be assessed using a Canon R-1 IR open-view autorefractor and alignment device with a varying stimulus to accommodation. Pupil size will also be assessed by direct measurement from a graticule located on the autorefractor monitor displaying the image of the eye.

3) The CA/C (convergence accommodation/convergence) ratio will be assessed using the autorefractor with the introduction of varying prisms.

4) Prism adaptation to 6^{Δ} base-in and 6^{Δ} base-out will be assessed using a flashed Maddox rod technique

5) Tonic accommodation will be assessed using the autorefractor after a period of dark adaptation

6) Tonic vergence will be assessed using a variation of the flashed Maddox rod technique after a period of dark adaptation

5. Substances to be administered (a substance is anything other than normal food. Chemical constituents of food stuffs, ethanol and variation of the diet should be included here):

None

6. Psychological assessment:

None

7. Questionnaires: (only to be completed when project contains questionnaire(s) which fall within the types of questionnaire requiring HSEC approval [Guidelines D(3)])

None

C
Subjects

1. Number of subjects to be used: Approximately 150

2. Over what time span? 2½ years

3. Age of subjects: 10-75

4. Sex of subjects: Male and female

5. Source: Staff and students of Aston University and patients in Vision Sciences department routine general clinics

6. Will payments be made to the subjects and if so, how much will each be paid?

There will be no payment although subjects will receive a standard sight test.

7. Are the subjects patients or healthy volunteers? (If patients, give diagnosis, clinic/responsible practitioner).

Healthy volunteers

8. Will any subjects be excluded and if so, on what grounds?

Subjects will be excluded if they present with any of the following:

1) Ametropia (refractive error) unless corrected by soft contact lenses.
2) A corrected visual acuity of less than 6/9 in either eye.
3) Any ocular pathology.
4) An amplitude of accommodation that is outside the normal range for the subject's age.
5) Any systemic disease or prescribed medication that may influence the results.

9. Is the activity of the subject to be restricted in any way before of after the procedure? (e.g. diet, driving).

No

10. Consent: Please attach a copy of the consent form you intend to use, detailing how procedures and hazards will be explained.

D
Hazards

1. Please give full details of any hazards which could affect the health, safety or welfare of any subject.

None

2. How do you propose to minimise these hazards?

3. Is there any precedent for these experiments? If so, please give details with references if possible.

Other researchers have used similar experiment methods to measure these parameters:

Bruce, A. S., Atchison, D. A., and Bhoola, H. (1995). Accommodation-convergence relationships and age. *Investigative Ophthalmology and Visual Science*, **36**, 406-413.

Ciuffreda, K. J., Rosenfield, M., and Chen, H. (1997). The AC/A ratio, age and presbyopia. *Ophthalmic and Physiological Optics*, **17**, 307-315.

Rosenfield, M., Ciuffreda, K. J., and Chen, H. (1995). Effect of age on the interaction between the AC/A and CA/C ratios. *Ophthalmic and Physiological Optics*, **15**, 451-455.

4. Has this project been considered/is it being considered by any other Ethical Committee? If so, please give details and decision made.

No

E

STATEMENT BY NAMED INVESTIGATORS, HEAD OF DEPARTMENT AND (if necessary) RESEARCH SUPERVISOR

I consider that the details given constitute a true summary of the projects and that the hazards and potential risks to any subject are accurately described.

Investigator..date.....................................

Investigator..date.....................................

Investigator..date.....................................

Investigator..date.....................................

Investigator..date.....................................

Head of
Department..date.....................................

Supervisor.. . date.....................................

The following should be attached:

- *subject consent form
- *insurance certificate (if available)
- *clinical trials certificate or clinical trials exemption certificate (if appropriate)
- *experimental protocol

ASTON UNIVERSITY **REG/85/456**

HUMAN SCIENCE ETHICAL COMMITTEE

CONSENT FORM FOR VOLUNTEER SUBJECTS

PROJECT TITLE

Incipient presbyopia: An investigation of oculomotor, refractive and biometric parameters.

RESEARCH WORKERS AND DEPARTMENT RESPONSIBLE

EXPLANATION OF ANY POSSIBLE HAZARDS AND THE PROCEDURES TO BE USED

The relationship between the accommodation (effort to focus at near) of the eyes and the extraocular muscle actions of the eye is being investigated in subjects representing a cross-section of ages. The following will be measured during two experimental sessions:

1) Subjective refraction – this determines any spectacle prescription
2) Amplitude of accommodation – an assessment of the ability to focus on near objects
3) Distance heterophoria – the resting position of the eyes in normal lighting
4) Stereopsis – quality of binocular vision
5) AC/A and CA/C ratios –the relationships between focusing at near and the position of the eyes
6) Prism adaptation – the ability of the eyes to overcome looking through a prism (a lens that deflects light)
7) Tonic accommodation – the resting focus of the eyes in the dark
8) Tonic vergence – the resting position of the eyes in the dark

The measurements will be made using standard optometric equipment that is used in routine general optometric practice or variations of this. No drugs need to be instilled into the eyes for any of the procedures and there are no reported significant side-effects from having any of the measurements taken.

CONFIDENTIALITY OF INFORMATION

The confidentiality of personal information and the anonymity of all subjects involved in this investigation will be preserved in the following way:

The subjects will be recorded as a number rather than a name and all patient information and data will be stored on computer, complying with the Data Protection Act.

VOLUNTEER'S STATEMENT

I have read and understood the above explanation. I have had the opportunity to discuss it with the investigators and to ask any questions. I agree to take part in the above project and I understand that I am free to withdraw at any time.

Signed: ....

Dated: ....

JGW/HSEC 1.10.97

Rationale and Experimental Protocol

Incipient Presbyopia: An investigation of oculomotor, refractive and biometric parameters.

Clinically it is known that around the age of forty the first symptoms of presbyopia are presented with reading and closework difficulties. The gradual reduction in accommodation that occurs will be accompanied by changes in the oculomotor system as it attempts to maintain the overall vergence response of the eyes. The method by which the oculomotor system is able to overcome the reduction in accommodation is of value to the clinician to explain why patients may or may not complain of asthenopic symptoms associated with poor overall vergence control.

There have been recent reports on measures of AC/A (accommodative convergence/accommodation) and CA/C (convergence accommodation/ convergence) ratios that have included pre- and post-presbyopes (Bruce *et al.* 1995; Rosenfield *et al.* 1995; Ciuffreda *et al.* 1997) but no previous study has attempted to correlate changes in accommodative status with the profile of oculomotor responses occurring within the incipient phase of presbyopia

The experiment will involve the assessment of a number of oculomotor functions in a cross-sectional and longitudinal study.

Longitudinal study

A group of subjects aged between 35 and 45 years of age (incipient presbyopes) will be assessed approximately every four months over a period of two years.

For comparison, a group of subjects aged between 25 and 35 years of age will also be followed over a two-year period.

There will be 30 subjects in each of these groups

Cross-sectional study

Subjects between the ages of 10 and 75 will be assessed with the subjects grouped into categories based on accommodative amplitude. There will be around 75 subjects in this study.

Subject selection criteria

1) Subjects must be emmetropes or soft contact lens wearers (due to the experimental design) and must have corrected visual acuities of 6/9 or better in each eye.

2) Binocular vision must be normal (assessed by stereopsis) and the distance heterophoria must be 3^{Δ} or less (to allow the use of the prism adaptation set-up).

3) There must be no ocular pathology present

4) Subjects must have an amplitude of accommodation that is normal for their age.

5) The subject's consent is required before any aspect of the experiment is undertaken

Baseline details to be measured

1) Refractive error (from subjective refraction)
2) Visual acuities
3) Amplitude of accommodation - monocular and binocular - RAF rule
4) Distance heterophoria
5) Stereopsis
6) Age
7) Gender
8) Eye colour

Experimental measures

1) Stimulus and response AC/A ratios will be assessed using a Canon R-1 IR open-view autorefractor and alignment device with a varying stimulus to accommodation. Pupil size will also be assessed by direct measurement from a graticule located on the autorefractor monitor displaying the image of the eye.

2) The CA/C ratio will be assessed using the autorefractor with the introduction of varying prisms.

3) Prism adaptation to 6^{Δ} base-in and 6^{Δ} base-out will be assessed using a flashed Maddox rod technique.

4) Tonic accommodation will be assessed using the autorefractor after a period of dark adaptation.

5) Tonic vergence will be assessed using a variation of the flashed Maddox rod technique after a period of dark adaptation.

To assess all the functions outlined above will take two experimental sessions lasting approximately 1 hour each.

References

Bruce, A.S., Atchison, D.A. and Bhoola, H. (1995). Accommodation-convergence relationships and age. *Investigative Ophthalmology and Visual Science,* **36**, 406-413

Ciuffreda, K.J., Rosenfield, M., and Chen, H. (1997). The AC/A ratio, age and presbyopia. *Ophthalmic and Physiological Optics*, **17**, 307-315

Rosenfield, M., Ciuffreda, K.J., and Chen, H. (1995). Effect of age on the interaction between AC/A and CA/C ratios. . *Ophthalmic and Physiological Optics*, **15**, 451-455

APPENDIX 5: THE GRADIENT AC/A RATIO

This study was designed to investigate whether there was any significant difference between the gradient AC/A ratio found using positive or negative lenses. The study was undertaken at the State University of New York (SUNY) - College of Optometry under the supervision of Dr Mark Rosenfield.

Both the stimulus and response AC/A ratios were measured in 28 young subjects (mean age = 23.5). Sixteen of these subjects were emmetropic with a mean refractive correction of +0.05D. The remaining 12 subjects were myopic, having a mean refractive correction of –4.35D. Eight of the myopes were corrected with soft contact lenses, and six with spectacles. All subjects could achieve a visual acuity (with correction if necessary) of at least 6/6 in either eye.

The stimulus and response AC/A ratios were determined while subjects viewed a near target at a distance of 33cm (accommodative stimulus of 3D). The accommodative stimulus and response were measured while subjects viewed the near target through their habitual distance refractive correction, or with +1.00, +2.00, –1.00 or –2.00D binocular near additions introduced over their refractive correction. The order of introducing each stimulus was randomised across subjects and five measurements were taken for each stimulus condition.

The accommodative response was measured using a stigmatoscope. The near heterophoria was measured using the Thorington technique. The target consisted of a black vertical arrow, with a horizontal line of high-contrast black letters and numbers on either side of the arrow. A 6^{Δ} base-up dissociating prism was introduced before the left eye to create vertical diplopia. Subjects were directed to view the lower arrow and to indicate which letter or number the arrow pointed to. The digits were spaced 3.3mm apart to correspond to a deviation of 1^{Δ}.

The table below shows the stimulus AC/A ratio found for the positive and negative lenses (AC/As+ and AC/As– respectively) and the response AC/A ratio found for the positive and negative lenses (AC/Ar+ and AC/Ar– respectively).

subject	AC/As+	AC/As-	AC/Ar+	AC/Ar-
vg	2.75	1.16	2.27	0.64
ch	1.92	0.15	1.45	0.06
ml	4.46	2.06	3.56	1.29
mf	0.88	0.52	1.17	0.56
dr	1.50	2.57	1.88	2.15
cal	0.54	1.18	0.33	1.66
fm	1.36	2.01	1.21	1.32
pl	2.66	2.00	3.16	2.72
chl	2.46	1.98	3.30	0.61
vn	3.76	2.17	5.34	2.71
km	0.42	2.15	0.43	1.97
dn	1.07	0.77	0.86	0.60
mch	1.51	0.38	1.33	0.59
ck	0.62	0.53	0.59	0.58
ab	1.63	1.25	1.70	0.82

fs	2.96	5.22	2.56	3.29
ms	2.28	4.12	1.69	3.62
cc	1.90	1.54	1.36	1.42
cw	2.91	1.54	2.70	1.50
lt	2.29	1.29	2.32	1.42
ak	0.90	1.69	0.88	1.28
kk	4.39	3.03	3.61	2.59
wc	2.50	1.09	1.37	0.50
mcr	1.83	1.19	1.96	1.92
cm	3.15	4.35	2.93	3.65
jr	0.76	2.90	0.69	2.34
am	3.80	0.29	3.34	0.24
jt	0.42	0.39	0.29	1.11
mean	2.06	1.77	1.94	1.54
SD	1.16	1.24	1.20	1.00
SEM	0.22	0.23	0.23	0.19

It was found that there was no significant difference between the mean value of the stimulus AC/A ratio found with positive and negative lenses ($t=1.088$, $p=0.29$) or the response AC/A ratio found with the different lenses ($t=1.582$, $p=0.13$). However, it can be seen looking at the data in the table that for many of the subjects there was a difference between the two ratios. This difference in the ratios must be due to a difference between the level of accommodation relaxed by the positive lenses compared to the increase in accommodation induced by the negative lenses.

The difference in the ratios for each individual suggests that the choice of lenses that are used to measure the gradient AC/A ratio should be based on which lenses are most appropriate to the particular situation. For example if the AC/A ratio is being measured in order to prescribe a positive addition to reduce an esophoria, then positive lenses should be used to assess the AC/A ratio. The use of negative lenses in such a situation may result in an inappropriate AC/A ratio since the subject's increase in accommodation to negative lenses may be different from the decrease in accommodative response induced by positive lenses.

In the assessment of proximal vergence in Chapter 6 the gradient AC/A ratio is being compared to the AC/A ratio found by comparing the distance and near heterophoria. The gradient AC/A ratio was thus measured using positive lenses only. This involves the assessment of heterophoria for accommodative stimuli of 3D (no lenses), 2D and 1D which will be more appropriate for the comparison to the difference in the distance and near heterophoria which represent stimuli of 0 and 3D.

APPENDIX 6: DATA RELATING TO THE AFFECT OF AGE ON THE AMPLITUDE OF ACCOMMODATION

Presented here is the amplitude of accommodation (D) for each subject at each of the 7 longitudinal study visits. The age given is for the subject at the first time of assessment.

subject	age	1	2	3	4	5	6	7
PS	43.00	4.62	4.50	4.25	4.25	3.75	3.25	3.25
RG	41.00	4.87	4.50	4.25	3.50	3.75	3.75	3.50
AD	42.00	5.75	6.00	5.50	4.62	4.75	3.75	4.00
PF	41.25	5.25	4.50	4.50	4.50	4.37	4.12	4.12
AC	43.50	4.75	4.75	4.00	3.75	3.75	3.75	3.50
IF	35.25	7.00	6.75	6.75	5.75	5.75	5.75	5.25
DS	45.75	4.50	4.00	3.50	2.75	3.25	2.37	2.00
CL	42.75	5.25	5.00	5.00	4.00	4.00	3.75	3.87
MD	42.50	5.50	5.50	5.25	5.25	4.75	4.75	4.50
CH	42.50	4.00	4.00	4.00	4.00	3.75	3.75	3.50
LR	41.50	3.75	3.50	3.50	3.00	2.87	2.75	2.62
BH	43.75	6.00	6.00	6.00	6.00	5.75	5.75	5.50
MN	43.75	3.50	3.50	2.87	2.87	2.87	2.87	1.87
GW	35.25	5.75	6.00	5.75	5.25	5.25	5.25	5.50
SK	45.25	4.50	4.75	4.50	4.50	4.25	4.00	3.87
SM	43.25	3.75	3.50	3.25	3.25	3.25	2.75	2.50
AM	41.25	4.00	3.50	3.50	3.50	3.00	3.00	2.75
AI	42.00	4.25	4.25	4.00	4.00	3.37	3.12	3.12
TW	37.00	5.75	5.50	5.50	4.75	4.87	4.75	4.62
AA	43.50	4.00	3.75	3.50	3.50	3.25	3.25	3.00
RT	44.25	4.50	3.50	3.00	3.00	3.00	3.00	2.75
SD	36.25	5.75	6.00	5.50	5.75	5.25	5.25	5.25
SB	37.75	7.25	7.00	7.00	7.00	7.00	6.50	5.87
MNO	42.25	4.25	4.25	4.25	4.25	4.00	4.25	3.75
DB	44.75	3.25	3.25	3.00	2.75	2.62	2.25	1.87
DH	44.50	5.25	4.75	5.25	5.25	4.25	4.25	4.25
RL	44.50	3.00	3.00	2.87	2.87	2.62	2.62	2.50
BY	40.00	6.25	6.00	6.00	5.75	5.75	5.25	4.75
MM	28.50	7.58	7.25	7.50	6.75	7.25	7.25	7.00
KB	26.75	7.25	7.50	7.75	7.75	7.50	7.25	7.25
ZB	20.75	9.00	8.50	8.50	7.75	8.50	8.50	8.00
EC	25.00	9.50	9.50	9.75	9.75	9.75	9.50	8.75
MA	27.25	7.00	6.75	7.25	7.25	7.25	7.00	7.75
JS	22.00	7.75	7.75	7.75	7.50	7.25	7.12	7.00
JL	25.25	7.00	7.00	7.00	6.50	6.75	6.75	6.50
RB	24.00	10.25	10.25	10.00	10.25	10.00	9.50	9.75
LD	20.00	13.00	12.75	12.75	12.00	10.75	12.00	12.00
JF	24.00	10.25	10.00	10.25	10.00	9.75	10.25	10.00

