FACTORS AFFECTING THE ACCOMMODATIVE RESPONSE TO SUSTAINED VISUAL TASKS

MARK ALLAN BULLIMORE

Doctor of Philosophy

THE UNIVERSITY OF ASTON IN BIRMINGHAM

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The University of Aston in Birmingham

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SUMMARY

In the absence of adequate visual stimulation accommodation adopts an intermediate resting position, appropriately termed tonic accommodation (TA). A period of sustained fixation can modify the tonic resting position, and indicate the adaptation properties of TA. This thesis investigates various factors contributing to the accommodative response during sustained visual tasks, in particular the adaptation of TA.

Objective infra-red optometry was chosen as the most effective method of measurement of accommodation. This technique was compared with other methods of measuring TA and the results found to be well correlated.

The inhibitory sympathetic input to the ciliary muscle provides the facility to attenuate the magnitude and duration of adaptive changes in TA. This facility is, however, restricted to those individuals having relatively high levels of pre-task TA. Furthermore, the facility is augmented by substantial levels of concurrent parasympathetic activity.

The imposition of mental effort can induce concurrent changes in TA which are predominantly positive and largely the result of an increase in parasympathetic innervation of the ciliary muscle although there is some evidence for sympathetic attenuation at higher levels of TA. In emmetropes sympathetic inhibition can modify the effect of mental effort on the steady-state accommodative response at near.

Late-onset myopes (onset after the age of 15 years) have significantly lower values of TA than emmetropes. Similarly, late-onset myopes show lower values of steady-state accommodative response for near stimuli. The imposition of mental effort, induces concurrent increases in TA and steady-state accommodative reponse in the myopic group which are significantly greater than those for emmetropes.

Estimates of TA made under bright empty-field conditions are well correlated with those made under darkroom conditions. The method by which the accommodative loop is opened has no significant effect on the magnitude and duration of post-task shifts in TA induced by a near vision task.

Significant differences in the post-task shifts in TA induced by a near vision task exist between emmetropes and late-onset myopes, the post-task shifts being more sustained for the myopic group.

Key Words:
Adaptation of tonic accommodation, sustained near-vision, myopia, ciliary muscle innervation, infra-red optometry.

To Mum and Dad, thanks.

"I'm not trying to prove anything, by the way. I'm a scientist and I know what constitutes proof. But the reason I call myself by my childhood name is to remind myself that a scientist must also be absolutely like a child. If he sees a thing, he must say that he sees it, whether it was what he thought he was going to see or not. See first, think later, then test. But always see first. Otherwise you will only see what you were expecting. Most scientists forget that................You can't possibly be a scientist if you mind people thinking that you're a fool."

from 'So Long and Thanks for all the Fish' by Douglas Adams.

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CONTENTS

CHAPTER PAGE

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

LIST OF APPENDICES

APPENDIX PAGE

GENERAL INTRODUCTION

The young human eye possesses the facility to alter its refractive state. This is achieved by contraction and relaxation of ciliary smooth muscle which results in a change in the shape and hence the refractive power of the crystalline lens. The process is under volitional control and is termed accommodation. When the ciliary muscle is relaxed the lens assumes its least convex form and the point in space conjugate with the retina is referred to as the far-point. When the ciliary muscle is contracted fully the lens takes on its most convex state and the refractive power of the eye is increased by up to +14 dioptres. The point conjugate with the retina in the fully accommodating eye is known as the near-point. The dioptric distance between the far- and near-points is termed the amplitude of accommodation. A subject's amplitude of accommodation shows a slow but steady decline from birth, decreasing from 14 dioptres at year to less than one dioptre at 55 years.

The accuracy of the accommodative response is dependent on a number of subject and target characteristics (see section 1.4 and Charman (1986) for review). In the absence of an adequate visual stimulus, however, accommodation adopts an intermediate resting position. It is appropriate to term this myopic shift, which may occur in darkness, in a bright empty-field (ganzfeld) or in the presence of small pupils, tonic accommodation (TA) although the terms 'dark focus' and 'resting focus of accommodation' may also be employed. The mean value of TA in a young population is typically around 1 to 1.5 dioptres with a standard deviation of approximately 0.70 D (Leibowitz and Owens, 1975a; 1975b; 1978).

Recent research has demonstrated that a period of sustained vision at a given distance can induce a shift in the tonic resting position in the direction of the task location. This phenomenon has been termed the 'adaptation of TA' (Schor *et al.*, 1984) and 'accommodative hysteresis' (Ebenholtz, 1983; 1985). The former is, perhaps, more appropriate since it parallels the term adaptation of the vergence system. In spite of much recent research, speculation remains as to the underlying mechanisms of the adaptation of TA, its possible role in accommodative asthenopia and the possible long-term effects of excessive tonic adaptation. This research programme will attempt to examine further certain factors pertaining to the accommodative response to sustained visual tasks.

Methodological considerations

The techniques by which accommodation can be measured are reviewed in section 1.6. Infra-red optometry will be adopted for the experimental programme since it has the advantage of being objective and requires very little judgement or manipulation on the part of the subject. Furthermore, the technique is able to produce a large number of estimates of an eye's refractive state within a short period of time. A commercially available instrument, *viz.* the Canon Autoref R-1, will be employed (see section 2.1). The subject is allowed a wide binocular field-of-view and the alignment of the instrument with the subject's eye can be monitored and easily maintained by means of an infra-red video monitor.

An early methodological consideration will be to compare estimates of TA obtained with infra-red optometry with those made by laser optometry and near retinoscopy (see section 2.2). The dioptric correction factors appropriate to each technique will also be considered. Under darkroom conditions a subject positioned on the Canon R-1 perceives two dim infra-red sources imaged 20 degrees either side of fixation. The possible contamination of measurements of TA due to these sources will be evaluated by investigating the relationship between retinal target eccentricity and the accommodative response (see section 2.3).

A further consideration for the experimental programme will be the conditions under which the adaptation of TA will be measured. Recently Schor *et al.* (1986) demonstrated the magnitude and time-course of the adaptation of TA induced by a sustained near-vision task is dependent on the method by which the accommodative loop is opened. They found that the TA after-effects following 1 minute fixation at -2 D took several minutes to dissipate under bright empty-field and Maxwellian view conditions. Under darkroom conditions, however, TA regressed to baseline levels within a few seconds. Wolfe and O'Connell (1987) found that in 16 of their 21 subjects there was no significant difference in the adaptation of TA for bright empty-field and darkroom conditions. In around 25% of subjects, however, they found that TA after-effects were significantly greater for the empty-field condition. A comparison will be made, therefore, of the adaptation of TA under empty-field and darkroom conditions (in section 7.1).

The role of sympathetic innervation of the ciliary muscle in the adaptation of the TA

Previous studies have produced various estimates of the duration of TA after-effects (Ebenholtz, 1983; Tan and O'Leary, 1986; Wolf *et al.*, 1987). These range from 3 minutes for a 45 minute task at -5 D (Wolf *et al.*, 1987) to 10 hours following 8 minutes of near-point fixation (Ebenholtz, 1983). A study will be undertaken in Chapter 3 to examine the rate of decay of TA towards baseline values following a ten minute visual counting task at far and near.

There is evidence for the presence of an inhibitory sympathetic input to the ciliary muscle (see Gilmartin (1986) for review) although its role in the control of accommodation remains the subject of some dispute. Gilmartin and Hogan (1985a) postulated that the sympathetic input serves to attenuate myopic shifts in TA induced by sustained near-vision tasks. The influence of the sympathetic input to the ciliary muscle on the magnitude and time-course of post-task shifts in TA will, therefore, be examined in Chapter 3. This is facilitated by employing a double blind protocol between the topical ophthalmic drugs timolol maleate, a non-selective beta-adrenergic antagonist, and normal saline.

The contribution of cognitive demand to the adaptation of TA

It seems reasonable to assume that the predominant influence on post-task changes in TA will be the task location. It is intersesting to note, however, that Pigion and Miller (1985) found that an hour spent in darkness listening to a tape recording induced a significant increase in mean TA of 0.47 D in 20 subjects. Furthermore, workers have demonstrated that the imposition of mental effort may induce significant changes in accommodation (Kruger, 1980; Malmstrom *et al.*, 1980; Post *et al.*, 1985). It is feasible, therefore, that the cognitive demand of a sustained visual task may contribute to the post-task shift in TA.

The influence of mental effort on accommodation will be examined extensively in this thesis. The study described in Chapter 4 will seek to determine whether the shifts in TA induced by the imposition of mental effort are the result of changes in sympathetic innervation to the ciliary muscle or due to alterations in parasympathetic activity. This will be facilitated by the use of the beta-adrenergic antagonist timolol maleate. This study will be followed by a comparison of the influence of mental effort on TA in emmetropes and late-onset myopes (in Chapter 5). These studies will be paralleled by an appraisal of the influence of mental effort on the steady-state accommodative response in Chapter 6.

The adaptation of TA in emmetropia and late-onset myopia

A large number of workers have sought to determine the role of accommodation in the development of myopia (see section 1.7) and recently interest in this research area has heightened. McBrien and Millodot (1986a) postulated that, if accommodation is a factor in the development of refractive errors, then one would expect fundamental differences in accommodative responses between various refractive groups. A significant portion of this thesis will be devoted, therefore, to a comparison of the accommodative characteristics of emmetropes and late-onset myopes (those subjects whose myopia has developed after the age of 15 years). The rationale for investigating this group of myopes is that Goldschmidt (1968) has proposed that myopia that develops after puberty has a different aetiology to myopia of earlier onset. Goldschmidt postulates that myopia which is late in onset is associated with environmental factors such as excessive near-work. It would seem pertinent, therefore, to compare aspects of the accommodative response in these individuals with emmetropes.

Various workers have investigated the relationship between TA and refractive error although the majority of results have proved inconclusive (see section 1.7C). Maddock *et al.* (1981) found, however, that emmetropes have values of TA which are significantly lower than those of hyperopes but significantly higher than those of myopes. McBrien and Millodot (1987) divided their myopes into two groups depending on their age of onset. They found that early-onset myopes (onset prior to 13 years) had similar values of TA to emmetropes whilst late-onset myopes have significantly lower values than both groups. The distribution of TA values in emmetropia and late-onset myopia will, therefore, be compared (in Chapter 5). A further comparison will be made of the influence of mental effort on TA in these two refractive groups.

It would seem a logical extension of the work in Chapter 5 to compare the steady-state accommodative response in late-onset myopia and emmetropia. A recent report suggests that myopes have significantly lower values of steady-state accommodative response for near stimuli than emmetropes (McBrien and Millodot, 1986a). An investigation (in Chapter 6) will, therefore, compare the steady-state accommodative response for targets at three stimulus vergences (-1, -3 and -5 D) in the two refractive groups. The influence of mental effort on the steady-state accommodative response of the groups will also be examined.

Ebenholtz (1983) demonstrated that an 8 minute period of fixation at the near-point could induce significant and sustained increases in TA. He suggested that this was a precursor to induced myopia, wherby short-term task-induced changes in TA accumulate such that the manifest refractive state of the eye is altered. If excessive tonic adaptation is a precursor to myopia one might predict significant differences in the adaptational facility of late-onset myopes and emmetropes. Indeed, it might be anticipated that late-onset myopes are more susceptible to TA after-effects than emmetropes. The experimental programme will be concluded, therefore, with a comparison of the adaptation of TA in these two refractive groups (in Chapter 7).

CHAPTER 1

THE ACCOMMODATIVE RESPONSE

1.1 - ANATOMY OF THE ACCOMMODATIVE MECHANISM

1.1A - The Ciliary Muscle

The ciliary muscle is triangular in shape, in antero-posterior section (see Fig. 1.1) and has some 70 processes to which the zonule is attached (see section 1.1B). The ciliary muscle is thought to contain three types of unstriped smooth muscle fibres (Salzmann, 1912) although Fincham (1937) considered such a classification to be too rigid:

1. *Meridional fibres* arising from the epichoroid and attaching to the scleral spur.
2. *Radial fibres*, situated more internally and anteriorly, arranged in the manner of a fan.
3. *Circular fibres*, continuous with and inseparable from the radial fibres, running round the free edge of the ciliary body just behind the root of the iris.

Smooth muscle is present in the walls of the gastrointestinal and urinogenital systems, in the walls of vascular structures and the bronchi, in the exocrine glands, the skin and, of course, the eye. Variations exist in the properties of smooth muscle and its characteristics depend on the organ in which they occur. It is likely that the diversity of properties reflects their adaptation to their particular functions (Bowman and Rand, 1980).