APPENDIX 7: DATA RELATING TO TONIC ACCOMMODATION

Presented here is the tonic accommodation (D) for each subject at each of the 7 longitudinal study visits.

subject	1	2	3	4	5	6	7
PS	1.01	1.23	1.86	1.69	1.64	1.86	2.54
RG	0.01	0.68	1.14	0.52	0.30	0.53	0.65
AD	0.62	0.92	0.88	0.81	0.90	0.85	0.56
PF	0.92	0.71	0.70	1.05	0.89	0.95	1.03
AC	0.41	0.72	0.92	0.37	0.85	0.95	1.18
IF	0.55	0.25	0.35	0.49	0.47	0.61	0.83
DS	0.81	1.51	0.50	0.75	0.39	0.66	0.08
CL	0.83	1.05	1.08	1.02	0.99	1.03	1.31
MD	0.06	0.57	0.02	-0.10	0.49	0.12	-0.09
CH	0.99	2.14	2.04	1.06	0.34	0.45	0.49
LR	0.17	-0.17	1.14	1.15	0.33	0.43	0.55
BH	1.11	1.31	0.73	0.89	0.91	0.85	1.02
MN	0.71	2.11	0.73	1.91	1.62	1.47	1.54
GW	2.44	2.14	1.67	1.40	1.19	1.50	2.52
SK	0.06	0.09	1.19	-0.03	0.67	0.49	0.93
SM	-0.06	0.70	0.90	0.77	0.15	0.88	1.54
AM	0.73	0.18	0.14	0.12	0.51	0.55	1.27
AI	0.23	0.48	-0.19	-0.17	0.27	0.14	0.11
TW	0.25	1.33	0.32	0.38	1.63	0.35	0.37
AA	0.75	0.51	0.46	1.17	0.28	0.75	0.77
RT	0.13	0.51	0.00	0.13	0.01	0.22	0.13
SD	1.09	1.20	0.49	0.70	0.18	0.85	0.35
SB	1.15	1.02	1.11	0.98	1.19	1.12	1.16
MNO	0.15	0.18	0.90	1.11	0.52	0.85	0.57
DB	0.56	1.19	0.54	0.91	-0.04	0.65	0.72
DH	1.24	1.29	1.94	0.85	0.88	0.75	0.72
RL	0.10	0.23	0.75	1.60	3.18	0.95	0.86
BY	0.57	0.23	1.00	0.62	0.65	0.85	0.25
MM	0.80	0.79	0.47	0.44	0.80	0.55	0.47
KB	0.76	0.89	0.35	0.44	0.35	0.36	0.47
ZB	0.94	0.86	1.31	0.38	0.06	0.85	1.09
EC	0.65	0.45	0.66	0.66	0.47	0.47	0.63
MA	1.32	2.12	0.90	1.59	1.88	1.59	2.89
JS	1.26	0.90	0.79	0.48	0.17	0.65	1.69
JL	0.04	0.13	0.14	-0.18	0.13	0.17	0.19
RB	0.78	0.55	0.81	1.20	0.80	0.95	0.68
LD	0.01	-0.03	-0.67	0.34	-0.22	0.13	-0.12
JF	0.76	0.99	0.85	1.27	1.06	0.95	-0.01

APPENDIX 8: DATA RELATING TO ACCOMMODATIVE ADAPTATION

Presented here is the time (in seconds) taken for accommodation to return to the baseline TA level after a 3 minute near-vision task, measured for each subject at the 4th, 5th and 7th experimental sessions.

subject	4	5	7
PS	6	3	7
RG	40	50	15
AD	30	25	20
PF	10	10	10
AC	3	0	3
IF	15	15	15
DS	10	5	10
CL	10	15	15
MD	4	5	4
CH	5	10	5
LR	12	12	10
BH	40	40	40
MN	5	5	5
GW	5	5	5
SK	0	0	0
SM	10	10	5
AM	4	5	15
AI	20	30	20
TW	10	20	10
AA	40	40	25
RT	20	20	20
SD	0	0	0
SB	70	45	28
MNO	0	0	0
DB	10	10	10
DH	25	5	5
RL	10	20	10
BY	10	10	10
MM	5	0	0
KB	15	15	15
ZB	40	40	40
EC	3	3	10
MA	10	10	10
JS	12	10	5
JL	10	8	10
RB	20	20	20
LD	20	20	20
JF	8	10	15

APPENDIX 9: DATA RELATING TO THE CA/C RATIO

Presented here is the CA/C ratio (D/MA) measured for each subject at each experimental session.

subject	1	2	3	4	5	6	7
PS	0.18	0.20	0.19	0.18	0.12	0.14	0.14
RG	0.61	0.39	0.23	0.30	0.30	0.29	0.22
AD	0.48	0.46	0.46	0.43	0.38	0.46	0.47
PF	0.52	0.54	0.58	0.47	0.51	0.59	0.58
AC	0.33	0.35	0.27	0.28	0.28	0.27	0.25
IF	0.54	0.37	0.43	0.29	0.34	0.30	0.27
DS	0.37	0.34	0.29	0.36	0.31	0.14	0.18
CL	0.41	0.31	0.42	0.43	0.35	0.40	0.40
MD	0.50	0.47	0.45	0.55	0.65	0.33	0.41
CH	0.47	0.47	0.39	0.53	0.49	0.53	0.51
LR	0.56	0.59	0.52	0.47	0.50	0.43	0.43
BH	0.56	0.65	0.76	0.69	0.38	0.65	0.59
MN	0.47	0.44	0.61	0.49	0.57	0.31	0.31
GW	0.70	0.62	0.67	0.63	0.48	0.64	0.83
SK	0.83	0.57	0.77	0.72	0.73	0.64	0.78
SM	0.55	0.47	0.43	0.46	0.46	0.42	0.37
AM	0.34	0.36	0.34	0.31	0.33	0.25	0.17
AI	0.54	0.49	0.53	0.51	0.51	0.39	0.42
TW	0.52	0.75	0.72	0.86	0.71	0.68	0.61
AA	0.32	0.32	0.32	0.35	0.27	0.22	0.35
RT	0.31	0.41	0.40	0.44	0.40	0.45	0.38
SD	0.63	0.41	0.58	0.52	0.51	0.47	0.42
SB	0.62	0.72	0.86	0.63	0.74	0.74	0.68
MNO	0.39	0.40	0.34	0.46	0.32	0.40	0.30
DB	0.43	0.41	0.35	0.36	0.28	0.26	0.26
DH	0.45	0.47	0.37	0.41	0.41	0.38	0.39
RL	0.18	0.20	0.20	0.14	0.14	0.14	0.14
BY	0.55	0.62	0.52	0.40	0.43	0.45	0.55
MM	0.66	0.70	0.67	0.57	0.76	0.60	0.63
KB	0.33	0.48	0.51	0.38	0.41	0.48	0.49
ZB	0.33	0.39	0.37	0.48	0.48	0.42	0.35
EC	0.41	0.34	0.34	0.37	0.27	0.32	0.41
MA	0.41	0.32	0.34	0.38	0.42	0.35	0.31
JS	0.37	0.43	0.37	0.55	0.53	0.49	0.51
JL	0.48	0.44	0.49	0.38	0.33	0.33	0.48
RB	0.76	0.76	0.71	0.85	0.67	0.72	0.83
LD	0.30	0.27	0.46	0.35	0.46	0.40	0.42
JF	0.59	0.57	0.63	0.53	0.54	0.47	0.50

APPENDIX 10: DATA RELATING TO THE STIMULUS AC/A RATIO

Presented here is the stimulus AC/A ratio (MA/D) measured for each subject at each experimental session.

subject	1	2	3	4	5	6	7
PS	0.40	0.59	0.50	0.77	0.56	0.76	0.77
RG	0.85	0.65	1.43	1.08	1.11	1.09	1.11
AD	0.26	0.56	0.47	0.66	0.58	0.60	0.70
PF	0.68	0.66	0.67	0.71	0.73	0.72	0.52
AC	0.76	0.91	0.87	0.90	1.28	0.93	0.94
IF	0.30	0.57	0.43	0.23	0.33	0.29	0.65
DS	0.67	0.64	0.66	0.47	0.69	0.57	0.53
CL	0.24	0.27	0.26	0.37	0.31	0.34	0.26
MD	0.25	0.36	0.37	0.28	0.29	0.33	0.34
CH	1.00	0.88	0.88	0.77	0.96	1.08	1.03
LR	0.49	0.71	0.60	0.82	0.78	0.99	0.68
BH	0.34	0.69	0.59	0.47	0.81	0.78	0.82
MN	0.36	0.32	0.42	0.42	0.29	0.52	0.34
GW	0.52	0.37	0.41	0.64	0.45	0.69	0.57
SK	0.50	1.17	0.52	0.74	0.75	0.88	0.71
SM	0.81	1.04	0.98	0.73	0.89	1.03	1.14
AM	0.27	0.46	0.43	0.46	0.73	0.60	0.52
AI	0.40	0.59	0.60	0.59	0.63	0.65	0.55
TW	0.41	0.69	0.49	0.64	0.52	0.56	0.62
AA	0.87	1.00	0.47	0.66	0.80	0.93	0.80
RT	0.33	0.32	0.37	0.43	0.24	0.30	0.47
SD	0.48	0.38	0.38	0.37	0.32	0.36	0.46
SB	0.55	0.49	0.61	0.77	0.72	1.02	0.98
MNO	0.57	0.62	0.59	0.55	0.42	0.40	0.67
DB	0.55	0.90	0.61	0.70	0.77	0.67	0.70
DH	0.28	0.75	0.44	0.37	0.37	0.21	0.34
RL	0.25	0.49	0.29	0.35	0.23	0.33	0.47
BY	0.72	0.70	0.70	0.74	0.74	1.07	0.77
MM	0.46	0.57	0.85	0.27	0.54	0.37	0.56
KB	0.50	0.28	0.59	0.32	0.49	0.48	0.61
ZB	0.56	0.55	0.53	0.50	0.35	0.48	0.74
EC	0.54	0.61	0.72	0.71	0.43	0.78	0.61
MA	0.67	0.72	0.87	0.79	0.82	1.15	1.11
JS	0.48	0.55	0.59	0.22	0.32	0.33	0.37
JL	0.88	0.82	0.84	0.63	0.73	0.73	0.73
RB	0.59	0.47	0.54	0.55	0.68	0.84	0.83
LD	0.88	0.93	0.77	0.64	0.88	1.02	0.98
JF	0.46	0.44	0.42	0.34	0.44	0.69	0.77

APPENDIX 11: DATA RELATING TO THE RESPONSE AC/A RATIO

Presented here is the response AC/A ratio (MA/D) measured for each subject at each experimental session.

subject	1	2	3	4	5	6	7
PS	0.59	0.99	0.98	1.37	0.87	1.12	1.30
RG	1.48	1.51	2.15	1.74	2.12	1.85	2.19
AD	0.52	0.92	0.89	1.24	1.19	1.57	1.65
PF	0.74	0.78	0.81	0.82	0.91	0.83	0.81
AC	1.41	1.38	1.94	1.81	2.32	2.15	2.01
IF	0.47	0.65	0.59	0.28	0.43	0.42	0.93
DS	1.84	1.87	1.75	2.17	1.57	2.41	1.78
CL	0.67	0.71	0.73	1.77	1.49	1.99	1.01
MD	0.90	0.93	0.99	0.98	0.72	1.11	1.19
CH	1.46	1.31	1.19	1.20	1.87	1.67	1.50
LR	1.72	2.01	1.93	2.06	2.10	2.24	3.23
BH	0.37	0.90	0.65	0.54	0.84	1.17	1.35
MN	0.78	0.65	0.88	1.98	1.06	1.55	1.29
GW	0.64	0.54	0.65	1.15	0.70	1.00	1.02
SK	0.79	1.50	0.85	1.18	1.09	1.41	1.24
SM	1.91	2.48	2.56	1.54	2.12	3.13	2.56
AM	0.87	1.39	1.00	1.14	2.13	2.15	2.52
AI	1.08	2.70	1.74	2.62	1.24	1.60	2.04
TW	0.68	0.99	0.76	1.11	0.78	0.99	1.19
AA	1.51	1.74	0.92	1.32	1.54	2.00	1.53
RT	1.29	0.92	1.30	2.19	1.04	2.41	2.31
SD	0.80	0.69	0.54	0.73	0.58	0.70	0.81
SB	0.79	0.56	0.68	1.16	0.99	1.21	1.16
MNO	1.38	1.52	2.36	1.30	1.66	1.73	3.05
DB	1.17	1.87	1.20	1.28	1.61	1.22	1.94
DH	0.77	1.63	1.18	0.97	1.70	0.73	1.53
RL	2.28	2.52	1.86	2.50	2.55	2.54	2.78
BY	1.31	1.46	1.01	1.02	1.20	1.61	1.59
MM	0.54	0.69	0.93	0.31	0.70	0.44	0.60
KB	0.70	0.37	0.83	0.44	0.66	0.69	0.81
ZB	1.43	1.72	1.35	1.01	1.04	1.15	1.66
EC	0.80	0.85	0.97	0.91	0.63	1.25	0.77
MA	0.80	0.91	0.96	0.93	0.98	1.35	1.47
JS	0.56	0.57	0.60	0.24	0.35	0.36	0.38
JL	0.94	0.90	0.89	0.83	0.88	1.01	0.78
RB	0.67	0.54	0.61	0.54	0.73	0.86	0.94
LD	0.93	0.91	0.92	0.76	0.91	1.10	1.09
JF	0.96	0.98	1.04	1.01	1.14	1.26	1.31

APPENDIX 12: DATA RELATING TO THE STIMULUS-RESPONSE CURVE GRADIENT

Presented here is the gradient of the stimulus-response curve measured under open-loop vergence conditions for each subject at each experimental session.

subject	1	2	3	4	5	6	7
PS	0.68	0.59	0.51	0.56	0.65	0.68	0.59
RG	0.57	0.43	0.66	0.62	0.52	0.59	0.51
AD	0.50	0.61	0.53	0.53	0.49	0.38	0.42
PF	0.92	0.85	0.83	0.86	0.80	0.86	0.64
AC	0.54	0.66	0.45	0.49	0.55	0.43	0.47
IF	0.65	0.88	0.74	0.85	0.76	0.70	0.69
DS	0.36	0.34	0.38	0.22	0.44	0.24	0.30
CL	0.36	0.38	0.36	0.21	0.21	0.17	0.26
MD	0.28	0.39	0.37	0.29	0.40	0.29	0.29
CH	0.69	0.68	0.74	0.64	0.51	0.65	0.69
LR	0.28	0.35	0.31	0.40	0.37	0.44	0.21
BH	0.90	0.76	0.90	0.88	0.96	0.67	0.61
MN	0.46	0.49	0.48	0.21	0.28	0.34	0.26
GW	0.80	0.68	0.64	0.55	0.64	0.69	0.56
SK	0.62	0.78	0.61	0.63	0.69	0.63	0.58
SM	0.42	0.42	0.38	0.47	0.42	0.33	0.45
AM	0.31	0.33	0.43	0.40	0.34	0.28	0.21
AI	0.37	0.22	0.35	0.22	0.50	0.41	0.27
TW	0.60	0.70	0.64	0.58	0.66	0.57	0.52
AA	0.58	0.58	0.51	0.50	0.52	0.46	0.52
RT	0.26	0.35	0.28	0.19	0.23	0.12	0.20
SD	0.60	0.56	0.69	0.50	0.56	0.51	0.57
SB	0.70	0.87	0.89	0.67	0.72	0.84	0.84
MNO	0.42	0.40	0.25	0.42	0.25	0.23	0.22
DB	0.47	0.48	0.51	0.54	0.48	0.55	0.36
DH	0.36	0.46	0.37	0.38	0.22	0.28	0.22
RL	0.11	0.20	0.15	0.14	0.09	0.13	0.17
BY	0.55	0.48	0.69	0.73	0.62	0.67	0.49
MM	0.85	0.82	0.91	0.87	0.77	0.85	0.93
KB	0.71	0.74	0.71	0.72	0.75	0.70	0.75
ZB	0.39	0.32	0.39	0.49	0.33	0.42	0.45
EC	0.68	0.73	0.74	0.78	0.68	0.62	0.79
MA	0.84	0.79	0.91	0.85	0.84	0.85	0.76
JS	0.86	0.96	0.98	0.91	0.90	0.91	0.96
JL	0.93	0.92	0.95	0.76	0.83	0.72	0.93
RB	0.88	0.88	0.89	1.01	0.92	0.98	0.88
LD	0.95	1.03	0.83	0.85	0.96	0.92	0.90
JF	0.48	0.45	0.41	0.34	0.38	0.55	0.59

APPENDIX 13: DATA RELATING TO TONIC VERGENCE

Presented here is the tonic vergence (MA) measured for each subject at the 1st, 2nd, 4th and 7th experimental sessions.

subject	1	2	4	7
PS	-0.39	-0.43	-0.35	0.09
RG	-0.16	-0.18	-0.18	-0.27
AD	0.30	0.31	0.25	0.25
PF	-0.23	-0.23	-0.17	-0.17
AC	0.16	0.44	0.27	0.25
IF	0.30	0.29	0.29	0.29
DS	0.29	0.65	0.11	0.25
CL	0.16	0.17	0.00	0.00
MD	0.14	0.15	0.19	0.15
CH	0.18	0.27	0.05	0.16
LR	-0.18	-0.23	-0.43	-0.34
BH	0.16	0.36	0.23	0.29
MN	0.18	0.41	0.54	0.25
GW	0.00	-0.04	0.00	0.52
SK	0.00	-0.26	0.00	-0.17
SM	0.00	0.28	0.25	0.17
AM	-0.03	0.00	0.00	0.00
AI	0.51	0.57	0.49	0.49
TW	0.40	0.14	0.17	0.17
AA	0.00	0.08	0.17	0.21
RT	0.22	0.33	0.33	0.25
SD	0.23	0.28	0.26	0.26
SB	0.12	-0.03	0.00	0.00
MNO	0.27	0.09	0.00	0.00
DB	0.26	0.40	0.71	0.34
DH	0.17	0.30	0.77	0.35
RL	0.44	0.00	0.08	0.08
BY	0.08	0.17	0.08	0.08
MM	0.50	0.48	0.40	0.48
KB	0.31	0.63	0.70	0.70
ZB	0.16	0.08	0.04	0.08
EC	0.59	0.65	0.97	0.81
MA	0.25	0.41	0.41	0.49
JS	0.29	0.36	0.36	0.29
JL	0.00	0.00	0.00	0.00
RB	0.16	0.16	0.16	0.16
LD	0.43	0.43	0.52	0.43
JF	0.25	0.33	0.25	0.25

APPENDIX 14: DATA RELATING TO PROXIMAL VERGENCE

Presented here are the p.d., the distance heterophoria and the near heterophoria with 0, +1.00D and +2.00D lenses. The gradient AC/A ratio, heterophoria AC/A ratio and proximal vergence in MA/D that were calculated from these are also shown. The measurements were made for each subject at the first and last experimental sessions.

subject	visit	pd	dist phoria	+2 lens	+1 lens	Near phoria	gradient AC/A	phoria AC/A	proximal vergence
		cm	Δ	Δ	Δ	Δ	(MA/D)	(MA/D)	(MA/D)
PS	1	6.4	0	-13	-8	-2	0.86	0.90	0.04
	7	6.4	0.5	-14	-8	-2.5	0.90	0.84	-0.05
RG	1	6.1	0.5	-10	-5	-1	0.74	0.92	0.18
	7	6.1	0.5	-10	-6	-2	0.66	0.86	0.21
AD	1	6.6	0.5	-11	-6	-1	0.76	0.92	0.17
	7	6.6	0	-7	-3	0	0.53	1.00	0.47
PF	1	6.4	-1.5	-12	-5	-2	0.78	0.97	0.19
	7	6.4	-0.5	-11	-4	-1	0.78	0.97	0.19
AC	1	6.8	2	0	1	2	0.15	1.00	0.85
	7	6.8	1	-6	0	2	0.59	1.05	0.46
IF	1	6.6	1	-4	-2	0	0.30	0.95	0.65
	7	6.6	2	-3	-1	0	0.23	0.90	0.67
DS	1	6.8	0	-8	-4	-2	0.44	0.90	0.46
	7	6.8	0.5	-4	-3	-1	0.22	0.93	0.71
CL	1	6.4	-0.5	-9	-7.5	-1.5	0.59	0.95	0.36
	7	6.4	-0.5	-8	-4	-2	0.47	0.92	0.45
MD	1	7.2	0	-5	-3	0	0.35	1.00	0.65
	7	7.2	1.5	-5.5	-2	0	0.38	0.93	0.55
CH	1	6.9	0	-10	-8	-4	0.43	0.81	0.37
	7	6.9	0.5	-10	-8	-8	0.14	0.59	0.44
LR	1	6.5	-2	-16	-9	-3	1.00	0.95	-0.05
	7	6.5	-2	-13	-9	-5	0.62	0.85	0.23
BH	1	6.4	0.5	-7	-2	-1	0.47	0.92	0.45
	7	6.4	0.5	-6	-4	-1	0.39	0.92	0.53
MN	1	6.8	-0.5	-12	-8	-4	0.59	0.83	0.24
	7	6.8	-0.5	-9	-7	-4	0.37	0.83	0.46
GW	1	6.9	0	-8	-4	-2	0.43	0.90	0.47
	7	6.9	0	-4	-3	-1	0.22	0.95	0.73
SK	1	6.5	1	-8	-4	0	0.62	0.95	0.33
	7	6.5	1.5	-13	-8	-2	0.85	0.82	-0.03
SM	1	6.6	0.5	-10	-4	0	0.76	0.97	0.22
	7	6.6	1	-8	-4	-1	0.53	0.90	0.37
AM	1	6.3	-1.5	-16	-14	-6	0.79	0.76	-0.03
	7	6.3	-1.5	-18	-12	-9	0.71	0.60	-0.11
AJ	1	6.8	1.5	-6	-2.5	0	0.44	0.93	0.49
	7	6.8	1	-2	-1	0.5	0.18	0.98	0.79
TW	1	6.7	2.5	-8	-2	0	0.60	0.88	0.28
	7	6.7	2	-7	-2	0	0.52	0.90	0.38

AA	1	6.6	0	-9	-4	0	0.68	1.00	0.32
	7	6.6	1	-13.5	-6	2	1.17	1.05	-0.12
RT	1	6.7	0.5	-6	-3	0	0.45	0.98	0.53
	7	6.7	0	-8	-5	-1	0.52	0.95	0.43
SD	1	6.5	1.5	-5	-2	-1	0.31	0.87	0.56
	7	6.5	2	-5	-3	-1	0.31	0.85	0.54
SB	1	6.2	0.5	-3	0	0	0.24	0.97	0.73
	7	6.2	0.5	-3	-2	0	0.24	0.97	0.73
MNO	1	6.2	0.5	-8	-4	-1	0.56	0.92	0.35
	7	6.2	0	-8	-5	-3	0.40	0.84	0.44
DB	1	6.5	2	-8	-5	-2	0.46	0.79	0.33
	7	6.5	1	-6.5	-3.5	-1	0.42	0.90	0.47
DH	1	6.7	0	-4	-2	1	0.37	1.05	0.68
	7	6.7	0.5	-1.5	0	5	0.49	1.22	0.74
RL	1	6.7	0.5	-6	-4	1	0.52	1.02	0.50
	7	6.7	0	-8	-5	0	0.60	1.00	0.40
BY	1	6.6	0	-9	-4	1	0.76	1.05	0.29
	7	6.6	-1	-8	-4	0	0.61	1.05	0.44
MM	1	6.3	-1	-16	-12	-7	0.71	0.68	-0.03
	7	6.3	-2	-17	-12	-8	0.71	0.68	-0.03
KB	1	6.4	0	-8	-6	-2	0.47	0.90	0.43
	7	6.4	0	-7	-5	-1	0.47	0.95	0.48
ZB	1	6.3	1	-4	-1	0	0.32	0.95	0.63
	7	6.3	0	-4	-1.5	0	0.32	1.00	0.68
EC	1	6.2	-1.5	-3	-4	0	0.24	1.08	0.84
	7	6.2	-1.5	-4	-3	0	0.32	1.08	0.76
MA	1	6.1	0.5	-2	0	1	0.25	1.03	0.78
	7	6.1	1	-1	0	1	0.16	1.00	0.84
JS	1	7	0	-8	-5	-3	0.36	0.86	0.50
	7	7	0	-7	-4	-2	0.36	0.90	0.55
JL	1	5.8	-0.5	-8	-4	-1	0.60	0.97	0.37
	7	5.8	-0.5	-8	-4	0	0.69	1.03	0.34
RB	1	6.3	0	-10	-3	2	0.95	1.11	0.15
	7	6.3	0	-9	-3	2	0.87	1.11	0.23
LD	1	5.8	-1	-10	-6	-2	0.69	0.94	0.25
	7	5.8	-1	-9	-5	-1	0.69	1.00	0.31
JF	1	6	-1	-7	-4	-2	0.42	0.94	0.53
	7	6	-1	-8	-4	-2	0.50	0.94	0.44

APPENDIX 15: DATA RELATING TO DISTANCE HETEROPHORIA

Presented here is the distance heterophoria ($^{\Delta}$) measured for each subject at the 1st, 2nd, 4th and 7th experimental sessions. Three measurements were taken at each session and the mean of these measurements calculated and is shown in both prism dioptres and metre angles. Positive values represent esophorias and negative values represent exophoric deviations.

subject	visit	1	2	3	mean phoria ($^{\Delta}$)	mean phoria (MA)
PS	1	0.00	0.00	0.00	0.00	0.00
	2	0.25	0.00	0.25	0.17	0.03
	4	-0.50	-0.50	-0.50	-0.50	-0.08
	7	0.25	0.50	0.50	0.42	0.07
RG	1	0.50	1.00	0.50	0.67	0.11
	2	1.00	1.00	0.50	0.83	0.14
	4	-0.50	0.50	0.50	0.17	0.03
	7	0.50	0.50	1.00	0.67	0.11
AD	1	0.00	0.50	0.00	0.17	0.03
	2	-1.00	-1.00	0.00	-0.67	-0.10
	4	0.00	-0.50	-0.50	-0.33	-0.05
	7	0.00	-0.50	-0.50	-0.33	-0.05
PF	1	1.50	2.00	1.50	1.67	0.26
	2	2.00	1.50	1.50	1.67	0.26
	4	1.50	1.50	1.50	1.50	0.23
	7	1.00	1.25	1.00	1.08	0.17
AC	1	0.00	0.00	0.00	0.00	0.00
	2	-0.50	-1.25	-1.00	-0.92	-0.13
	4	-1.00	-1.00	-1.00	-1.00	-0.15
	7	-1.00	-1.00	-1.00	-1.00	-0.15
IF	1	-1.00	-1.00	-1.00	-1.00	-0.15
	2	-1.50	-1.00	-1.00	-1.17	-0.18
	4	-1.00	-1.00	-1.00	-1.00	-0.15
	7	-0.50	-1.00	-1.00	-0.83	-0.13
DS	1	0.50	1.00	0.50	0.67	0.10
	2	1.00	1.00	1.00	1.00	0.15
	4	-1.00	-1.00	0.00	-0.67	-0.10
	7	0.00	1.00	0.00	0.33	0.05
CL	1	1.00	0.50	1.50	1.00	0.16
	2	0.00	0.75	0.00	0.25	0.04
	4	1.00	0.75	1.25	1.00	0.16
	7	0.25	0.25	0.25	0.25	0.04
MD	1	-2.00	-1.75	-1.50	-1.75	-0.24
	2	-1.50	-1.00	-2.00	-1.50	-0.21
	4	-1.50	-1.50	-1.50	-1.50	-0.21
	7	-2.50	-1.50	-1.50	-1.83	-0.25
CH	1	1.00	0.50	0.25	0.58	0.08
	2	0.00	0.25	0.50	0.25	0.04

	4	0.00	-0.50	-0.50	-0.33	-0.05
	7	0.25	0.50	0.50	0.42	0.06
LR	1	2.50	2.00	2.50	2.33	0.36
	2	3.00	3.00	3.00	3.00	0.46
	4	3.00	2.25	2.50	2.58	0.40
	7	3.00	2.50	2.50	2.67	0.41
BH	1	-0.50	-0.50	-1.00	-0.67	-0.10
	2	-0.50	0.00	-0.50	-0.33	-0.05
	4	-1.00	-1.00	-1.00	-1.00	-0.16
	7	0.50	0.00	0.00	0.17	0.03
MN	1	0.50	-0.50	-0.50	-0.17	-0.02
	2	1.00	0.50	-0.50	0.33	0.05
	4	0.00	1.00	-0.50	0.17	0.02
	7	1.00	0.25	0.25	0.50	0.07
GW	1	0.25	0.75	0.25	0.42	0.06
	2	0.50	0.50	0.75	0.58	0.08
	4	0.50	0.50	0.75	0.58	0.08
	7	1.00	0.75	1.00	0.92	0.13
SK	1	-1.00	-1.00	-1.00	-1.00	-0.15
	2	-1.00	-0.75	-0.75	-0.83	-0.13
	4	-1.00	-0.75	-1.00	-0.92	-0.14
	7	0.50	0.00	-0.50	0.00	0.00
SM	1	-1.00	-1.00	-1.00	-1.00	-0.15
	2	-2.00	-2.00	-1.00	-1.67	-0.25
	4	-1.50	-1.50	-2.00	-1.67	-0.25
	7	-1.00	-1.00	-1.00	-1.00	-0.15
AM	1	3.00	3.50	3.00	3.17	0.50
	2	2.00	1.50	1.50	1.67	0.26
	4	1.75	2.00	1.50	1.75	0.28
	7	1.25	1.00	1.00	1.08	0.17
AI	1	-0.50	-0.25	-0.25	-0.33	-0.05
	2	-0.50	-0.25	-0.50	-0.42	-0.06
	4	-1.00	-0.50	-1.00	-0.83	-0.12
	7	0.50	0.50	0.50	0.50	0.07
TW	1	-1.00	-0.50	-1.50	-1.00	-0.15
	2	-1.00	-1.00	-1.00	-1.00	-0.15
	4	-2.00	-2.00	-1.50	-1.83	-0.27
	7	-1.50	-2.00	-1.00	-1.50	-0.22
AA	1	-1.00	-1.00	-1.00	-1.00	-0.15
	2	-1.00	-1.00	-1.00	-1.00	-0.15
	4	-0.50	-0.50	-0.50	-0.50	-0.08
	7	0.00	-0.25	-0.50	-0.25	-0.04
RT	1	-1.50	-1.25	-1.50	-1.42	-0.21
	2	-1.50	-1.50	-1.50	-1.50	-0.22
	4	-2.00	-1.00	-1.00	-1.33	-0.20
	7	-1.50	-1.50	-1.00	-1.33	-0.20
SD	1	-2.00	-1.50	-1.50	-1.67	-0.26
	2	-2.00	-2.00	-2.00	-2.00	-0.31
	4	-2.00	-2.00	-2.00	-2.00	-0.31

	7	-2.00	-1.75	-2.00	-1.92	-0.29
SB	1	0.00	-0.50	-0.75	-0.42	-0.07
	2	-1.00	-1.50	-1.25	-1.25	-0.20
	4	-0.50	-0.50	-0.50	-0.50	-0.08
	7	-0.50	-0.50	-0.50	-0.50	-0.08
MNO	1	-1.00	-0.25	-1.00	-0.75	-0.12
	2	0.00	0.00	0.00	0.00	0.00
	4	0.00	-0.50	0.00	-0.17	-0.03
	7	0.00	0.00	0.50	0.17	0.03
DB	1	-3.00	-2.00	-2.50	-2.50	-0.38
	2	-1.50	-2.00	-2.00	-1.83	-0.28
	4	-1.50	-2.50	-2.50	-2.17	-0.33
	7	-1.50	-1.50	-1.00	-1.33	-0.21
DH	1	-0.50	0.00	-0.25	-0.25	-0.04
	2	-1.00	-0.50	-0.50	-0.67	-0.10
	4	-1.50	-0.50	-1.25	-1.08	-0.16
	7	-0.50	0.25	0.00	-0.08	-0.01
RL	1	1.50	1.50	1.50	1.50	0.22
	2	1.00	1.00	1.00	1.00	0.15
	4	1.00	1.00	1.00	1.00	0.15
	7	-1.00	1.00	1.00	0.33	0.05
BY	1	0.00	-0.50	-0.50	-0.33	-0.05
	2	-0.50	-0.50	-0.25	-0.42	-0.06
	4	0.00	0.00	0.00	0.00	0.00
	7	0.00	-0.50	0.00	-0.17	-0.03
MM	1	1.75	1.00	1.50	1.42	0.22
	2	1.50	1.00	0.75	1.08	0.17
	4	0.50	2.00	2.00	1.50	0.24
	7	2.00	2.50	2.00	2.17	0.34
KB	1	1.00	1.00	1.00	1.00	0.16
	2	2.50	2.00	1.75	2.08	0.33
	4	3.00	2.00	2.50	2.50	0.39
	7	3.00	2.00	2.00	2.33	0.36
ZB	1	1.00	1.50	0.50	1.00	0.16
	2	0.00	-0.50	-1.00	-0.50	-0.08
	4	0.50	0.50	0.00	0.33	0.05
	7	-0.50	-0.50	0.00	-0.33	-0.05
EC	1	2.00	2.00	3.00	2.33	0.38
	2	1.50	1.75	2.00	1.75	0.28
	4	1.50	2.00	2.00	1.83	0.30
	7	1.50	1.00	1.50	1.33	0.22
MA	1	1.00	0.00	0.00	0.33	0.05
	2	0.50	-1.00	-0.50	-0.33	-0.05
	4	0.00	0.50	0.00	0.17	0.03
	7	1.00	0.25	0.25	0.50	0.08
JS	1	-0.50	0.00	-0.50	-0.33	-0.05
	2	0.00	-0.50	0.00	-0.17	-0.02
	4	-0.50	0.00	0.00	-0.17	-0.02