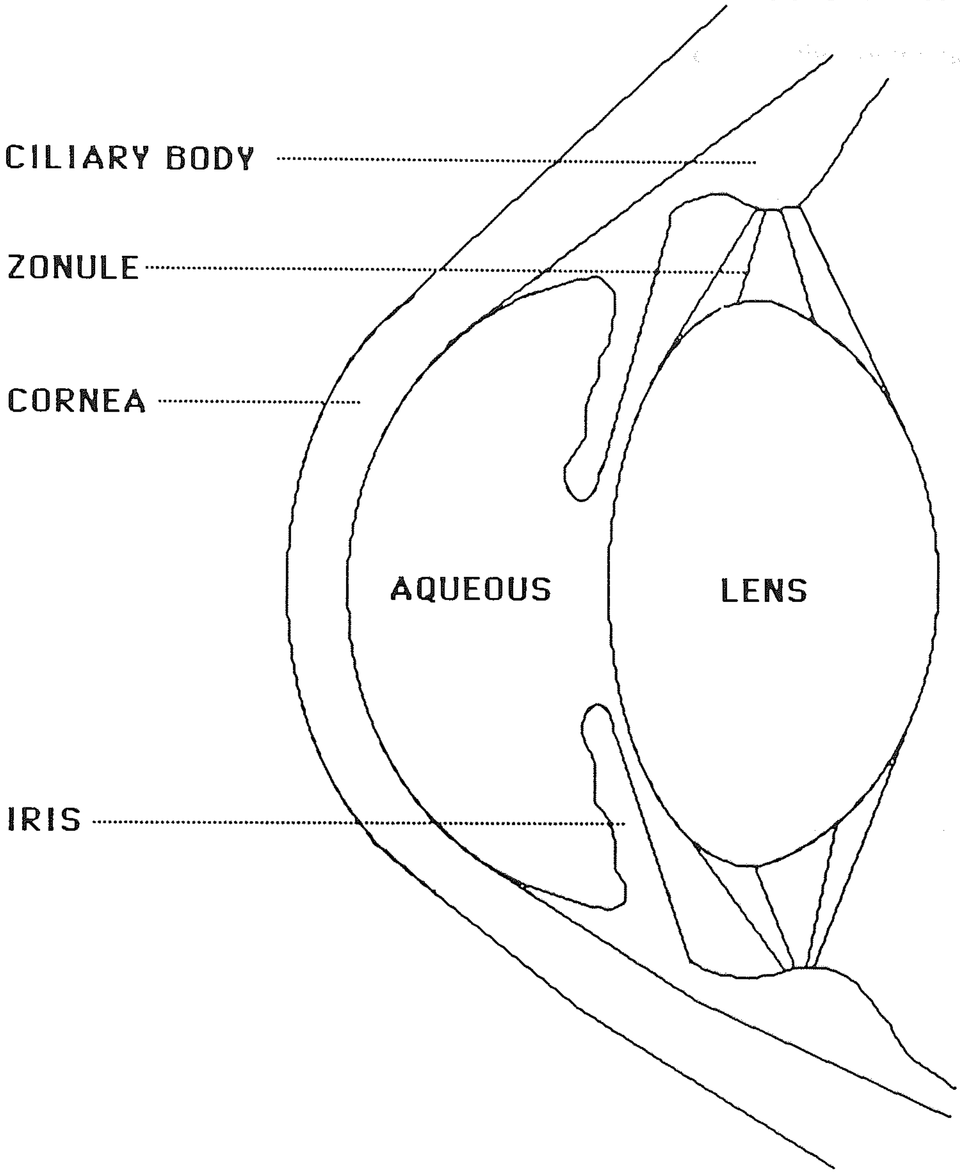


FIG. 1.1 - The accommodative mechanism.

Bundles and layers of smooth muscle cells contain numerous elastic fibres which are continuous with those in surrounding connective tissue. This aids uniform transmission of tension throughout the tissue. The speed of contraction of smooth muscle is slow compared with that of striated muscle and the persistence of the contraction is long. The tone of smooth muscle is an expression of the amount of background activity exhibited. Tone may *neurogenic*, being due to a steady autonomic neural input or it may be *myogenic* and be due to an intrinsic activity (Bowman and Rand, 1980).

Ciliary smooth muscle is different in several respects from smooth muscle in other structures of the body. First, ciliary muscle is susceptible to volitional control. In addition, the post-ganglionic fibres which innervate the ciliary muscle are myelinated and larger than those elsewhere in the body (Ruskell and Griffiths, 1979). It has been shown that the speed of conduction increases with increasing fibre diameter and myelinated fibres conduct much faster than non-myelinated fibres (Bowman and Rand, 1980). It is likely, therefore, that such features of ciliary muscle innervation are associated with the substantial voluntary control of accommodation, unique in parasympathetically controlled tissues (Warwick, 1956). In contrast, the post-ganglionic sympathetic fibres to the ciliary muscle are non myelinated (Wolffe, 1976). Ciliary muscle shows no spontaneous activity suggesting any physiological tone is neurogenic in origin (Suzuki, 1983; Lograno and Reibaldi, 1986).

1.1B - The zonule

The zonule consists of a series of tranparent fibres passing from the ciliary body to the lens (see Fig. 1.1). Rohen and Rentsch (1969) proposed the existence of two classes of fibres. The main system of *holding fibres* run forward towards the pars orbicularis and insert into the lens capsule. Branching off from the holding fibres is the second system of *tension fibres* inserting into the ciliary epithelium. The role of the zonule is to transmit the force produced by contraction of the ciliary muscle to the lens capsule (see section 1.2 pps. 28-29).

1.1C - The crystalline lens

The crystalline lens is a transparent, biconvex, elastic structure located between the iris and the vitreous and held in place by the zonules (see Fig. 1.1). The diameter of the lens is 9-10 mm and its thickness varies from 4 to 5 mm depending on whether the eye is focused for distance or near. The ability of the lens to alter its refractive power is termed 'accommodation' a facility which decreases from ~14 D in a 10 year old to less than 1 D in a 52 year old (Hamasaki *et al.*, 1956). The lens is divided into the following structures:

1. *The capsule*; an elastic basement membrane which is attached to the zonule. The capsule possesses a Young's modulus of around 2,000 times greater than that of the underlying lens substance.
2. *The epithelium*; extending as a single layer of cells under the anterior portion of the capsule.
3. *The lens substance*; made up of fibres and interstitial material.

The lens substance possesses a layered structure, a consequence of the growth process, with new fibres being laid down on the surface throughout life. The fibres taper as they pass from the equator to their termination in the lens sutures at the centre or apex of the lens. A further consequence of the layered structure is a variation in refractive index with the highest (~1.41) in the nucleus and the lowest (~1.38) in the outer cortical layers (Nakoa *et al.*, 1969a; 1969b). It thus forms a gradient-index optical element (Marchand, 1978) which together with the asphericity of its external and iso-index surfaces (Parker, 1972; Brown, 1973; Howcroft and Parker, 1977) may reduce aberration, particularly spherical aberration (Charman, 1983). Furthermore there are differences in elasticity between the nucleus and cortex (Fisher, 1971).