	7	0.00	0.00	0.50	0.17	0.02
JL	1	0.00	0.00	0.00	0.00	0.00
	2	0.00	0.50	0.00	0.17	0.03
	4	0.50	-0.50	0.00	0.00	0.00
	7	0.00	0.00	0.50	0.17	0.03
RB	1	-1.00	-1.00	-0.50	-0.83	-0.13
	2	-1.00	-0.50	-1.00	-0.83	-0.13
	4	-0.50	-0.50	-0.50	-0.50	-0.08
	7	-0.50	-0.50	-0.50	-0.50	-0.08
LD	1	2.00	2.00	2.00	2.00	0.34
	2	2.00	2.50	2.50	2.33	0.40
	4	4.00	2.00	3.00	3.00	0.52
	7	4.00	2.00	2.00	2.67	0.46
JF	1	1.00	1.50	1.50	1.33	0.22
	2	1.00	2.00	2.00	1.67	0.28
	4	1.00	1.50	2.00	1.50	0.25
	7	1.00	2.00	1.00	1.33	0.22

APPENDIX 16: DATA RELATING TO PRISM ADAPTATION TO BASE-OUT AND BASE-IN PRISM

16a) Presented here is the heterophoria measured (in $^{\Delta}$) using the flashed Maddox rod technique at 15-second time intervals while adapting to 6^{Δ} base-out prism. The measurements have been adjusted to take into account the baseline heterophoria and positive values represent exophoria and negative values are esophorias. The measurement at 0 seconds was the reading taken initially, prior to any adaptation. The prism was removed after 225 seconds of binocular viewing and thus the measurement at 225 seconds represents the heterophoria prior to any recovery. The measurements from 225 to 360 seconds represent the recovery from the adaptation. For the graphical and statistical analysis the values of heterophoria were converted to metre angles.

subjt	visit	0	15	30	45	60	75	90	105	120	135	150	165
PS	1	4.44	2.78	1.67	1.11	1.11	1.11	1.11	1.11	1.11	0.83	0.56	0.56
	2	5.37	3.15	2.59	2.04	2.04	2.59	2.59	2.59	2.59	2.59	1.76	2.04
	4	6.11	3.89	2.78	2.78	2.78	2.78	2.22	2.22	3.33	2.78	2.22	1.94
	7	5.09	3.70	2.87	3.43	2.87	3.43	3.43	2.87	2.87	2.87	2.59	2.87
RG	1	5.33	4.33	4.33	2.33	2.33	2.33	2.33	2.33	1.33	2.33	2.33	1.33
	2	5.19	2.41	1.85	2.41	1.85	2.41	1.85	1.30	1.30	1.85	1.30	1.30
	4	5.93	3.15	3.15	2.59	3.15	3.15	3.15	3.15	3.15	3.15	3.15	3.15
	7	5.93	3.70	2.59	2.59	2.04	2.04	2.04	2.04	2.04	2.04	1.76	2.04
AD	1	5.83	5.83	4.83	4.83	3.33	2.33	1.83	1.83	1.83	1.58	1.83	1.58
	2	4.63	4.63	4.63	4.07	4.07	3.80	2.96	3.52	2.96	2.69	1.85	2.13
	4	5.37	4.81	3.70	4.26	3.70	3.70	3.70	3.43	3.15	2.59	2.59	2.59
	7	6.48	4.26	3.70	3.15	2.59	2.04	1.48	1.48	1.76	1.76	1.48	1.76
PF	1	5.83	4.83	4.08	3.33	3.33	3.33	3.08	2.83	2.83	2.83	2.83	2.83
	2	4.81	3.70	3.70	3.43	3.43	3.43	3.43	3.15	3.15	2.59	2.59	2.59
	4	5.56	4.44	4.44	4.44	3.89	4.44	3.89	3.89	3.33	3.89	3.33	3.33
	7	6.02	5.46	4.35	3.80	3.24	3.24	3.24	2.96	2.96	2.96	2.96	3.24
AC	1	6.50	4.00	3.00	3.00	2.00	1.75	2.50	1.75	1.00	1.50	1.75	1.50
	2	5.46	3.80	3.24	4.35	4.35	3.24	2.69	3.24	2.69	2.69	2.41	2.41
	4	6.11	4.44	3.33	3.33	3.89	3.33	2.22	1.67	2.78	2.22	2.22	2.50
	7	5.56	5.56	4.44	3.89	3.33	3.33	3.33	3.06	2.78	3.06	2.78	2.78
IF	1	6.00	3.00	3.50	3.00	3.00	3.00	3.00	2.50	2.50	2.00	2.00	2.00
	2	5.74	3.80	3.52	3.52	4.07	2.96	3.52	2.96	2.41	2.96	2.41	2.41
	4	5.56	4.44	3.33	3.33	2.78	2.22	2.78	2.22	2.22	2.78	2.22	2.78
	7	5.37	3.15	3.15	3.15	2.87	2.59	2.59	2.31	2.04	2.04	2.04	2.04
DS	1	6.33	5.33	5.33	4.33	3.33	3.33	2.83	2.33	3.33	3.33	3.83	3.33
	2	5.56	5.56	3.33	2.22	3.33	2.22	2.22	3.33	2.22	3.33	1.11	1.11
	4	6.30	5.19	4.63	4.07	4.07	2.96	2.96	2.96	4.07	4.63	2.96	2.96
	7	6.30	5.19	4.07	5.19	4.07	2.96	2.96	5.19	2.96	2.96	2.96	2.96
CL	1	5.50	4.00	3.00	3.00	3.00	2.00	2.00	2.00	2.00	2.00	2.00	1.00
	2	4.72	3.89	3.61	3.06	2.50	2.50	3.06	2.50	2.50	2.50	2.22	3.06
MD	1	5.75	4.00	3.25	2.75	2.75	2.00	1.75	1.50	1.50	0.75	1.25	0.75
	2	6.11	3.89	2.78	2.50	2.50	2.50	2.22	1.94	1.94	1.67	1.67	1.67
	4	5.56	3.89	3.06	2.50	1.94	1.94	1.67	1.11	1.11	1.11	1.11	1.39

	7	6.48	4.26	3.70	3.70	3.15	2.04	2.04	2.04	2.59	2.04	2.04	2.59
CH	1	6.42	4.42	3.42	3.42	2.67	1.42	1.92	1.42	1.42	1.42	1.42	0.67
	2	5.83	4.17	3.89	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94	1.94
	4	5.93	3.70	3.70	2.59	2.59	2.59	2.59	2.59	2.59	2.59	3.15	2.59
	7	5.09	3.43	2.87	2.31	2.31	2.31	2.31	2.04	2.04	1.76	1.76	2.31
LR	1	6.67	4.67	3.67	3.67	4.17	3.67	3.17	3.67	3.67	3.92	3.17	3.67
	2	5.56	4.44	3.89	4.44	4.44	3.89	4.44	5.00	3.33	4.44	4.44	3.61
	4	6.02	4.35	3.80	2.69	3.80	4.91	4.35	2.69	3.80	3.80	2.69	2.69
	7	5.93	4.26	4.26	3.70	3.70	4.81	4.81	3.70	4.26	3.70	4.26	3.70
BH	1	5.67	3.67	2.67	3.67	2.67	2.17	3.17	3.17	2.17	2.17	2.17	1.17
	2	5.93	3.70	3.70	2.59	3.70	3.15	3.15	2.59	1.48	2.04	0.93	2.04
	4	5.56	3.89	3.89	4.44	4.44	4.44	3.89	3.89	3.89	3.89	3.33	3.33
	7	5.37	3.70	2.04	2.04	3.15	2.59	1.48	1.48	1.48	1.48	1.48	1.48
MN	1	6.30	4.35	4.63	3.80	3.24	3.24	2.96	2.41	2.41	2.41	2.13	2.41
	2	6.30	4.07	3.52	4.07	3.52	3.52	3.24	2.96	2.96	2.69	2.41	2.41
	4	6.48	4.26	4.26	3.70	3.15	3.15	2.59	2.59	2.59	1.48	1.48	1.48
	7	5.56	3.89	3.61	3.33	2.78	2.50	2.22	1.39	1.67	1.39	1.39	1.67
GW	1	6.20	3.98	2.87	3.43	2.31	2.59	2.87	2.87	1.76	2.04	2.31	2.31
	2	6.02	3.24	2.96	3.80	3.24	3.80	3.80	3.24	3.24	2.96	2.96	3.52
	4	6.02	4.07	2.96	3.24	3.80	3.80	3.24	3.24	2.57	2.69	2.41	2.69
	7	5.65	3.15	3.43	2.87	2.87	2.04	2.04	2.31	2.04	2.31	2.04	2.04
SK	1	6.00	5.00	4.00	3.00	3.00	2.75	2.50	3.00	3.00	1.75	2.00	1.75
	2	6.20	4.26	2.59	2.04	2.04	1.76	2.04	2.04	1.48	1.48	0.93	1.48
	4	6.57	4.91	3.80	2.69	2.13	2.13	2.69	2.13	1.57	1.02	1.02	1.57
	7	5.56	2.78	1.67	2.22	2.22	2.22	1.67	1.39	1.39	1.67	1.39	1.39
SM	1	5.56	1.11	1.67	2.22	1.11	1.11	0.56	1.11	0.00	0.00	0.56	0.83
	2	6.30	3.80	2.96	3.52	3.52	2.96	2.96	1.85	2.96	2.41	1.85	2.41
	4	6.30	4.07	3.52	2.96	2.96	2.41	2.41	2.41	2.41	1.85	1.85	1.30
	7	5.56	3.89	3.33	2.22	2.22	2.78	2.22	2.22	2.50	2.22	2.22	2.50
AM	1	4.81	2.04	1.48	1.20	1.20	1.48	0.37	0.37	-0.19	-0.74	-0.74	-0.74
	2	5.37	3.70	2.31	2.04	2.31	2.59	3.15	2.31	2.04	2.59	2.04	2.04
	4	6.39	3.61	2.50	1.94	2.50	1.94	1.94	1.94	1.94	2.22	1.94	1.94
	7	5.46	3.24	2.69	2.69	2.69	2.69	2.13	2.13	1.85	1.85	1.85	1.85
AI	1	5.93	4.81	4.26	3.70	3.43	3.70	2.59	3.15	0.93	1.48	2.59	2.04
	2	5.46	5.46	3.80	2.69	2.69	2.69	3.24	2.69	2.13	2.13	2.13	2.13
	4	5.93	4.26	4.26	4.26	3.70	3.15	3.15	2.59	2.59	0.93	1.48	0.93
	7	5.56	3.89	2.78	1.11	0.56	1.11	0.56	0.56	1.11	0.56	0.56	1.11
TW	1	5.56	3.89	3.33	2.78	3.89	3.89	2.78	2.50	2.50	2.22	2.78	1.94
	2	5.56	2.78	3.33	2.78	2.78	2.78	3.33	3.33	2.22	2.22	1.67	2.22
	4	5.93	3.15	3.15	3.70	2.59	2.59	3.70	3.70	3.70	2.59	2.59	2.59
	7	5.56	3.89	3.33	3.33	2.78	2.78	3.33	2.78	2.78	2.22	2.22	2.78
AA	1	6.11	3.33	2.78	3.33	3.33	3.33	3.33	2.78	1.94	2.50	2.50	2.78
	2	5.56	3.33	3.33	2.22	2.78	2.78	2.22	2.78	2.78	2.22	2.78	2.78
	4	5.56	3.33	1.78	2.78	2.22	2.56	2.22	2.22	2.22	1.94	2.22	1.94
	7	5.28	2.50	2.50	2.50	1.94	2.50	1.39	1.11	1.39	1.11	1.39	1.39
RT	1	6.57	4.91	4.35	4.07	3.80	3.52	3.80	3.24	3.24	3.80	3.80	3.24
	2	6.67	5.00	3.89	4.44	4.44	5.00	3.89	3.89	3.89	2.78	3.33	3.33
	4	5.93	4.81	3.70	3.70	3.15	3.70	3.43	3.15	3.15	3.70	3.15	3.70
	7	5.93	5.93	5.37	4.81	4.81	4.81	3.70	4.81	3.70	4.81	3.70	4.81

SD	1	6.30	2.96	1.85	1.30	1.57	1.30	0.74	0.74	0.74	1.85	1.85	0.74
	2	5.56	2.22	1.11	1.11	1.11	1.11	1.11	1.67	1.11	1.11	1.11	1.11
	4	6.11	2.78	1.94	1.11	1.11	1.67	1.11	1.11	1.11	1.39	1.11	1.11
	7	6.02	3.24	2.69	2.13	2.69	1.57	2.13	1.57	1.57	1.57	1.57	1.57
SB	1	6.02	3.52	3.24	2.96	2.96	2.41	2.69	2.41	3.24	2.41	2.41	2.96
	2	6.39	4.17	3.61	3.61	3.61	4.72	4.72	4.17	4.17	3.61	3.61	4.17
	4	5.56	4.44	3.33	4.44	3.61	3.89	3.33	3.33	3.06	3.06	2.78	2.78
	7	6.11	4.17	3.89	3.89	3.61	3.89	3.61	3.61	3.33	3.61	3.61	3.61
MNO	1	6.94	5.28	3.61	4.17	2.78	3.06	3.61	3.33	3.06	3.06	2.78	3.33
	2	5.56	4.44	4.17	3.33	3.33	2.78	3.33	3.33	3.33	3.89	3.89	3.33
	4	5.74	5.19	4.63	4.07	4.07	3.52	3.52	4.07	4.07	4.07	3.52	3.52
	7	6.48	4.26	3.15	4.26	3.70	3.70	4.26	3.70	3.15	3.15	2.59	3.15
DB	1	6.11	4.17	3.89	3.89	4.44	3.06	3.61	3.06	3.06	3.06	3.06	3.06
	2	5.93	3.98	3.15	4.26	3.15	2.87	2.59	2.59	2.59	2.59	2.59	2.59
	4	5.74	4.07	3.52	4.07	4.07	2.96	2.69	2.69	3.52	2.96	3.52	2.96
	7	5.93	3.70	3.15	3.43	2.87	2.31	2.59	2.59	2.31	2.59	2.59	2.31
DH	1	5.28	3.61	3.61	3.06	2.50	2.50	2.22	2.50	2.22	1.94	1.94	2.50
	2	5.19	3.52	3.52	3.52	2.96	2.96	2.96	2.96	2.69	2.41	2.96	2.96
	4	6.20	3.98	3.15	3.43	3.15	2.87	2.87	2.59	2.04	2.31	2.31	2.04
	7	5.65	3.15	2.59	2.31	2.59	1.76	1.76	1.76	2.04	1.76	1.76	2.04
RL	1	6.11	3.89	3.33	3.89	5.00	3.33	3.89	2.78	3.89	2.78	2.50	2.22
	2	5.56	5.00	4.44	4.44	3.33	4.44	3.89	3.89	3.89	2.78	2.78	2.22
	4	5.56	4.44	3.89	3.33	3.89	3.33	3.33	3.06	2.78	2.22	2.22	2.22
	7	6.30	5.19	4.63	4.63	4.07	3.52	3.52	2.96	3.52	2.96	2.96	2.96
BY	1	5.93	5.37	4.81	4.81	3.70	3.15	3.15	3.15	2.59	2.59	3.15	2.59
	2	5.46	5.46	4.91	3.80	3.24	3.24	3.24	3.24	2.69	2.69	2.69	2.69
	4	5.56	4.44	3.89	3.89	3.33	3.89	3.33	3.06	3.06	2.78	2.78	3.06
	7	5.74	3.52	4.63	4.07	4.07	4.07	3.52	2.96	3.52	2.96	3.52	2.96
MM	1	6.58	2.58	1.58	1.58	1.08	1.08	0.58	1.08	0.83	0.58	0.83	0.58
	2	6.02	2.13	1.85	2.41	2.41	1.57	2.13	2.13	2.13	2.13	1.57	2.13
	4	6.11	3.33	2.22	2.22	1.67	2.78	1.67	1.67	2.22	1.67	2.22	1.67
	7	6.48	2.04	1.76	0.93	1.76	2.59	0.93	0.93	1.48	1.48	1.48	1.48
KB	1	5.00	4.00	3.50	3.00	3.00	2.50	2.00	1.75	1.50	1.50	1.00	1.00
	2	5.46	4.35	3.24	3.24	3.24	3.24	3.24	2.69	2.13	2.13	1.85	1.85
	4	6.11	3.89	2.78	2.22	2.22	2.22	1.67	1.67	1.11	1.11	0.56	0.56
	7	6.30	4.07	2.96	2.41	2.41	2.41	1.85	1.85	1.85	1.85	2.41	1.85
ZB	1	5.50	4.50	3.00	3.00	2.50	1.00	1.50	0.00	0.50	1.00	1.50	1.50
	2	6.11	3.89	2.78	2.78	2.78	2.22	1.67	2.22	2.78	2.22	1.67	2.22
	4	5.19	4.07	3.52	2.96	2.96	2.41	2.41	1.85	1.85	1.30	1.85	1.30
	7	7.04	4.81	4.81	3.70	3.15	2.59	2.59	2.59	2.59	2.04	2.04	2.59
EC	1	5.67	4.67	3.17	2.67	2.67	2.17	1.67	1.67	1.17	1.67	1.17	2.17
	2	6.39	4.72	4.17	4.17	3.06	3.06	3.06	2.50	2.50	2.50	2.50	2.50
	4	5.74	5.19	4.07	3.52	2.96	2.96	2.96	2.96	2.96	2.41	2.41	2.41
	7	6.30	4.07	2.96	2.96	2.96	2.96	3.52	2.96	2.96	2.96	3.52	2.96
MA	1	4.67	2.67	1.67	1.67	1.67	1.67	1.67	1.67	0.67	0.67	0.67	0.67
	2	5.93	3.70	2.59	2.59	2.31	2.59	2.59	2.04	1.48	1.48	2.04	0.37
	4	5.37	2.59	2.04	2.04	2.04	2.04	1.48	0.93	0.93	1.48	0.93	0.93
	7	6.11	2.78	2.22	1.94	1.67	1.39	1.39	1.39	0.28	0.56	0.28	0.56