1.2 - THE MECHANISM OF ACCOMMODATION

The mechanism of accommodation has provided a source of great controversy in the past and, indeed, some aspects of the process are still disputed. The current understanding of the accommodative process is, however, as follows. In the unaccommodated state the ciliary muscle is relaxed and the holding fibres are stretched, maintaining the tension on the capsule which flattens the lens, thus decreasing its refractive power. The meridional ciliary fibres contract thereby pulling on the epichoroid tissue and drag the ciliary body forward by around 0.5 mm. The circular fibres of the ciliary muscle shorten hence producing a decrease in the diameter of the ciliary ring. Contraction of the ciliary muscle and changes in the shape of the ciliary body cause the tension fibres to be stretched, permitting the holding fibres to be relaxed.

Relaxation of the holding zonular fibres allows the elastic capsule to exert tension on the lens substance, in proportion to the variation in its capsular thickness (Fincham, 1937, Fisher, 1969a). The capsule is thickest and strongest at the equator and exerts its maximum force here to reduce the transverse diameter of the lens. In the central anterior region, where the capsule is relatively thin, the lens bulges forward resulting in an decrease in radius of curvature (Fincham, 1937; Fisher, 1969b). Fincham (1937) considered that this change in anterior surface curvature resulted in a conoidal surface. Fisher (1969b) proposed, however, that the anterior surface took up an elipsoidal shape. There is little change in the posterior surface of the lens where the capsule is thinner and of more constant thickness.

The role of the vitreous in accommodation is a subject of some debate. Coleman (1970) proposed that the the lack of change in posterior lens curvature was due to vitreous pressure on the posterior lens surface. He used ultrasonography to demonstrate that the posterior lens surface moved backwards by 0.20 mm when subjects accommodated in a normal seated position. There was no displacement, however, when the eye was looking up. He concluded, therefore, that the vitreous played a supporting role in accommodation. Fisher (1982), however, is of the opinion that the vitreous plays a negligible role in the modification of lens shape or position and that the lack of posterior pole movement is due to elastic anisometry.

1.3 - NEURAL CONTROL OF ACCOMMODATION

The accommodative response is activated by the image of the stimulus on the retina. The afferent pathway transmits the information to the calcarine cortex (area 17) and, thereafter a relay is made to areas 19 and 22. From the peristriate cortex (area 19) the efferent pathway travels down the internal corticotectal tract to the hypothalamus, a co-ordinating area in the tectal or diencephalic region, and continues to the Edinger-Westphal nuclei. From here the signal passes along the parasympathetic fibres of the oculomotor (3rd cranial) nerve. These fibres are thought to synapse in the ciliary ganglion with the post-ganglionic fibres of the short ciliary nerve (Behr, 1924; Kuntz, 1929; Warwick, 1954; Ruskell and Griffiths, 1979). Westheimer and Blair (1973a) proposed, however, that the fibres pass through the ganglion without synapsing. Thereafter the fibres enter the globe via the short ciliary nerves and the nerve impulse stimulates the release of acetylcholine which acts on muscarinic receptors in the ciliary muscle (Alpern, 1969; Duke-Elder, 1971).

The sympathetic supply to the ciliary muscle passes from the hypothalamus to the lower cervical and upper thoracic segments of the spinal cord. It leaves the spinal cord by the first, second and third thoracic nerves and travels up the cervical sympathetic chain where the majority of fibres synapse in the superior cervical ganglion. The sympathetic nerve fibres then pass along the carotid plexus and enter the eye as the long ciliary nerves (Duke-Elder, 1971).

Elliott (1904) found that adrenaline was released from sympathetic nerve endings. Von Euler (1946) modified this finding and established that noradrenaline is the main endogenous sympathomimetic catecholamine. Ahlquist (1948) observed that noradrenaline could excite some smooth muscle but inhibit others and suggested that two types of receptors are present in smooth muscle, termed alpha- and beta-receptors. Lands *et al.* (1967) divided beta-receptors into two sub-types based on the differential sensitivity of various tissues to a series of beta-stimulating drugs. The receptors found in the heart and intestinal smooth muscle were of one type, designated beta$_1$ receptors while those found in the bronchial, vascular and uterine smooth muscle were of another type, designated beta$_2$ receptors.

1.3A - Sympathetic innervation of the ciliary muscle

Although evidence for predominant parasympathetic control of accommodation is unequivocal, confusion and disagreement exist concerning the existence and nature of the sympathetic innervation to the ciliary muscle. The evidence for sympathetic innervation has been comprehensively reviewed by Gilmartin (1986). Early proposals for dual ciliary innervation (Henke, 1860) were doubted by other authorities (Helmholtz, 1855; Donders, 1864). The first evidence for adrenergic innervation was provided by Jessop (1886) who found that the instillation of cocaine (a sympathomimetic) produced relaxation of accommodation in human subjects. Jessop (1888) induced accommodation in dogs and cats with pilocarpine (a parasympathometic) and found that stimulation of the long ciliary nerves produced hyperopic shifts in accommodation. Morat and Doyon (1891) stimulated the cervical portion of the sympathetic chain in dogs and reported similar results, however, subsequent studies were failed to support their findings (Hess and Heine, 1898; Romer and Dufour, 1902).

Cogan (1937) reviewed the evidence for sympathetic innervation of the ciliary muscle and presented evidence based on sympathectomies (producing partial Horner's syndrome) and subconjunctival injections of adrenaline. The partial Horner's syndrome produced a mean increase in amplitude of accommodation of 1.4 D in the affected eye for 5 subjects. Although Cogan compensated for the concurrent pupil miosis by the use of 2 mm artificial pupils, no compensation could be made for the increase in ciliary body volume due to the vascular engorgement associated with sympathetic denervation. Indeed the differentiation between changes in the accommodative response induced by changes in the ciliary vasculature and and those initiated by genuine sympathetic neural control has complicated the interpretation of many subsequent studies (e.g. Olmstead and Morgan, 1941; Fleming and Olmstead, 1955).

1.3B - Anatomical evidence for sympathetic innervation

Agababow (1893) identified four nerve endings in the ciliary body: motor, vasomotor, sensory and proprioceptive and presumed the motor and vasomotor fibres were parasympathetic and sympathetic, respectively. Mohney *et al.* (1942) traced sympathetic nerve fibres from the first and second thoracic nerves via the superior cervical ganglia to the long ciliary nerves and on to the ciliary body and iris.

Wolter (1953) found that the radial fibres of the ciliary muscle were supplied by two different nerve fibre groups and suggested that one of the groups was sympathetic. Génis-Gálvez (1957) confirmed that the ciliary body was innervated by both parasympathetic and sympathetic fibres but could not determine whether they were mutually antagonistic or not.

The advent of sophisticated histofluorescence techniques led to the identification of adrenergic terminals in primates (Malmfors, 1965; Ehinger, 1966; 1971; Laties and Jacobowitz, 1966). Ruskell (1973) observed the absence of terminals with small granular vesicles (of a type known to be sympathetic), in monkey ciliary muscle following superior cervical ganglionectomy. He concluded that, on average, fewer than 1% of the terminal varicosities were sympathetic and concluded that the sympathetic terminals were too few to provide a significant role in the control of accommodation.

1.3C - Physiological evidence for sympathetic innervation

Olmstead and his co-workers studied the effect of cervical sympathetic nerve stimulation in rats, rabbits, guinea pigs, cats, dogs and monkeys and were able to demonstrate inhibition of accommodation in all animals (Morgan *et al.*, 1940; Olmstead and Morgan, 1941; Mohney *et al.*, 1942; Olmstead, 1944). They also noted that sympathetic stimulation had greater effect in lower animals than in monkeys. Olmstead and his collaborators questioned, however, whether these hyperopic changes in accommodation were due to constriction of the ciliary vasculature causing a flattening of the lens. This concept was supported in subsequent papers (Morgan, 1944a; 1946; Kuntz *et al.*, 1946; Fleming and Olmstead, 1955; Fleming, 1957; 1959; Fleming and Hall, 1959).

Melton *et al.* (1955) measured ciliary muscle movement in enucleated cat's eyes by means of a mechano-electric transducer. They demonstrated that stimulation of the long ciliary nerve (sympathetic) produced shortening of the radial muscle fibres and flattening of the lens although they did not preclude the possibility of a vascular mechanism.

Törnqvist (1966) employed a Thorner optometer to measure accommodation in 13 monkeys under general (pentobarbital) anaesthesia. He demonstrated that stimulation of the cervical sympathetic nerve produced hyperopic shifts in accommodation which were unaffected by the instillation of alpha-adrenergic antagonists. Instillation of beta-adrenergic antagonists, however, eliminated the sympathetic-induced relaxation of accommodation. Conversely, Chin *et al.* (1968) found that the instillation of phenylephrine (an alpha-adrenergic agonist) depressed the accommodative response induced by mid-brain stimulation, although Chin and his co-workers suggested that this was probably due to the slight beta-adrenergic effects of the drug.

Törnqvist (1967) used electrical stimulation of the oculomotor nerve to induce accommodation in monkeys under general (pentobarbital) anaesthesia, varying the level of parasympathetic activity by altering the stimulation frequency. Törnqvist found that the magnitude of the inhibitory activity produced by cervical sympathetic nerve stimulation (maintained at a constant stimulation frequency) varied according to the level of background parasympathetic activity. In the absence of oculomotor stimulation, cervical stimulation produced a hyperopic shift of 0.6 D. When the level of concurrent parasympathetic activity was increased, however, there was a steady increase in the inhibitory effects of sympathetic stimulation up to a maximum of 1.5 D. It is important to note that in the absence of parasympathetic stimulation Törnqvist's monkeys were probably exerting a significant level of accommodation. Westheimer and Blair (1973b) employed retinoscopy to measure the refractive state of monkeys under anaesthesia produced by pentobarbital, as used by Törnqvist. They found that monkeys adopted an intermediate resting position of 2.5 - 3.0 D. Törnqvist (1967) also demonstrated that the hyperopic shifts in accommodation produced by sympathetic stimulation developed very slowly, taking 10 - 40 seconds to reach maximal effect. Conversely he found that parasympathetic stimulation took 1 to 2 seconds to reach maximal effect, a finding consistent with previous investigations on the temporal accommodative response characteristics in humans (Campbell and Westheimer, 1960). Törnqvist's work has shown, therefore, that sympathetic innervation of the ciliary muscle, while present in monkeys, is too slow to provide an effective temporal response to a constantly changing visual environment.

Hurwitz *et al.* (1972a) induced positive accommodation by electrical stimulation of the midbrain in monkeys and investigated the effects of stimulating ciliary muscle beta receptors with subconjunctival injections of the non-selective beta-agonist isoproterenol and of blocking ciliary beta receptors with the non-selective beta-antagonist propranolol. They found that the inhibitory effects of isoproterenol were only significant for accommodation levels greater than 4 D. This is consistent with Törnqvist's finding that the effect of sympathetic inhibition increases proportionately with increases in concurrent levels of parasympathetic background tone. In a second study, Hurwitz *et al.* (1972b) found no evidence for alpha-adrenergic innervation to the ciliary muscle.

1.3D - Pharmacological evidence for sympathetic innervation

Several authors have examined the effects of pharmacological agents on dissected-out strips of ciliary muscle. Van Alphen (1961) showed that adrenaline and noradrenaline produced relaxation of pieces of cat ciliary muscle. In a more extensive study Van Alphen *et al.* (1965) investigated the effects of various adrenergic blocking drugs on strips of ciliary muscle obtained from the enucleated eyes of monkeys, rabbits and cats. They found that both alpha- and beta-receptors were present in cat ciliary muscle, with beta-receptors predominating. The receptors in rabbit ciliary muscle were predominantly alpha whereas only beta-receptors were found in the ciliary muscle of the monkey.

Kern (1970) studied human ciliary muscle obtained from 80 enucleated eyes using a range of alpha- and beta-adrenergic blocking drugs. He found the vast majority of the adrenergic receptors to be of the beta sub-type and inhibitory in nature. This work was later substantiated by Van Alphen (1976).

TABLE 1.1. - The distribution of adrenergic receptors in man and other species (after Van Alphen, 1976)

	DILATATOR	**SPHINCTER**	**CILIARY MUSCLE**
CAT	mainly α, some β	mainly β, some α	mainly β, some α
RABBIT	mainly α, few β	mainly β, few α	mainly α, few β
MONKEY	mainly α, very few β	mainly α perhaps β	exclusively β, no α
MAN	mainly α very few β	α & β in equal amounts	mainly β very few or no α

Lograno and Reibaldi (1986) obtained fresh ciliary muscle strips from enucleated human eyes and found that they did not respond to adrenergic agents unless they were precontracted with carbachol (a muscarinic agonist). This finding is consistent with earlier observations that the infuence of sympathetic innervation increases proportionately with increases in concurrent levels of parasympathetic background tone

(Törnqvist, 1967; Hurwitz *et al.*, 1972a). Isoprenaline induced relaxation of the ciliary muscle and was antagonised by propranolol. The beta$_1$-selective antagonists, practolol and atenolol had no effect on the isoprenaline-induced relaxation therefore indicating that beta$_2$-adrenergic receptors are present in human ciliary muscle. In addition, phenylephrine did not cause contractile responses thus demonstrating the absence of alpha-adrenergic receptors in ciliary muscle.