JS	1	6.33	2.33	2.83	2.33	2.33	1.83	1.33	1.33	1.33	1.83	1.33	1.83
	2	5.74	2.41	2.96	2.96	2.96	2.41	2.96	2.41	2.41	1.85	1.85	1.30
	4	5.74	3.52	2.41	2.41	2.41	1.85	1.85	1.85	1.30	1.30	1.85	1.30
	7	6.48	3.15	3.15	2.59	2.59	2.04	2.04	2.59	2.04	2.04	2.04	2.04
JL	1	5.50	2.25	1.75	1.25	1.00	1.00	1.00	1.25	0.75	1.00	0.75	0.50
	2	5.93	2.04	2.31	2.59	2.04	2.04	1.76	1.48	0.93	0.93	0.93	0.37
	4	6.11	2.78	2.22	2.22	1.94	1.67	1.11	0.56	1.11	1.11	0.56	0.56
	7	5.93	2.04	2.31	2.04	2.04	1.76	1.48	0.93	1.48	0.93	0.93	0.37
RB	1	5.83	3.83	2.33	2.83	2.33	2.33	1.83	2.33	1.33	1.33	1.33	1.33
	2	6.48	3.70	2.59	3.15	3.15	2.59	2.59	2.59	2.04	2.04	1.48	1.48
	4	6.11	3.89	2.78	2.22	2.22	2.78	2.50	2.22	1.67	1.67	2.22	1.67
	7	6.11	2.78	2.78	2.22	2.50	1.67	1.39	1.67	1.67	1.39	1.39	1.67
LD	1	5.00	4.00	3.50	4.00	3.00	3.00	2.50	1.50	2.00	1.00	1.00	1.00
	2	5.74	4.07	2.96	2.96	3.52	2.96	2.96	1.85	2.41	1.85	1.85	0.74
	4	5.56	3.33	3.33	2.22	3.33	2.22	2.22	2.22	2.22	3.33	2.22	2.22
	7	5.93	3.70	1.48	2.59	1.48	1.48	1.48	0.93	0.93	0.37	0.93	0.93
JF	1	5.67	3.67	3.17	2.67	2.17	1.67	1.67	1.17	0.67	1.17	0.67	1.17
	2	5.93	3.15	1.48	2.04	2.04	0.37	0.93	0.37	0.93	0.37	0.93	0.37
	4	5.56	3.89	1.67	2.22	1.11	0.56	0.83	1.11	1.11	0.56	1.11	0.56
	7	5.74	4.07	2.96	2.96	1.85	1.85	1.85	1.30	1.30	1.30	1.02	1.30

subjt	**180**	**195**	**210**	**225**	**240**	**255**	**270**	**285**	**300**	**315**	**330**	**345**	**360**
PS	0.56	0.28	0.00	-5.00	-2.78	-2.22	-2.22	-2.22	-2.22	-2.22	-1.94	-1.11	-1.11
	2.04	2.04	2.04	-4.63	-1.85	-1.30	-1.30	-1.85	-1.30	-1.30	-1.30	-1.30	-1.30
	2.22	2.22	1.67	-3.89	-2.78	-1.67	-1.11	-1.11	-1.11	-1.11	-1.11	-1.11	-1.11
	2.87	2.87	2.87	-2.41	-1.57	-1.02	-1.02	-0.46	-0.46	-0.19	0.09	-0.19	0.09
RG	2.33	2.33	1.33	-3.67	-0.67	-1.67	-1.67	-1.67	-1.17	-0.67	-1.17	-1.17	-1.17
	1.30	1.30	1.30	-4.26	-2.59	-2.04	-1.48	-2.04	-1.48	-2.04	-0.93	-0.37	-0.37
	3.15	3.15	3.15	-3.52	-1.85	-1.30	-1.30	-0.74	-0.74	-0.19	-0.19	0.37	0.37
	2.04	2.04	2.04	-4.07	-2.41	-1.85	-1.85	-1.30	-1.30	-1.02	-0.74	-0.46	-0.46
AD	1.58	1.58	1.58	-4.17	-2.17	-2.17	-1.92	-1.17	-0.67	-0.67	-0.67	-0.42	-0.42
	1.30	1.30	1.30	-3.70	-2.59	-2.04	-2.04	-1.48	-0.93	-0.93	-1.48	-0.93	-0.93
	2.04	2.59	2.04	-3.52	-1.85	-1.85	-1.30	-0.74	-1.30	-0.74	-0.74	-0.19	-0.19
	1.76	1.76	1.76	-3.52	-2.41	-2.41	-0.74	-0.19	-0.19	-0.74	-0.19	-0.19	-0.19
PF	2.83	2.83	2.83	-2.67	-2.17	-1.17	-0.67	-0.42	-0.17	-0.17	0.08	0.08	0.08
	2.59	2.59	2.59	-4.07	-2.41	-1.85	-1.85	-1.30	-1.30	-0.74	-0.74	-1.30	-1.30
	3.89	3.33	3.06	-2.78	-1.67	-1.94	-1.67	-1.11	-0.56	0.00	0.00	0.00	0.00
	2.96	3.24	3.24	-2.87	-1.20	-0.65	-0.93	-0.93	-0.09	-0.09	0.19	-0.09	-0.09
AC	2.50	1.00	0.75	-5.50	-5.50	-5.00	-4.50	-3.00	-2.00	-1.50	-1.50	-1.75	-1.75
	2.69	2.96	2.13	-2.87	-1.20	-0.93	-0.65	-0.65	-0.09	0.19	-0.09	-0.65	-0.65
	2.22	2.78	2.22	-3.33	-1.67	-1.67	-1.11	-1.11	-0.56	0.00	0.00	0.00	0.00
	3.06	2.78	3.06	-2.78	-1.11	-1.67	-1.11	-1.11	-0.83	-1.11	-0.83	-0.56	-0.28
IF	2.00	2.25	2.00	-4.00	-1.50	-1.50	-1.50	-1.00	-1.00	-1.00	-1.00	-1.00	-0.50
	2.41	2.41	2.41	-3.15	-0.93	-0.93	-0.93	-0.93	-0.93	-0.93	-0.93	-0.93	-0.93
	2.22	2.22	2.22	-3.33	-1.11	-1.11	0.00	0.00	-0.56	0.00	0.00	0.00	0.00
	2.04	2.04	2.04	-3.80	-1.85	-1.30	-1.30	-0.74	-0.46	-0.19	-0.19	0.09	-0.19
DS	3.33	2.33	2.33	-2.67	-2.67	-1.67	-0.67	-1.67	-1.17	-0.67	-0.67	-0.17	-0.17
	2.22	3.33	2.22	-3.33	-2.22	-2.78	-2.22	-2.78	-2.22	-3.33	-1.11	-2.22	-2.22

	2.96	2.96	2.96	-2.59	-1.48	-0.37	-0.37	0.19	-0.37	0.19	-0.37	-0.37	-0.37
	2.41	2.96	2.96	-3.15	-1.48	-3.70	-0.37	-1.48	-0.37	0.19	0.74	0.74	-0.37
CL	2.00	1.00	1.00	-4.50	-2.00	-2.00	-1.50	-2.00	-1.50	-1.50	-1.25	-1.50	-1.00
	2.78	2.50	1.94	-3.61	-1.67	-1.39	-1.11	-1.39	-1.39	-1.39	-1.11	-1.39	-1.39
MD	1.25	1.25	0.75	-4.25	-3.75	-3.50	-3.25	-3.25	-3.25	-2.75	-2.75	-2.25	-2.25
	1.67	1.67	1.67	-3.89	-1.67	-1.67	-0.56	-0.56	-0.56	0.00	-0.56	-0.56	-0.56
	1.11	1.11	1.11	-3.89	-2.78	-2.78	-2.22	-2.78	-2.78	-2.22	-1.67	-1.11	-1.11
	2.04	2.04	2.26	-2.96	-1.85	-1.30	-1.85	-1.30	-0.74	-1.30	-1.30	-1.30	-1.30
CH	0.42	0.92	1.17	-5.08	-3.58	-2.58	-2.33	-2.08	-2.33	-2.33	-2.08	-2.08	-2.08
	1.39	1.94	1.94	-4.72	-3.61	-3.06	-3.06	-2.50	-2.50	-2.22	-1.94	-1.94	-1.39
	2.59	2.59	2.59	-4.07	-1.85	-1.30	-0.74	-1.30	-0.74	-0.74	-0.74	-0.19	-0.74
	2.04	1.76	2.04	-4.35	-2.69	-1.57	-1.57	-1.57	-1.02	-1.57	-1.02	-0.46	-0.46
LR	3.17	3.67	3.17	-2.33	-1.33	-0.83	-1.33	-0.33	-0.33	-0.08	-0.33	0.67	-0.33
	4.44	4.44	4.44	-1.39	0.00	0.00	-0.83	-0.56	0.00	0.00	0.00	0.00	0.00
	2.69	3.24	2.69	-2.87	-1.20	-1.20	-0.09	-0.09	0.46	0.46	-0.09	0.46	0.46
	3.70	3.70	3.70	-1.85	-1.85	-1.30	-1.85	-1.30	-1.30	-1.85	-1.30	-1.30	-0.74
BH	2.17	2.17	2.17	-3.83	-2.33	-1.33	-0.33	-0.83	-0.33	-1.33	-0.83	-0.33	-0.83
	1.48	2.04	1.76	-5.19	-1.30	-1.30	-1.85	-1.85	-1.30	-0.74	-0.74	-0.74	-0.74
	3.33	3.33	2.78	-3.33	-2.22	0.00	0.00	0.00	0.00	0.56	0.00	0.00	0.00
	1.48	1.76	1.48	-4.07	-0.74	-1.30	-1.85	-1.30	-0.74	-0.19	-0.74	-0.19	-0.19
MN	2.41	1.85	2.41	-4.26	-3.15	-2.59	-2.04	-1.48	-0.93	-1.20	-0.93	-1.48	-1.48
	2.41	2.13	2.41	-3.70	-2.04	-2.04	-1.48	-0.93	-0.93	-0.37	-0.93	-0.37	0.19
	1.48	2.04	1.48	-4.63	-2.69	-2.13	-0.74	-0.74	-0.19	-0.74	-0.19	-0.19	0.37
	1.39	1.67	1.67	-3.89	-0.56	-0.28	-0.56	-1.11	-0.56	-0.28	-0.28	0.00	0.00
GW	1.76	2.31	2.59	-4.35	-1.57	-1.57	-1.02	-1.57	-0.46	-1.02	-0.74	-0.46	-0.46
	2.13	1.85	1.57	-3.43	-1.20	-0.09	-0.65	-0.09	-0.65	-0.65	-0.09	-0.65	-0.65
	2.69	2.69	2.69	-3.43	-1.76	-0.93	-0.93	-0.09	-0.37	-0.09	-0.09	-0.09	-0.09
	2.31	2.31	2.31	-3.80	-1.85	-1.57	-1.57	-1.02	-1.02	-0.74	-0.46	-0.46	-1.02
SK	1.50	0.50	1.00	-4.00	-2.50	-2.00	-1.50	-1.25	-1.00	-1.00	-0.75	-0.75	-0.75
	0.93	0.93	1.48	-4.63	-2.41	-1.30	-1.30	-1.02	-0.74	-0.74	-1.02	-0.74	-0.19
	1.57	1.02	1.02	-4.54	-3.43	-1.76	-1.20	-0.65	-0.09	-0.09	-0.09	0.46	-0.09
	1.67	1.67	1.39	-3.89	-2.22	-1.94	-1.67	-1.67	-1.11	-1.67	-0.83	-0.83	-0.56
SM	0.83	0.83	0.56	-4.44	-4.44	-3.33	-2.22	-2.22	-2.22	-2.22	-1.67	-1.67	-1.67
	3.52	2.13	1.85	-3.70	-1.48	-0.37	-0.93	-0.93	-1.48	-0.37	-0.37	-0.37	-0.37
	1.85	1.85	1.85	-3.70	-2.59	-1.48	-0.93	-0.37	-0.37	0.19	-0.37	-0.37	0.19
	2.22	2.22	2.50	-3.33	-1.67	-1.11	-1.11	-1.67	-1.11	-0.83	-0.56	-0.28	0.00
AM	-0.19	-0.74	-1.30	-6.85	-5.74	-4.63	-3.52	-2.96	-2.96	-2.41	-2.41	-1.85	-1.85
	2.04	1.76	1.48	-5.19	-3.80	-2.41	-1.85	-1.85	-1.85	-1.57	-1.57	-1.30	-1.30
	1.94	1.94	1.94	-4.72	-3.61	-2.50	-1.39	-1.94	-1.39	-0.83	-0.28	-0.28	-0.28
	1.85	2.13	2.13	-3.43	-1.76	-1.20	-0.93	-1.20	-0.93	-0.65	-0.65	-0.65	-0.65
AI	2.04	2.04	1.48	-4.07	-2.96	-3.52	-1.85	-2.41	-1.85	-0.74	-1.30	-0.74	-0.74
	1.57	0.46	1.02	-4.54	-3.98	-3.43	-1.76	-1.76	-1.76	-0.65	-1.20	-0.65	-0.65
	0.93	1.48	0.93	-4.63	-3.52	-2.41	-2.41	-1.30	-1.30	-0.74	-0.19	-0.19	-0.19
	0.56	0.56	0.56	-5.56	-3.89	-2.78	-2.78	-2.22	-1.67	-2.22	-1.11	-1.67	-1.67
TW	2.22	1.67	2.22	-4.44	-2.22	-1.67	-1.11	-0.56	-1.67	-1.11	-2.22	-1.11	-1.11
	2.22	2.78	2.22	-3.33	-2.22	-1.67	-1.67	-1.11	0.00	0.00	0.00	0.00	0.00
	2.59	2.59	2.59	-4.63	-2.41	-1.85	-1.30	-1.85	-1.30	-0.19	-0.19	0.37	-0.19
	2.78	2.22	2.22	-3.89	-2.22	-1.67	-1.11	-0.56	0.00	-0.56	0.00	-0.56	-0.56
AA	2.22	2.22	2.78	-3.89	-2.22	-1.11	-1.11	0.28	0.00	0.00	0.00	0.28	-0.56