Wax and Molinoff (1987) investigated beta-adrenergic receptors in the iris and ciliary body taken from patients shortly after death. They found that approximately 90% of the beta receptors in human iris-ciliary body demonstrate pharmacological characteristics consistent with adrenergic receptors of the beta$_2$ sub-type. They proposed that two receptor sites are present in ciliary smooth muscle and that 30% of the receptors were of the beta$_1$ sub-type. They assumed, therefore, that 70% of the receptors were of the beta$_2$ sub-type, a finding consistent with the observations of Lograno and Reibaldi (1986).

1.3E - Psychological evidence for sympathetic innervation

It is well established that changes in a subject's psychological state may be reflected in changes in their autonomic balance and hence certain physiological variables such as heart rate and pupil size (Hess and Polt, 1964; Libby *et al.*, 1973). It is thought that stress induces an increase in sympathetic activity which is accompanied by a release of adrenaline from the adrenal medulla (Cannon and de la Paz, 1911; Cannon, 1914) and the activation of both central and peripheral catecholaminergic mechanisms (Stone, 1975; Anisman, 1978; Dunn and Kramarcy, 1984).

Olmstead and Morgan (1939) were able to produce hyperopic shifts of up to 1.5 D in rabbits by sharp taps on the nose, jostling, head-shaking and noise. Comparable shifts were found when human subjects were exposed to noise and electric shocks (Olmstead and Morgan, 1941; Olmstead, 1944). Conversely, Westheimer (1957) and Leibowitz

(1976) found that anger induced myopic shifts in human subjects. Leibowitz also measured tonic accommodation (TA) in a doctoral candidate the day before his *viva-voce* exam and found that it had increased. The candidate's TA returned to his normal level the day after the exam. This is in contrast to previous observations that some subjects show a reduction in accommodative facility immediately prior to examinations (Cogan, 1937).

Further evidence for the involvement of sympathetic innervation in accommodation was provided by Ong and Fisher (1973) who found that an increase of 4 D in accommodative demand produced an increase in the galvanic skin response (a well established measure of autonomic activity). They propose that this increase may be associated with increased accommodation or the 'averseness' of the increased accommodative demand.

Miller (1978a) studied the relationship between mood and the variability of TA. He found that changes in subject mood were frequently associated with significant variability of TA. Miller and LeBeau (1982) measured TA in 33 undergraduate students under two experimental conditions: a 'stressed' condition where the subjects were told their performance was being assessed and a control condition, where no assessment was implied. Subjects also completed a stimulus-response inventory of general trait anxiety whereby a measure of "situationally specific trait anxiety" could be obtained. Miller and LeBeau found a high anxiety score was accompanied by a significant myopic shift in accommodation and suggested that such an effect was mediated by the cholinergic system.

Certain workers have examined the influence of cognitive demand or mental effort on the accommodative response. Malmstrom *et al.* (1980) demonstrated that a written backward-counting task could produce a decrease in accommodative response of 0.25-0.75 D for a 3.00 D target. No systematic shifts were observed under open-loop conditions (analogous to empty-field). Malmstrom and his co-workers suggested that cognitive induced shifts in accommodation are caused by changes in the autonomic balance of the subject. Furthermore Birnbaum (1984) postulates that, during a near visual task, mental activity may induce an increase in sympathetic input to the ciliary muscle and hence produce a hyperopic shift in accommodation. Gawron *et al.* (1985) had difficulty reproducing the results of Malmstrom *et al.* (1980) yet reached similar conclusions. In contrast, Kruger (1980) showed that when 20 subjects changed from passive reading of two-digit numbers at 40 cm to adding the numbers the mean accommodative response increased significantly by 0.28 D. Recently Post *et al.* (1985) demonstrated that the imposition of mental effort could produce shifts in tonic accommodation although large intersubject differences existed. Whilst it may be inappropriate to equate the imposition of mental effort or cognitive demand with stress it is clear from the literature that increased mental activity or heightened attention can produce physiological changes consistent with other forms of stress (Hess and Polt, 1965; Libby *et al.*, 1973).

Hogan (1985) suggests that the contradictory results of studies of stress and the accommodative response may be explained by the duration and time-course of the physiological response to stress. Wenger *et al.* (1956) state that the sympathetic nervous system provides the initial response to stress by increasing sympathetic activity and that this is subsequently counteracted by an increase in parasympathetic activity. It appears that in some individuals the activity of the parasympathetic system not only compensates for the increased sympathetic activity but may in some circumstances overcompensate. Wenger *et al.* (1956) cite the phenomenon of defaecation and urination which may, on occasion, accompany highly stressful situations as examples of 'parasympathetic overcompensation'.

Sternbach (1966) showed that physiological variables such as heart rate returned to pre-stress levels following a single intense shock and in some cases overshot them. Porges (1976) proposes a 'two component model of attention" which comprises up to three phases of response to stress. An immediate parasympathetic response occurs during the first second following stimulation. The second phase has a latency of 4-5 seconds and is characterised by sympathetic excitation or parasympathetic inhibition. The final phase is a more sustained parasympathetic response. Anisman (1975) reviews the neurochemical changes that occur in response to stress and states that stress elicits a transient catecholamine (sympathetic) reaction followed by a cholinergic (parasympathetic) rebound. Anisman (1975) concludes that excessive stimulation of one system induces a compensatory antagonistic rebound in the complementary system thereby maintaining neurochemical homeostasis. It is feasible that different accommodative studies have measured different phases of the physiological response to stress.

1.3F - Recent evidence for the influence of sympathetic innervation on accommodation in humans

Recent studies have examined the influence of various pharmacological agents on the accommodative response in humans. Garner *et al.* (1983) demonstrated that the alpha-adrenergic agonist phenylepherine (10%) produced a regression of the near-point of accommodation of around 2.75 D but had no effect on tonic accommodation [TA (see section 1.5 pps. 46-55)]. Mordi *et al.* (1986) estimated TA values from the intersection of the monocular stimulus/response function with the unit ratio line, as measured with the laser optometer and suggested that phenylephrine (10%) produced a small hyperopic shift in TA (≈0.25 D). Mordi and his co-workers acknowledge, however, the limitations of this technique of determining TA values. In addition previous research suggests (e.g. Törnqvist, 1966; 1967) that the sympathetic receptors in smooth ciliary muscle are of the beta sub-type and that no alpha alpha receptors are present (Lograno and Reibaldi, 1986). It is likely, therefore, that changes in accommodation produced by alpha adrenergic agents are due to changes in the ciliary vasculature.

Gilmartin *et al.* (1984) examined the effect of the topical beta-adrenergic antagonist timolol maleate (0.5%) on TA using the laser optometer. Employing a double-blind protocol between timolol and saline they demonstrated a mean myopic shift of 0.84 D in 10 subjects 40 minutes after the instillation of timolol. They concluded that TA was a consequence of steady-state equilibrium between parasympathetic and sympathetic innervation of the ciliary muscle. The myopic shift was not, however, accompanied by a significant change in the rank-order distribution of TA values and led Gilmartin *et al.* (1984) to suggest that variations in TA evident in the population were a consequence of variations in parasympathetic rather that sympathetic tone.

Gilmartin and Hogan (1985b) subsequently used the beta-adrenergic agonist isoprenaline (3.0%) and the antimuscarinic tropicamide (0.5%) to examine the importance of parasympathetic innervation in TA variation. Isoprenaline produced a significant mean hyperopic shift in of 0.47 D but did not significantly alter the rank-order distribution of TA values. Tropicamide produced a significant mean hyperopic shift in TA of 1.06 D. In addition it was found that the hyperopic shift in TA was directly proportional to the the pre-drug level of TA, thus inducing a significant change in the rank-order distribution of TA values. The results confirm that parasympathetic innervation is the main determinant of a subjects TA position and variations in TA among subjects are a consequence of parasympathetic rather than sympathetic ciliary muscle tone. It is important to note that neither timolol nor isoprenaline affected standard consulting room measures of acuity, far-point, near-point of accommodation or oculomotor balance.

1.3G - Summary

The literature relating to the existence and nature of the sympathetic innervation to the ciliary muscle may summarised as follows:

1. The sympathetic input is inhibitory in nature and mediated by beta-adrenergic receptors, predominantly of the beta$_2$ sub-type (Lograno and Reibaldi, 1986; Wax and Molinoff, 1987).
2. The input is relatively small in magnitude relative to the predominant

parasympathetic input with a maximum dioptric value of around -1.5 D (Törnqvist, 1966;1967; Gilmartin *et al.*, 1984).

3. The time-course of sympathetic activity is significantly slower than that of parasympathetic activity, taking 10 - 40 seconds to reach maximal effect (Törnqvist, 1966; 1967).
4. Sympathetic inhibitory activity is augmented by higher levels of concurrent parasympathetic activity (Törnqvist, 1966; 1967; Hurwitz *et al.*, 1972a).

The above characteristics suggest that the role of the sympathetic input to the ciliary muscle is more relevant to to tasks which require sustained high levels of accommodation rather than those tasks requiring a low or rapid change in accommodative response.

1.4 - THE STIMULUS TO ACCOMMODATION

The relationship between the steady-state accommodative response and stimulus vergence is typically represented by the stimulus/response function (see Fig. 1.2). An emmetropic eye viewing a near object will exert a level of accommodation less than the stimulus vergence, a phenomenon referred to as 'accommodative lag' (Sheard, 1920; Morgan, 1944b). Conversely, for distant objects the accommodative response exeeds the stimulus vergence and this steady-state error is termed 'accommodative lead' (Morgan, 1944b). The accommodative response matches the stimulus vergence at only one point on the curve and Toates (1972) proposed that this intersection of the unit-ratio line represents the physiological resting state of accommodation (i.e. tonic accommodation). The curve is further characterised by a quasi-linear region with a gradient between zero and 1.

Previous research has demonstrated that the accommodative response is dependent on a number of target characteristics such as: **luminance** (Wald and Griffin, 1947; Campbell, 1954; Nadell and Knoll, 1956; Alpern, 1958a; Alpern and David, 1958; Johnson, 1976); **spatial frequency** (Charman and Tucker, 1978a; Owens, 1980; Raymond *et al.*, 1984; Charman and Tucker, 1977; Charman and Heron, 1979; Bour, 1981; Ciuffreda and Hokoda, 1983; Tucker *et al.*, 1986; Ciuffreda *et al.*, 1987; Tucker and Charman, 1987); **contrast** (Wolfe and Owens, 1981; Ciuffreda and Rumpf, 1986; Ward, 1987); **colour** (Fincham, 1951; Charman and Tucker, 1978b; Wolfe and Owens, 1981); **retinal target eccentricity** (Whiteside, 1957; Hennessy and Leibowitz, 1972; Phillips, 1974; Semmlow and Tinor, 1978).

The accommodative response may also be influenced by subject characteristics such as: **pupil size and depth-of-focus** (Campbell, 1957; Ogle and Schwartz, 1959; Ripps *et al.*, 1962; Tucker and Charman, 1975; Hennessy *et al.*, 1976; Ward and Charman, 1985; 1987); **age** (Hamasaki *et al.*, 1956; Braddick *et al.*, 1979; Simonelli, 1983;