	2.22	2.22	2.22	-3.89	-2.22	-1.94	-0.56	0.28	-0.56	0.00	0.00	0.00	0.00
	2.22	2.22	2.22	-3.33	-1.67	-1.39	-1.00	-1.00	-1.11	-0.56	-0.56	0.00	-0.56
	1.11	1.39	1.67	-3.61	-3.06	-0.83	-0.28	-0.28	-0.28	-0.56	0.00	-0.28	-0.28
RT	3.24	3.80	3.24	-2.31	-0.65	0.46	0.46	0.46	0.46	0.46	0.19	-0.09	0.46
	3.33	3.89	3.89	-2.78	-0.56	-0.56	-0.56	0.00	0.56	0.00	0.00	0.56	0.00
	3.70	3.15	3.70	-1.85	0.37	0.93	0.37	0.37	0.37	0.93	0.37	0.37	0.37
	3.70	4.26	3.70	-1.85	0.37	0.37	1.48	2.59	2.59	2.04	1.48	1.48	1.48
SD	0.74	1.30	0.74	-4.81	-1.48	-1.48	-0.37	-0.37	-0.37	-0.37	-0.37	0.19	-0.37
	1.11	1.11	1.11	-4.44	-2.78	-1.11	-1.11	-1.11	0.00	0.00	0.00	0.00	0.00
	1.39	1.11	1.11	-3.89	-2.22	-1.11	-1.11	0.00	0.28	0.00	0.00	0.00	0.00
	1.30	1.57	1.30	-3.43	-1.76	-0.65	-1.20	-0.65	-0.09	-0.09	-0.65	-0.09	0.19
SB	2.96	2.41	2.41	-3.15	-1.20	-1.20	-0.93	-0.09	-0.37	-0.09	-0.09	-0.09	-0.09
	3.61	3.61	3.61	-1.94	-0.28	0.28	-0.28	0.28	0.28	0.83	0.83	0.83	0.83
	3.06	2.78	2.78	-2.78	-0.83	-0.56	-0.56	0.00	-0.56	-0.56	0.00	0.00	0.00
	3.33	3.61	3.33	-1.94	-0.56	-0.83	-0.56	-0.83	-0.56	-0.56	0.00	0.00	0.00
MNO	2.78	2.78	1.94	-3.61	-1.94	-1.11	-1.94	-1.94	-1.11	-1.11	-1.39	-1.39	-1.11
	3.89	3.33	3.33	-2.78	-0.83	-0.28	-0.83	-0.83	-0.83	-0.56	-0.56	-0.56	-0.56
	3.52	3.52	3.52	-2.59	-1.48	-0.93	-0.37	-0.37	0.19	0.19	-0.37	0.19	0.19
	3.15	3.43	3.15	-2.41	-0.74	-0.74	-0.74	-0.19	-0.74	-0.74	-0.74	-0.19	-0.74
DB	2.78	2.78	3.33	-1.67	-0.56	-0.56	0.00	0.00	0.28	0.28	1.11	0.56	0.83
	2.59	2.59	2.59	-2.96	-1.30	-0.74	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19
	2.96	2.96	2.96	-2.59	-2.04	-2.04	-1.48	-0.93	-0.93	-0.93	-0.37	-0.37	-0.37
	2.59	2.87	2.87	-2.96	-1.30	-1.02	-1.30	-1.30	-0.74	-0.74	-0.46	-0.74	-0.19
DH	1.94	1.94	1.67	-3.61	-2.50	-1.94	-1.94	-1.39	-1.39	-0.83	-0.83	-0.83	-0.83
	2.41	2.96	2.41	-3.70	-2.31	-2.31	-1.48	-1.48	-2.04	-1.48	-1.48	-1.48	-1.48
	2.31	2.31	2.31	-3.24	-1.85	-1.30	-1.02	-0.74	-0.46	-0.46	-0.19	0.09	0.09
	1.76	1.76	2.04	-3.80	-2.13	-1.57	-1.30	-1.02	-1.30	-1.02	-0.46	-1.02	-0.46
RL	2.78	2.78	2.78	-3.33	-2.50	-2.22	-1.67	-1.39	-1.11	-0.56	-0.83	-0.56	-0.56
	2.78	2.22	1.67	-3.33	-1.94	-2.78	-1.67	-1.11	-0.56	0.00	0.00	0.00	0.00
	2.22	2.78	2.22	-3.33	-2.22	-1.67	-1.11	-1.11	-0.56	0.00	0.00	0.00	0.00
	2.96	2.96	2.96	-2.59	-2.59	-2.59	-2.31	-0.37	-0.93	-0.37	-0.37	-0.93	0.19
BY	2.59	3.15	2.59	-2.96	-0.74	-0.19	0.37	0.37	-0.19	-0.19	0.37	0.37	-0.19
	2.69	2.69	2.69	-2.87	-0.09	-0.09	-0.09	-0.09	-0.09	-0.09	-0.09	-0.09	-0.09
	2.78	2.78	2.78	-2.78	-0.56	-0.28	-0.28	0.28	0.00	0.00	0.00	-0.28	0.00
	2.96	2.96	2.96	-3.15	-0.93	-0.37	-0.93	-0.37	0.19	-0.37	-0.37	0.19	-0.37
MM	0.58	0.83	0.58	-4.42	-2.42	-1.17	-1.17	-0.92	-0.42	-0.17	-1.17	-0.17	-0.42
	2.13	1.57	2.13	-1.76	-1.48	-1.48	-0.65	-0.09	0.46	-0.09	0.46	-0.09	-0.09
	1.67	1.67	1.67	-4.44	-1.67	-1.11	-1.11	-1.67	-1.11	-1.67	-1.11	-0.56	-0.56
	1.48	1.48	1.48	-6.30	-2.41	-0.74	-1.30	-0.74	-1.30	-1.30	-0.74	-0.19	-0.74
KB	1.00	1.00	1.00	-4.00	-1.00	-0.50	-0.50	-0.75	0.00	0.00	0.00	0.00	0.00
	1.57	1.57	1.57	-3.98	-2.04	-1.76	-1.76	-1.20	-1.20	-0.65	-0.65	-0.65	-0.65
	1.11	0.56	0.56	-3.89	-0.56	-1.11	-1.11	-0.56	-0.56	-1.11	-0.56	0.00	0.00
	1.85	1.85	1.85	-3.15	-1.48	-0.93	-0.37	-0.93	-0.37	-0.37	0.19	-0.37	-0.37
ZB	0.50	1.50	1.00	-5.00	-4.50	-3.00	-3.00	-3.50	-3.50	-3.50	0.00	-1.50	-1.50
	1.67	2.22	1.67	-3.89	-1.11	-1.11	-1.11	-0.56	-0.56	-0.56	0.00	-0.56	-0.56
	1.30	1.30	1.30	-3.70	-2.04	-0.93	-0.37	-0.37	-0.37	0.19	-0.37	-0.37	0.19
	2.04	2.04	2.04	-2.96	0.37	-0.19	0.37	-0.19	0.37	-0.19	-0.19	-0.19	-0.19
EC	2.67	1.67	1.67	-4.33	-4.83	-3.33	-1.83	-1.33	-1.33	-0.83	-0.83	-0.58	-0.83

	2.50	2.50	2.50	-3.61	-0.28	-0.83	-0.28	-0.83	0.00	-0.28	-0.28	-0.28	-0.28
	2.96	2.41	2.41	-3.70	-1.48	-0.37	-0.37	0.19	-0.37	0.19	0.19	-0.37	0.19
	2.96	2.96	2.96	-2.04	-0.37	-0.37	-0.37	-0.37	0.19	-0.37	-0.37	0.19	-0.37
MA	0.67	0.42	0.42	-5.33	-5.33	-2.83	-2.33	-1.33	-1.33	-1.33	-0.83	-0.83	-0.33
	0.37	0.37	0.37	-5.19	-2.96	-1.85	-1.30	-0.74	-0.19	-0.19	-0.19	-0.19	-0.19
	1.48	0.93	0.93	-4.63	-1.30	-1.30	-0.74	-0.74	-1.30	-0.74	-0.74	-0.74	-0.19
	0.56	0.56	0.28	-5.56	-0.83	-1.67	-1.39	-0.56	-0.56	-0.28	-0.56	-0.56	-0.56
JS	1.83	1.33	1.33	-4.17	-4.17	-3.67	-3.67	-3.17	-2.67	-3.17	-2.67	-1.67	-1.17
	1.85	1.30	1.30	-4.81	-2.04	-1.48	-1.48	-0.93	-0.93	-0.37	-0.37	-0.37	0.19
	1.30	1.30	1.30	-4.26	-2.04	-1.48	-0.93	-0.93	-0.93	-0.93	-0.65	-0.93	-0.37
	2.04	2.04	2.04	-4.07	-0.74	-0.74	-0.19	-0.74	-0.19	0.37	-0.19	0.37	-0.19
JL	0.50	0.00	0.25	-5.00	-3.00	-1.00	0.00	-0.50	0.00	0.00	0.25	0.00	0.00
	0.37	-0.19	-0.19	-6.30	-3.52	-1.30	-0.74	-0.19	0.09	-0.19	-0.19	-0.19	-0.19
	1.11	0.56	0.56	-5.56	-3.33	-1.11	-1.67	-0.56	-0.56	0.00	0.56	0.00	0.00
	0.37	0.93	0.37	-5.74	-2.96	-2.41	-1.30	-1.85	-1.30	-0.74	-0.74	-0.19	-0.46
RB	1.83	1.33	1.33	-4.17	-1.67	-1.17	-0.67	-0.67	-0.17	-0.17	0.33	-0.17	0.33
	1.48	2.04	1.48	-4.63	-1.57	-1.30	-0.74	-0.74	-0.19	-0.19	0.37	0.37	0.37
	1.67	1.11	1.11	-5.00	-2.22	-1.67	-1.39	-1.11	-0.56	-0.56	-0.28	0.00	0.00
	1.67	1.39	1.39	-3.89	-2.22	-1.67	-0.56	-1.11	-0.56	0.00	0.00	0.00	0.28
LD	1.00	1.00	1.00	-3.00	-1.50	0.00	0.00	0.00	0.00	-0.50	0.00	0.00	0.00
	0.74	0.74	0.74	-5.37	-3.70	-4.26	-3.15	-2.59	-0.37	-0.37	-0.93	-0.37	-0.37
	2.22	2.22	2.22	-3.89	-1.11	0.00	-0.56	0.00	0.00	0.00	-0.56	0.00	0.00
	0.93	0.37	0.37	-4.07	-0.74	-0.19	-0.74	-0.74	-0.74	-0.19	0.37	-0.19	-0.74
JF	0.67	1.17	0.67	-4.83	-2.33	-1.83	-1.33	-0.83	-0.33	-0.33	-0.83	-0.33	-0.33
	0.37	0.93	0.37	-5.19	-2.96	-2.69	-1.85	-1.30	-0.74	-0.74	-1.30	-0.74	-0.74
	1.11	0.56	1.67	-4.44	-2.78	-2.22	-2.78	-2.22	-1.67	-1.11	-0.56	0.00	-0.56
	1.57	1.30	1.30	-4.81	-2.59	-0.93	-0.93	-1.48	-0.93	-0.37	-0.93	-0.37	-0.37

16b) Presented here is the heterophoria measured (in $^{\Delta}$) using the flashed Maddox rod technique at 15-second time intervals while adapting to 6^{Δ} base-in prism. The measurements have been adjusted to take into account the baseline heterophoria and positive values represent esophoria and negative values are exophorias. The measurement at 0 seconds was the reading taken initially, prior to any adaptation. The prism was removed after 225 seconds of binocular viewing and thus the measurement at 225 seconds represents the heterophoria prior to any recovery. The measurements from 225 to 360 seconds represent the recovery from the adaptation. For the graphical and statistical analysis the values of heterophoria were converted to metre angles.

subjt	**visit**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**120**	**135**	**150**	**165**
PS	1	6.00	4.50	3.50	3.50	3.00	3.00	3.00	3.00	3.00	2.75	2.75	2.50
	2	5.83	4.17	3.61	3.06	2.78	2.78	2.50	2.50	2.50	2.50	2.50	1.94
	4	5.56	4.44	4.44	4.17	3.33	3.33	3.06	2.78	2.22	2.22	2.22	2.22
	7	5.56	3.33	3.33	3.33	2.22	2.00	1.94	1.67	1.11	1.67	1.11	1.67
RG	1	6.00	5.00	4.50	4.00	4.50	4.00	4.00	3.00	3.00	3.00	3.50	3.00
	2	6.30	5.19	3.52	4.07	3.52	3.52	2.96	2.96	3.52	2.96	2.41	2.41
	4	5.56	3.89	4.44	3.33	2.78	1.67	1.67	1.11	1.11	1.11	1.67	1.11
	7	6.11	5.00	2.78	3.33	2.78	2.78	2.22	1.67	1.67	1.67	1.94	1.67
AD	1	6.17	6.17	5.67	5.67	5.67	5.67	5.67	5.17	5.17	5.17	5.17	4.92
	2	6.11	5.56	5.56	5.56	5.00	5.00	5.00	5.00	5.56	5.00	5.00	5.00
	4	6.11	5.56	5.56	5.56	5.00	5.56	5.00	5.00	5.00	5.00	5.56	5.00
	7	6.30	6.30	6.30	6.30	6.30	6.30	5.74	6.30	6.30	5.74	5.74	5.74
PF	1	6.08	5.08	4.58	4.33	4.08	3.83	3.58	3.33	3.08	3.08	3.08	3.08
	2	5.74	5.19	4.63	4.07	4.07	4.63	4.07	4.07	4.07	3.52	3.52	4.07
	4	5.56	5.00	3.89	4.44	3.89	3.89	3.89	3.33	3.33	3.33	3.33	3.89
	7	6.30	5.19	4.63	4.07	3.80	3.52	3.24	2.69	1.85	1.85	1.85	2.41
IF	1	6.00	6.00	6.00	5.50	6.00	5.50	5.50	5.50	5.50	6.00	5.50	5.50
	2	6.39	4.72	4.17	4.17	4.17	3.61	3.89	3.61	3.61	3.61	3.61	3.61
	4	5.56	5.00	4.44	4.44	3.89	3.89	3.89	3.33	3.89	3.33	3.33	3.33
	7	5.93	5.93	5.93	5.37	5.37	5.93	5.93	5.37	5.37	4.81	5.37	4.81
DS	1	6.17	5.67	4.67	5.67	5.17	4.67	3.67	4.17	3.67	4.17	4.67	4.67
	2	6.48	6.48	6.48	5.37	5.37	5.37	5.37	6.48	6.48	6.48	6.48	5.37
	4	6.67	6.67	6.67	5.56	5.56	6.67	5.56	5.56	5.56	6.67	5.56	5.56
	7	6.30	6.30	7.41	7.41	5.19	6.30	6.30	6.30	6.30	5.74	6.30	6.30
MD	1	5.56	4.44	4.44	4.44	5.00	5.00	5.00	4.44	4.44	4.44	4.44	4.44
	2	5.83	5.83	4.72	4.72	4.72	4.17	4.17	4.17	4.17	4.17	4.17	4.17
	4	5.74	5.19	4.63	4.63	5.19	4.63	4.63	4.07	4.63	4.63	4.07	4.07
	7	6.11	4.44	6.11	6.11	5.56	5.56	5.00	5.00	5.56	5.56	5.00	5.00
CH	1	5.74	5.19	4.91	4.63	4.63	4.63	4.63	4.63	4.63	4.35	4.35	4.35
	2	5.93	5.93	4.81	4.81	4.81	4.81	4.81	4.81	4.81	5.37	4.81	4.81
	4	6.48	5.37	4.26	4.26	4.81	4.26	4.26	5.37	5.37	4.81	4.81	4.81
	7	6.30	6.30	6.30	6.30	5.74	6.30	6.30	5.74	6.30	5.74	6.30	6.30
LR	1	6.11	5.00	5.00	4.44	4.72	5.56	3.89	4.17	3.89	3.89	3.33	3.06
	2	6.30	6.30	6.30	5.19	5.74	5.19	4.91	5.19	5.19	5.19	5.19	5.19
	4	6.30	5.74	5.74	5.74	5.19	5.19	5.19	5.19	5.74	4.91	5.19	5.19
	7	6.11	6.11	6.11	5.56	5.67	5.56	5.56	5.28	5.56	5.56	5.56	5.56

GW	1	6.11	4.72	3.61	3.89	3.33	2.78	2.78	2.50	2.50	2.78	3.06	2.22
	2	6.11	3.89	3.61	3.61	3.06	2.50	2.22	3.33	3.06	2.50	2.22	3.61
	4	6.20	4.54	3.98	4.54	3.98	3.43	2.87	3.15	3.43	2.87	2.31	2.87
	7	5.65	5.37	3.15	2.87	2.04	2.59	2.04	2.59	2.59	2.04	2.59	2.04
SK	1	6.08	5.58	5.08	5.08	4.58	4.58	4.08	4.08	3.58	4.08	3.58	3.58
	2	5.74	4.91	4.63	4.07	4.07	4.35	3.80	3.80	3.80	3.80	3.80	3.52
	4	5.74	5.19	4.63	5.19	4.63	4.07	4.35	3.52	3.52	4.07	3.52	3.52
	7	5.93	5.93	5.65	5.93	5.93	5.65	5.93	5.65	5.65	5.93	5.65	5.37
SM	1	6.30	4.07	4.07	4.07	4.07	4.07	4.07	4.07	4.07	3.80	4.07	4.07
	2	5.56	4.44	4.44	4.44	3.89	3.89	3.33	4.44	3.89	4.44	4.44	3.89
	4	5.19	5.19	5.19	5.19	4.07	4.07	4.07	5.19	4.07	4.07	4.07	4.63
	7	5.93	5.93	5.37	5.37	5.93	5.37	5.37	5.37	5.93	5.37	5.37	5.93
AM	1	6.57	5.19	4.91	4.63	4.35	4.07	3.52	4.07	4.07	3.80	4.07	4.07
	2	6.11	5.28	4.72	5.00	4.44	3.89	3.89	3.89	3.61	3.33	3.61	3.61
	4	5.74	4.91	4.91	5.19	4.63	4.35	4.63	4.63	4.63	4.35	4.63	4.63
	7	6.30	5.19	5.19	4.91	4.63	5.19	5.19	4.91	5.19	5.19	4.63	4.63
AI	1	5.65	3.98	3.43	2.31	2.87	2.31	1.76	1.20	1.20	1.20	1.76	1.76
	2	5.93	4.81	3.15	3.15	3.70	2.59	3.15	2.04	2.59	2.59	2.04	2.59
	4	5.93	4.81	3.70	3.15	3.70	3.15	3.15	3.15	2.59	2.59	3.15	2.59
	7	6.11	2.78	3.33	1.67	1.67	1.67	2.22	2.22	2.78	1.67	1.67	1.67
AA	1	5.56	4.44	4.44	3.89	3.33	3.33	3.33	3.33	2.78	2.78	2.22	2.22
	2	5.37	4.81	4.54	3.70	3.15	3.15	2.59	2.59	2.04	1.76	2.04	1.48
	4	6.74	6.74	6.74	5.07	5.07	5.63	5.07	4.52	5.07	4.52	5.07	4.52
	7	6.30	5.74	5.19	4.63	3.52	4.07	2.96	2.96	2.13	1.57	2.13	1.57
RT	1	7.04	3.70	3.15	4.26	3.70	3.70	3.70	4.26	4.81	3.70	4.81	4.26
	2	6.30	4.07	4.07	4.07	4.07	4.07	4.07	3.52	4.07	4.07	3.52	4.07
	4	6.30	5.19	4.07	5.19	4.07	4.07	4.07	3.52	4.63	4.07	4.07	4.07
	7	6.30	5.19	5.19	6.30	6.30	5.19	5.19	4.07	5.19	4.07	5.19	4.07
SD	1	6.11	4.44	2.22	1.11	1.11	1.11	1.11	0.00	0.00	0.00	0.00	0.00
	2	5.56	4.44	3.33	2.78	2.78	2.22	2.22	2.22	2.22	1.67	1.11	1.11
	4	6.11	4.44	3.33	2.22	2.78	2.22	1.11	1.11	1.67	1.11	1.11	1.67
	7	6.11	5.00	4.44	3.89	3.33	2.78	2.22	2.22	2.22	1.67	1.67	1.67
SB	1	5.83	4.44	3.89	3.61	3.61	3.33	3.06	3.06	3.06	3.06	2.50	1.67
	2	5.56	4.44	4.44	4.44	3.89	4.44	3.33	3.33	3.33	3.33	3.33	3.33
	4	5.93	4.81	4.26	3.70	4.26	4.26	3.70	3.70	3.70	3.70	3.70	3.98
	7	6.85	6.85	6.85	6.02	4.63	5.74	5.74	5.74	5.74	5.19	4.63	4.63
MNO	1	6.57	5.19	4.91	4.35	4.35	4.07	4.07	3.80	4.35	3.80	3.80	3.80
	2	5.28	4.17	4.44	4.17	4.72	4.44	4.17	3.89	3.61	3.61	4.17	3.61
	4	5.56	4.44	5.00	4.44	4.44	4.44	4.17	4.44	4.72	4.44	4.44	4.44
	7	6.85	6.30	6.30	6.30	5.74	5.19	5.19	5.19	5.19	5.19	5.19	4.91
DH	1	6.39	5.28	4.72	4.17	3.61	3.06	3.06	3.06	3.06	3.06	3.06	3.06
	2	5.93	5.37	4.26	3.98	4.26	4.26	3.70	3.15	3.15	2.59	3.15	2.59
	4	5.56	5.56	5.56	5.28	5.28	5.00	5.00	5.00	4.72	5.00	5.00	5.00
	7	6.11	5.00	5.00	4.44	5.00	4.44	5.00	4.44	4.44	4.44	4.44	4.44
RL	1	6.11	4.44	3.33	2.78	2.50	2.22	2.22	2.78	1.67	2.22	1.67	1.67
	2	6.30	6.30	6.85	7.41	6.85	6.85	6.85	7.41	6.85	7.41	6.85	6.85
	4	5.74	5.19	5.74	5.74	5.74	5.74	5.19	5.74	5.74	5.74	5.19	5.19
	7	6.11	6.11	5.56	5.56	5.56	5.56	6.11	5.56	5.56	5.28	5.28	5.56
BY	1	6.11	5.00	5.56	5.00	5.00	5.00	5.56	5.00	5.56	5.00	5.00	5.00

	2	6.11	5.56	6.11	6.11	5.56	5.56	5.56	5.56	5.56	5.56	5.56	5.56
	4	5.93	5.37	5.37	5.37	5.93	5.93	5.37	5.37	5.37	5.93	5.37	5.37
	7	6.11	5.56	5.56	5.56	5.56	5.28	5.56	5.56	5.28	5.56	5.56	5.56
MM	1	5.08	5.08	3.58	3.08	2.83	1.58	1.83	1.58	1.33	1.58	1.33	1.08
	2	5.65	4.26	3.98	2.87	2.59	2.31	2.59	1.76	1.76	1.76	1.76	1.20
	4	6.57	4.35	3.24	2.69	2.69	2.13	1.57	2.13	1.57	1.57	1.57	1.57
	7	5.56	4.44	3.89	2.78	2.22	1.94	1.67	2.78	1.67	1.94	1.67	1.94
KB	1	6.33	6.33	5.83	5.33	4.83	4.33	4.33	3.58	2.83	2.83	2.58	2.33
	2	5.00	3.89	3.89	3.33	3.33	3.06	3.06	2.78	2.78	2.50	2.22	2.22
	4	5.74	3.52	3.52	2.96	2.96	2.96	2.96	2.41	2.41	2.41	2.41	2.69
	7	5.56	4.44	3.33	2.22	2.22	2.22	1.94	1.94	1.94	2.22	1.94	1.67
ZB	1	5.33	4.33	4.83	4.83	3.83	3.83	4.33	4.83	4.83	3.33	3.33	4.33
	2	6.11	3.89	3.33	3.33	2.78	3.33	3.33	3.33	3.33	3.33	2.78	3.33
	4	6.67	5.56	4.44	3.89	3.33	3.89	3.33	3.33	3.33	3.06	3.33	3.06
	7	6.11	5.00	4.44	3.89	3.33	2.78	3.33	2.22	2.22	2.22	2.50	2.22
EC	1	5.67	5.67	4.17	3.67	3.17	2.67	2.17	2.17	2.17	2.67	2.67	2.17
	2	5.19	3.52	2.96	2.96	2.41	1.85	2.41	2.41	1.85	1.85	1.85	2.41
	4	5.19	3.52	2.96	2.96	2.96	2.96	2.96	2.96	2.96	3.52	2.96	2.96
	7	6.30	6.30	6.30	5.19	4.07	2.96	2.41	2.13	1.85	1.85	1.85	2.13
MA	1	5.50	5.50	5.00	4.00	3.50	3.00	3.00	3.00	3.00	2.00	2.00	2.00
	2	5.74	4.63	3.52	3.52	3.52	3.52	2.41	2.41	2.41	1.85	1.85	1.85
	4	5.93	5.93	3.70	3.15	3.15	3.15	2.59	2.59	2.59	3.15	2.59	2.59
	7	6.11	4.44	3.33	2.50	2.50	2.22	2.22	2.22	1.94	1.67	1.94	1.67
JS	1	6.00	5.50	5.00	4.50	4.00	4.00	4.00	3.00	3.00	3.00	3.00	2.50
	2	6.11	4.44	3.89	3.89	3.89	3.89	3.33	3.33	2.78	2.78	2.78	2.78
	4	5.74	4.07	3.80	3.52	3.52	3.52	3.52	2.96	2.96	2.41	2.41	2.96
	7	5.93	5.37	3.70	3.70	3.15	2.59	3.15	2.59	2.59	3.15	2.59	2.59
JL	1	5.50	4.50	4.50	4.75	3.50	2.75	2.25	1.75	1.75	1.75	1.75	1.75
	2	6.30	4.63	5.19	4.63	4.07	3.52	3.24	2.96	2.41	2.41	2.13	2.13
	4	6.11	5.00	3.89	3.33	3.33	2.78	2.22	2.22	2.22	1.94	2.22	2.22
	7	6.11	4.44	3.89	3.33	3.33	3.06	2.78	2.78	2.22	2.78	1.94	2.22
RB	1	5.83	4.83	3.83	4.33	3.83	3.33	2.83	2.83	2.33	2.08	2.08	1.83
	2	5.93	5.37	3.70	4.26	4.26	3.15	2.87	2.59	2.59	2.04	1.76	1.48
	4	6.30	5.19	3.52	3.80	3.52	3.52	4.07	3.52	4.07	3.52	2.96	2.41
	7	6.30	5.19	4.63	2.96	3.52	2.41	2.69	2.13	2.96	2.13	2.41	2.41
LD	1	5.50	4.00	3.00	3.00	3.00	3.00	2.75	2.00	2.00	2.00	2.00	2.50
	2	6.30	5.19	4.63	3.52	3.52	3.52	3.24	2.69	2.41	2.41	2.41	2.69
	4	5.19	5.19	4.63	4.63	4.07	3.52	4.07	4.07	3.52	3.52	2.96	3.52
	7	5.19	2.96	2.96	1.85	1.85	1.85	1.85	2.96	2.41	1.85	1.85	1.85
JF	1	5.17	5.17	5.17	5.17	4.42	4.42	4.17	4.42	4.17	3.92	4.42	4.17
	2	5.93	4.81	4.81	4.26	4.81	4.26	3.98	3.98	3.98	3.98	3.15	3.98
	4	6.11	4.17	4.44	4.44	4.72	4.44	4.44	4.17	4.44	4.44	4.17	4.44
	7	5.93	5.37	4.81	5.37	4.81	4.81	4.54	4.26	4.81	4.81	4.26	4.54

subjt	180	195	210	225	240	255	270	285	300	315	330	345	360
PS	2.00	2.00	1.50	-3.00	-1.50	-1.00	-1.00	-1.00	-0.75	-0.50	-0.50	-0.50	0.00
	1.94	1.67	1.94	-3.61	-1.94	-0.83	-1.94	-0.83	-0.83	-0.83	-0.56	-0.56	-0.56
	2.22	2.22	2.22	-2.78	-1.67	-1.11	-1.11	-1.67	-1.11	-0.56	-0.56	0.00	0.00
	1.11	1.11	1.11	-3.89	-1.94	-1.67	-1.67	-1.67	-1.67	-1.11	-1.11	-1.11	-1.11
RG	3.50	3.00	2.50	-3.00	-1.00	-0.50	-1.00	-0.50	0.00	0.00	-0.50	0.50	0.50
	2.41	2.41	2.41	-4.26	-1.48	-0.93	-1.48	-0.37	-1.48	-0.37	-0.37	-0.37	-0.37
	1.67	1.67	1.67	-4.44	-3.89	-2.78	-2.22	-1.11	-0.56	0.00	0.00	-0.56	0.00
	1.67	1.67	1.67	-5.00	-2.22	-2.22	-1.67	-1.67	-1.67	-2.22	-1.67	-1.11	-1.11
AD	5.17	5.17	5.17	-0.33	-0.58	-0.33	-0.08	0.17	0.17	0.67	0.17	-0.33	-0.33
	5.56	5.00	5.00	-1.11	-0.56	-0.56	0.00	-0.56	-0.56	0.00	0.00	0.00	0.00
	5.00	5.00	5.00	-1.11	-0.56	0.00	-0.56	0.00	0.56	0.00	0.56	0.56	0.00
	5.74	5.19	5.74	-0.37	-0.37	0.19	-0.93	-0.37	-0.37	-0.09	-0.37	-0.37	-0.37
PF	2.83	2.83	2.83	-3.42	-2.42	-1.67	-1.42	-0.67	-0.67	-0.42	0.08	0.08	0.08
	4.07	2.96	3.52	-2.04	-0.93	-0.93	-0.37	-0.37	0.19	0.19	-0.37	0.19	0.19
	3.33	3.33	3.33	-1.67	-1.67	-0.56	-1.11	-0.56	0.00	0.00	0.00	0.00	0.00
	2.41	1.85	2.41	-3.70	-2.04	-1.48	-1.48	-0.93	-1.48	-0.93	-0.37	-0.37	-0.37
IF	5.50	5.50	5.50	-0.50	-0.50	0.00	-0.50	-0.25	0.00	-0.50	-0.50	0.00	0.00
	3.61	3.61	3.61	-1.94	-0.28	0.00	0.28	0.00	0.28	0.28	0.28	0.28	0.28
	3.89	3.33	3.33	-2.22	-1.11	-1.39	-1.11	-0.56	0.00	0.00	0.00	0.00	0.00
	5.37	4.81	5.37	-1.30	-0.74	-0.74	-0.46	-0.74	-0.46	-0.19	-0.19	-0.19	-0.19
DS	4.67	4.67	4.67	-0.33	0.67	0.67	-0.33	0.67	0.17	-0.33	-0.33	0.17	0.17
	5.37	5.37	6.48	2.04	2.04	0.93	0.93	0.93	-0.19	-0.19	-0.19	-0.19	-0.19
	6.67	5.56	5.56	0.00	1.11	1.11	0.00	1.11	0.56	0.00	0.00	1.11	1.11
	6.30	6.30	6.30	0.19	0.19	0.74	0.74	1.30	1.30	0.74	1.30	1.30	1.30
MD	5.00	5.00	5.00	-0.56	-0.56	0.56	0.00	-0.56	-0.56	0.00	0.00	0.00	0.00
	4.17	4.17	4.17	-0.56	-0.56	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28	-0.28
	4.63	4.07	4.07	-0.93	-0.65	-0.37	-0.37	0.19	-0.37	0.19	0.19	-0.37	-0.37
	4.44	5.00	4.44	-2.22	-2.22	-1.67	-1.11	-1.11	-0.56	0.00	0.00	-0.56	0.00
CH	4.35	4.35	4.35	-0.37	0.74	0.46	0.46	0.46	0.46	0.19	0.46	0.74	0.46
	4.81	4.81	4.81	-1.30	-1.30	-0.74	-0.74	-0.46	-0.74	-0.46	-0.19	-0.19	-0.19
	4.26	4.81	4.81	-1.30	-0.74	0.37	0.37	-0.19	0.37	0.37	-0.19	0.37	0.37
	5.74	5.74	5.74	-0.37	0.19	0.19	0.19	0.46	0.19	-0.09	0.19	0.19	0.19
LR	2.78	2.78	2.78	-2.78	-1.67	-1.11	-1.67	-1.11	-2.22	-0.56	-0.56	-0.56	-0.56
	5.19	5.19	5.19	-0.93	-0.37	-0.09	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37	-0.37
	5.19	5.19	5.19	-0.93	-0.93	-0.37	0.19	-0.37	0.19	0.19	-0.37	0.19	0.19
	5.56	5.56	5.56	-0.56	0.00	0.00	0.00	-0.56	0.00	0.00	0.00	0.00	0.00
GW	2.22	1.67	2.78	-3.89	-1.11	-0.83	-0.83	-0.83	-1.11	-0.56	-0.28	0.00	0.00
	1.94	2.50	2.22	-3.89	-2.22	-1.94	-1.67	-0.56	-0.56	-0.83	-0.83	-0.56	-0.56
	2.87	2.87	2.87	-3.24	-2.69	-1.02	-1.02	-1.02	-0.46	-0.46	-0.46	0.09	-0.46
	2.04	2.04	2.04	-3.52	-1.30	-1.30	-1.85	-1.30	-1.30	-0.74	-0.74	-1.30	-0.74
SK	4.08	4.08	3.58	-1.92	-1.42	-0.92	-1.42	-1.42	-0.42	-0.92	-0.42	0.08	0.08
	3.52	3.52	3.52	-1.48	-0.37	0.19	0.19	0.19	0.19	0.19	0.46	0.19	0.19
	3.52	3.52	3.52	-2.04	-1.48	-0.93	-0.37	-0.37	0.19	-0.37	-0.37	-0.37	0.19
	5.37	5.65	5.37	-1.02	-0.74	-0.74	-0.74	-0.19	-0.19	-0.74	-0.74	-0.19	-0.46
SM	4.07	2.96	2.96	-3.15	-2.04	-0.93	-0.37	0.19	0.19	0.19	0.19	0.74	0.19
	3.89	3.89	3.89	-0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	4.07	4.63	4.63	-0.93	-0.37	-0.37	-0.93	-0.37	0.19	0.74	0.19	0.74	0.74
	5.37	5.37	5.37	-0.74	-0.74	-1.30	-0.74	-0.74	-0.19	-0.19	-0.74	-0.19	-0.19
AM	4.07	3.52	3.80	-1.76	-0.93	-0.09	0.19	0.19	0.19	0.46	0.46	0.46	0.46
	3.89	3.33	3.33	-2.22	-0.56	0.28	-0.56	0.00	0.00	-0.56	0.00	0.28	0.00
	4.63	4.63	4.63	-1.48	-0.93	-0.37	-0.37	0.19	0.19	-0.37	0.19	0.19	0.19
	4.91	5.19	5.19	-0.65	-0.37	0.19	0.46	0.19	0.19	0.19	0.19	0.19	0.19
AI	1.48	1.76	1.76	-3.80	-2.13	-2.13	-1.57	-2.13	-2.13	-2.69	-1.02	-0.46	-0.19
	2.59	2.04	2.04	-3.52	-2.41	-1.85	-1.85	-1.30	-0.74	-0.74	-0.19	-0.19	-0.19
	3.15	2.59	2.59	-2.96	-1.85	-2.41	-1.85	-1.85	-1.30	-0.19	-0.74	-0.74	-0.19
	1.67	1.67	1.67	-3.33	-1.11	-1.11	-1.67	-1.11	-1.11	-0.56	-1.11	-1.11	-0.56
AA	2.78	2.78	2.22	-3.89	-3.33	-2.22	-1.67	-2.22	-1.67	-1.11	-0.56	-0.56	0.00
	1.48	1.48	1.48	-4.07	-1.30	-0.74	-1.30	-1.30	-0.46	-0.74	-0.19	-0.19	0.37
	5.07	5.07	4.52	-1.70	-2.70	-2.15	-1.59	-1.04	-0.48	0.07	-0.48	-0.48	-0.48
	1.85	1.57	1.57	-3.70	-0.93	-1.48	-0.93	-1.48	-0.93	-0.93	-0.93	-0.37	-0.93
RT	2.59	3.15	4.26	-2.96	-0.74	-1.02	-0.74	-0.74	-0.74	-1.30	-1.30	-1.30	-0.74
	4.07	4.07	4.07	-1.48	-0.65	-0.93	-0.65	-0.37	-0.37	0.19	-0.37	-0.37	-0.37
	4.07	4.07	4.07	-2.04	-1.48	-1.48	-0.37	-1.48	-0.37	-0.37	-0.37	-0.37	-0.37
	5.19	4.07	4.07	-1.48	-1.48	-0.93	-0.37	-0.37	-0.37	0.19	-0.37	-0.37	-0.37
SD	0.00	-0.56	0.56	-5.56	-2.78	-1.67	-1.11	-1.67	-1.11	-1.11	-0.56	-1.11	-0.56
	1.11	1.11	1.11	-3.33	-2.22	-1.11	-1.11	-0.56	-0.56	0.00	0.00	0.56	0.00
	1.11	1.11	1.11	-5.00	-3.33	-2.22	-1.67	-1.11	0.00	0.00	-0.56	0.00	0.00
	1.67	2.22	1.67	-4.44	-3.33	-3.33	-3.33	-2.78	-2.22	-2.22	-1.11	-1.11	-0.56
SB	1.11	1.94	1.94	-3.61	-2.22	-2.22	-2.22	-1.94	-1.67	-1.11	-0.83	-0.83	-0.28
	3.61	3.33	3.33	-2.22	-1.11	-0.56	-1.11	-1.11	-1.11	-0.56	0.00	-0.56	-1.11
	3.70	3.70	3.70	-2.41	-1.85	-0.74	-1.30	-0.19	-0.19	0.37	0.37	-0.19	-0.19
	4.63	4.63	4.63	-1.48	-1.48	-0.93	-0.93	-0.37	-0.37	-0.09	-0.37	-0.09	-0.37
MNO	4.07	3.80	4.35	-1.76	-0.37	0.19	-0.09	-0.09	0.19	-0.09	-0.09	-0.09	-0.09
	4.17	3.61	4.17	-0.83	-0.28	0.28	0.83	0.83	0.28	0.83	0.83	0.28	0.83
	4.44	4.44	4.44	-1.39	-1.11	-1.11	-0.56	-1.11	-0.56	0.00	0.00	0.00	0.00
	5.19	5.19	5.19	-0.65	-0.37	-0.37	-0.37	-0.09	0.19	0.74	0.19	0.19	0.19
DH	3.06	3.06	3.06	-2.22	-1.39	-1.11	-0.56	-0.28	-0.28	0.00	-0.28	0.00	-0.28
	2.59	2.04	2.04	-3.52	-2.96	-2.41	-2.41	-2.13	-2.13	-2.41	-1.30	-0.74	-0.19
	5.28	5.00	5.00	-2.78	-3.06	-2.78	-3.33	-3.33	-3.33	-2.78	-3.33	-3.33	-3.33
	4.44	4.44	4.44	-1.67	-1.67	-1.11	-1.11	-1.11	-0.56	-1.11	-0.56	-0.56	0.00
RL	1.94	2.22	2.22	-3.89	-2.22	-2.22	-1.67	-2.22	-0.56	-0.28	-1.11	0.00	-0.56
	6.85	6.85	6.85	1.30	1.30	0.74	1.30	0.19	0.19	0.74	0.74	0.74	0.74
	5.19	5.19	5.19	-0.37	0.19	0.19	0.19	0.19	-0.37	0.19	0.19	0.19	0.19
	5.56	5.28	5.28	-0.56	-0.28	0.00	0.00	0.00	0.28	0.00	0.00	0.00	0.00
BY	5.00	5.00	5.00	-1.11	-0.56	-1.11	-0.56	-0.56	0.00	0.00	0.00	0.00	0.00
	5.56	5.56	5.56	-0.56	-0.56	0.00	0.00	0.00	0.00	-0.56	0.00	0.00	0.00
	5.37	5.37	5.37	-0.74	-0.19	0.37	0.37	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19
	5.56	5.28	5.56	-0.28	-0.56	0.00	0.00	0.00	0.28	0.00	0.00	0.00	0.00
MM	0.83	1.08	1.58	-4.92	-3.42	-1.92	-1.92	-1.92	-1.67	-1.42	-1.42	-0.92	-0.92
	1.76	1.76	1.76	-3.80	-2.13	-1.30	-1.02	-1.02	-1.02	-1.02	-0.46	0.09	-0.19
	2.13	1.57	1.57	-3.98	-2.31	-0.65	-1.20	-1.20	-0.09	-0.65	-0.09	0.46	-0.09
	1.94	1.67	1.94	7.78	6.67	5.56	5.56	5.56	5.00	4.44	4.44	4.44	4.44
KB	2.33	2.33	2.33	-2.67	-2.17	-1.17	-0.17	0.33	0.33	0.33	0.83	0.83	0.83
	2.22	2.22	2.22	-3.33	-1.67	-0.56	-0.28	-0.56	-0.56	-0.28	0.00	0.00	0.00

	2.96	2.41	2.41	-3.15	-2.04	-0.93	-0.37	-0.37	-0.37	-0.37	0.19	-0.37	0.19
	2.22	2.22	2.22	-3.33	-1.67	-1.67	-1.67	-1.11	-1.11	-0.56	-0.56	-1.11	-0.56
ZB	4.33	3.33	3.83	-2.67	0.33	0.33	0.33	-0.17	-0.17	-0.67	-0.67	-0.17	-0.17
	3.33	3.33	2.78	-2.22	-1.11	-0.56	-0.56	-0.56	0.00	0.28	0.28	0.00	0.00
	3.06	3.33	3.06	-2.78	0.56	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.00
	2.22	2.22	2.22	-3.33	-2.22	-1.67	-1.67	-1.11	-1.67	-1.11	-1.11	-1.11	-1.11
EC	2.17	2.17	2.17	-3.83	-1.83	-0.83	0.17	0.17	-0.33	0.17	0.17	0.17	0.17
	1.85	1.85	1.85	-3.70	-2.59	-2.04	-1.48	-0.93	-0.93	-0.93	-0.37	-0.37	-0.37
	2.96	2.96	2.96	-2.59	-1.48	-0.93	-0.65	-0.37	-0.37	0.19	-0.37	0.19	0.19
	1.85	1.85	1.85	-3.70	-2.04	5.19	-0.93	-0.93	-0.93	-1.48	-0.93	-0.93	-0.93
MA	2.00	1.50	1.50	-4.00	-1.50	-1.00	-1.00	-1.00	0.00	0.00	0.00	0.00	-0.50
	1.30	1.30	1.30	-3.70	-2.04	-1.48	-0.93	-0.93	-0.37	-0.37	-0.37	-0.93	-0.37
	2.59	2.59	2.59	-3.52	-1.30	-1.02	-0.19	-0.74	-0.19	-0.19	-0.19	-0.19	-0.19
	1.67	1.67	1.94	-3.89	-1.39	-1.39	-0.56	-0.28	-0.28	-0.56	-0.28	-0.28	-0.28
JS	2.50	2.50	2.50	-3.50	-1.00	-0.50	-1.00	-0.50	-1.00	-1.50	-1.00	-1.00	-1.00
	2.78	2.78	2.78	-3.33	-1.67	-1.11	0.00	0.00	0.00	0.56	0.00	0.00	0.00
	2.41	2.41	2.41	-3.70	-2.04	-1.48	-0.93	-0.93	-0.37	-0.37	0.19	0.19	-0.37
	2.59	2.59	2.59	-4.07	-2.41	-1.85	-1.85	-1.30	-1.30	-0.74	-0.74	-0.19	-0.19
JL	2.00	1.75	1.75	-2.25	-0.50	-1.00	0.00	-0.50	-0.50	-0.50	0.00	-0.50	-0.50
	2.41	2.13	2.13	-2.87	-0.65	-0.93	-0.37	0.19	0.19	0.19	-0.37	0.19	0.19
	2.22	1.94	2.22	-3.33	-1.11	-1.11	-0.83	-0.56	0.00	0.00	0.28	-0.56	-0.56
	1.94	1.94	1.67	-3.89	-2.78	-0.56	0.56	-0.56	0.00	0.00	0.28	0.00	0.00
RB	1.83	2.33	1.83	-3.67	-3.17	-2.17	-1.67	-1.17	-1.17	-0.67	-0.17	-0.67	-0.67
	1.48	2.04	1.48	-4.63	-4.07	-3.52	-2.69	-1.85	-1.30	-0.74	-0.74	-0.74	-0.74
	2.41	1.85	2.41	-3.43	-2.59	-2.04	-2.59	-2.59	-2.04	-1.48	-0.93	0.19	-0.37
	2.69	2.41	2.41	-3.15	-1.48	-0.93	-0.93	-0.37	-0.37	0.19	0.19	0.19	0.19
LD	2.00	2.00	2.00	-3.00	-1.00	-1.00	-1.00	-0.50	-1.00	-0.50	0.00	-0.50	-0.50
	2.69	2.69	2.41	-3.70	-2.04	0.19	-0.37	-0.37	-0.37	-0.37	0.19	-0.37	0.19
	3.52	3.52	3.52	-3.15	-0.93	-0.93	0.19	1.30	0.19	0.74	0.19	0.19	0.19
	1.85	2.41	1.85	-3.70	-1.48	-1.48	-1.48	-0.37	-0.93	-1.48	-0.37	-0.37	-0.37
JF	4.17	4.17	4.17	-1.58	0.17	0.67	0.67	0.67	0.17	0.17	0.67	0.17	0.17
	3.98	3.98	3.98	-2.13	-0.19	0.37	-0.19	-0.46	-0.19	-0.19	-0.19	-0.19	-0.19
	4.44	4.44	4.17	-2.22	-1.11	0.00	0.00	0.00	-0.28	0.00	0.00	0.00	0.00
	4.26	4.54	4.54	-1.85	-1.30	0.37	0.37	0.09	-0.19	0.37	-0.19	0.37	0.65

APPENDIX 17: SUPPORTING PUBLICATIONS

Refereed published abstracts from conference proceedings

Baker, F.J., Rappon, J.M., James, M.F., Rosenfield, M. and Portello, J.K. (1998) Form and repeatability of the accommodative stimulus response function *Investigative Ophthalmology and Visual Science* **39** S1048.

Baker, F.J., and Gilmartin, B. (1999) The AC/A and CA/C ratios in incipient presbyopia *Investigative Ophthalmology and Visual Science* **40** S363.

Rosenfield, M. and Baker, F.J. (1998) Testing the gradient AC/A ratio with plus or minus lenses: Does it matter? *Optometry and Vision Science* **75** **(Suppl)** 257.

FORM AND REPEATABILITY OF THE ACCOMMODATIVE STIMULUS RESPONSE FUNCTION

((Fiona J. Baker[1], Joseph M. Rappon[2], Meredith F. James[2], Mark Rosenfield[2], Joan Portello[2])) [1]Aston University, Birmingham UK. [2]SUNY College of Optometry, New York, NY.

Purpose The relationship between the accommodative stimulus and response function over a range of dioptric levels is widely used to assess accommodative responsivity. However, there has been relatively little examination of the inter- and intra-subject repeatability of this relationship. **Methods** The accommodative response to a series of binocular stimuli located at viewing distances ranging from 6.0 to 0.20m was measured objectively using a Canon R-1 open-field, infra-red optometer in 31 visually-normal young-adult subjects. Stimuli were varied by physically displacing the target in order to simulate naturalistic viewing conditions. Additionally, in 14 subjects, the stimulus-response function was measured on five separate occasions over a two week period, with each session being separated by at least 18 hours. **Results** For stimuli between 1 and 5D, the mean (±1SEM) slope, y-axis intercept and accuracy index (mean accommodative error divided by the correlation coefficient) were 0.97D/D (0.09), -0.26D (0.21) and 0.39D (0.20), respectively. The 95% limits of repeatability of these parameters were ±0.17D/D, 0.63D and 0.23D. The departure from linearity for the lower dioptric stimuli was extremely small. When stimuli between 0.17 and 5D were considered, the mean gradient and intercept were 0.91D/D (0.10) and –0.06D (0.27), respectively. **Conclusions.** These findings verify the high degree of repeatability of this function, and indicate that slopes close to unity represent normal values in young adults under naturalistic testing conditions. The lower gradients reported by other workers using alternative stimuli may have been a function of the method of testing, with one or more accommodative cues being removed.

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THE AC/A AND CA/C RATIOS IN INCIPIENT PRESBYOPIA

((F. J. Baker, B. Gilmartin)) Vision Sciences, Aston University, Birmingham, U.K.

Purpose The incipient phase of presbyopia represents a loss in accommodative amplitude of approximately 3 dioptres between the ages of 35 and 45 and is the prelude to the need for a reading addition. The need to maintain single binocular vision during this period requires recalibration of the correspondence between accommodation and vergence response. Whereas previous work has investigated the correspondence principally when the ratio of accommodative amplitude to accommodative effort for near is relatively high, we examine the correspondence when the ratio is low as is evident during the course of the incipient phase of presbyopia. **Methods** The CA/C, stimulus AC/A (AC/As) and response AC/A (AC/Ar) ratios were determined for 28 subjects aged 35 to 45 years. For the AC/A ratios accommodation was measured objectively using a Canon R-1 open-view IR optometer and vergence measurements were made subjectively with a haploscope device (i.e. vergence open-loop). Accommodative stimuli of 0 to 4D were presented using a Badal optometer with a high contrast Maltese cross target. The CA/C ratio was calculated by measuring the accommodative response to vergence stimuli of 6^{Δ} base in to 12^{Δ} base out while the subject observed a Difference of Gaussian grating (spatial frequency 0.1cpd; accommodation open-loop). **Results.** A significant correlation was found between the CA/C ratio and amplitude of accommodation ($r=0.46$ $p<0.002$) with a reduction of 14.06% of the mean CA/C ratio per dioptre of accommodation reduction or 4.98% reduction per year. AC/As was found to be unrelated to the amplitude of accommodation. A significant correlation was found between AC/Ar and the amplitude of accommodation ($r=0.57$ $p<0.002$) with an increase of 2.20^{Δ}/D per dioptre of accommodation reduction (25.8% of mean) or 0.57^{Δ}/D per year (6.67%). **Conclusions.** As the accommodative amplitude of the incipient presbyope decreases, the CA/C ratio is reduced and AC/Ar increases. This would indicate that as the accommodative amplitude declines with age, an increased accommodative effort is required to produce a unit change in accommodation; the increased effort then induces increased convergence.

Supported by the college of Optometrists (UK) None

TESTING THE GRADIENT AC/A RATIO WITH PLUS OR MINUS LENSES: DOES IT MATTER? Mark Rosenfield, MCOptom, PhD, *State University of New York, College of Optometry, New york, NY;* Fiona Baker, MCOptom, *Aston University, Birmingham, U.K.*

PURPOSE. There has been some debate in the literature as to whether plus or minus lenses should be used to stimulate changes in the accommodative stimulus during assessment of the gradient accommodative convergence to accommodation (AC/A) ratio. It has previously been suggested that minus lenses would produce more linear changes in accommodation. Accordingly, the present study has compared these two methods of assessing the crosslink ratio. METHOD. Both the stimulus and response AC/A ratios were measured in 28 young subjects while they viewed a target at a viewing distance of 33cms. Changes in accommodation were induced by introducing –2, –1, 0, +1 and +2D spherical lenses in random order, with the resulting steady-state accommodative response being quantified subjectively using a stigmatoscope. Near heterophoria was measured concurrently using the Von Graefe procedure. RESULTS The mean plus and minus lens stimulus AC/A ratios were 2.05 and 1.77 PD/D, respectively, while the mean plus and minus lens response ratios were 1.94 and 1.54 PD/D. There was no significant difference between theses mean values. Furthermore, the changes in accommodative response produced by the plus and minus lenses were similar, with stimulus-response gradients of 0.99 and 0.97D/D, respectively. CONCLUSIONS These findings indicate that within the accommodative stimulus range tested, i.e., between 1 and 5D, plus and minus lenses produce similar values of gradient AC/A ratio.