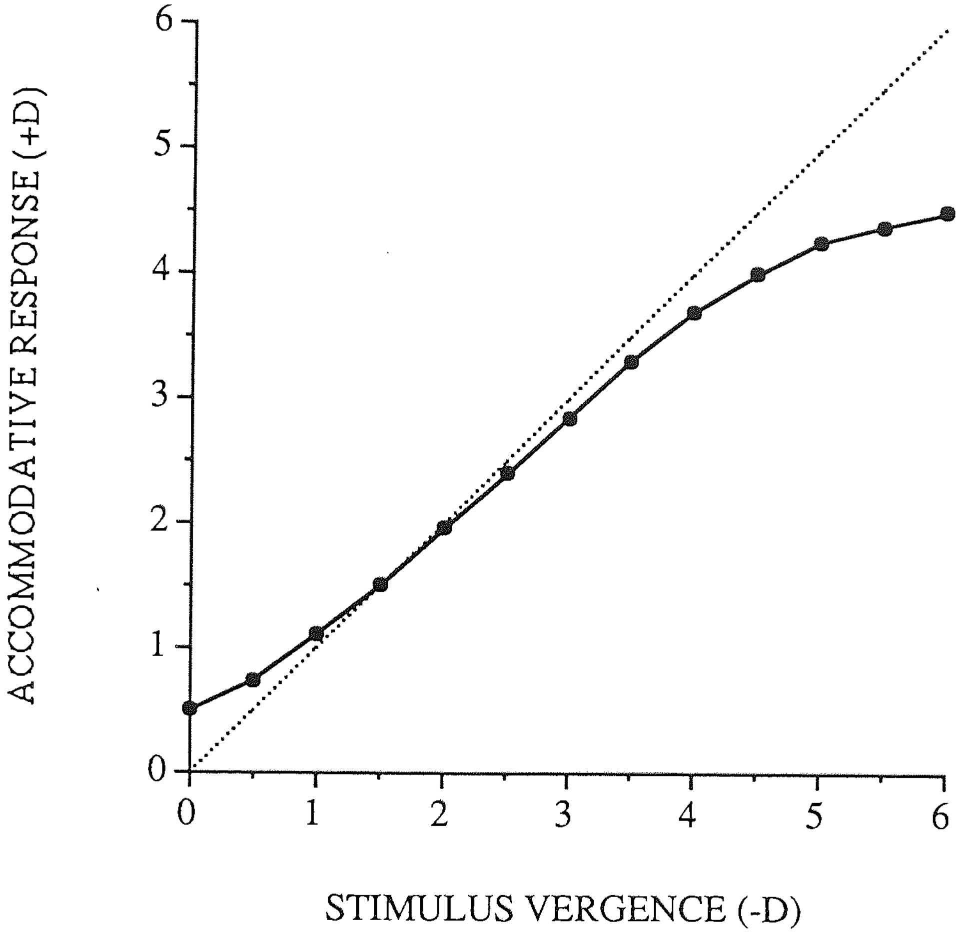


FIG. 1.2. - The accommodative response as a function of stimulus vergence.

Banks, 1980); **visual acuity/target detail** (Heath,1956a; Otto and Saffra, 1974; Korge and Krueger, 1984); **amblyopia** (Wood and Tomlinson, 1975; Kirschen *et al.*, 1981; Hokoda and Ciuffreda, 1982; Ciuffreda *et al.*, 1983; Ciuffreda *et al.*, 1984; Ciuffreda and Hokoda, 1983; Ukai *et al.*, 1986; Ciuffreda *et al.*, 1986); **refractive error** (Ramsdale, 1978; Fledelius, 1981; Maddock et al., 1981; Ramsdale 1982; McBrien and Millodot, 1986a; 1986b); **vergence** (Fincham and Walton, 1957; Semmlow and Hung, 1981; Kersten and Legge, 1983; Schor and Kotulak, 1986); **chromatic aberration** (Fincham, 1951; Fincham, 1953; Campbell and Westheimer, 1959; Millodot and Sivak, 1973; Charman and Tucker, 1978b) and **spherical aberration** (Campbell and Westheimer, 1959; Jenkins, 1963; Charman *et al.*, 1978).

Furthermore, the accommodative response is afffected by temporal factors, *viz.*, **reaction time** (Campbell and Westheimer, 1960; Shirachi *et al.*, 1978; Tucker and Charman, 1979) and **microfluctuations** (Campbell *et al.*, 1959; Millodot, 1968; Denieul, 1982; Kotulak and Schor, 1986), in addition, **perceived stimulus distance** (Hofstetter, 1942; Ittleson and Ames, 1950; Johnson, 1976) and **perceived stimulus size** (Alpern, 1958b; Benel, 1980; Kruger and Pola, 1986; Kruger and Pola, 1987).

Accommodation may be modified further by such non-ocular factors as: **volitional control** (Marg, 1951; Randle, 1970; Provine and Enoch, 1975); **cognitive demand** (Malmstrom and Randle, 1976; Kruger, 1980; Malmstrom *et al.*, 1980; Gawron *et al.*, 1985) and **fatigue** (Berens and Sells, 1944; Berens and Sells, 1950; Malmstrom *et al.*, 1981; Miller *et al.*, 1983).

Recently Charman (1986) has considered the various optical factors associated with the accuracy of the accommodative response and concludes that the slope (**m**) of the linear portion of the stimulus/response function is linearly related to the minimum angle of resolution (**MAR**) achievable by the observer under the observation conditions. Using some basic assumptions and incorporating the constant **C** Charman derives the equation:

$$|m| = 1 - C(MAR)$$

Charman (1986) compares this prediction with previously reported data for the influence of luminance, spatial frequency, contrast, visual acuity and pupil size on the accommodative response and concludes that the data from the majority of studies predicts a value for C between ~0.1 and 0.5 min^{-1}.

In summary, the accuracy of the accommodative response is dependent on the quality of the target and the retinal image. As stimulus quality decreases accommodation becomes increasingly biased towards an intermediate resting position, the extreme situation being stimulus-free conditions e.g. darkness. The study of accommodation under darkroom conditions has the advantage that changes and variations in response are not limited by depth-of-focus and the stimulus-dependency of the accommodative response.

1.5 - THE TONIC RESTING STATE OF ACCOMMODATION

1.5A - Night myopia and tonic accommodation

It is now generally accepted that in the absence of adequate visual stimuli, accommodation adopts an intermediate resting position. It is appropriate to use the term 'tonic accommodation' (TA) to describe this myopic shift which may occur in darkness or an empty-field (ganzfeld), although the phenomenon is also referred to as the 'resting focus' or 'dark focus' of accommodation.

The concept of TA and an intermediate resting position is based on observations from as early as 18th century that distance visual acuity decreases under reduced illumination, the phenomenon being referred to as 'night myopia'. Early studies suggested that this increase in refractive state of the eye was partly due to spherical aberration (Rayleigh, 1883; Otero and Duran, 1941; 1942; Le Grand, 1942; Ivanoff, 1947a; Koomen *et al.*, 1951) or chromatic aberration and the purkinje shift (Wibaut, 1919; Wald and Griffin, 1947; Ivanoff, 1947b; Ronchi, 1948).

Otero and Duran (1941; 1942) provided early evidence for accommodation being the primary cause of night myopia. They found levels of up to 2.0 D of low luminance myopia and found that this was almost eliminated by the instillation of homatropine, a finding later confirmed by Wald and Griffin (1947). Campbell (1953) used purkinje image photography and foveal scotoma fixation to demonstrate a mean myopic shift of 0.64 D in darkness but concluded that chromatic and spherical aberration were of greater importance than accommodation. Campbell and Primrose (1953) used the same technique and found a mean increase in lens power of 0.8 D in 5 subjects which they considered to be too small a change to account for the reported value of 1.5 D for night myopia. They concluded that accommodation and ocular aberrations contributed equally to low-luminance myopia.

Heath (1962) employed a variety of techniques, *viz.*, subjective coincidence optometry, infra-red retinoscopy, purkinje image photography and infra-red optometry and found a variable low-luminance myopia of up to 1.5 D. He also found similar values of refractive state under empty-field conditions and hence concluded that the spherical aberration associated with pupil dilation in darkness was not the major cause of night myopia. Heath (1956b) was also the first worker to adopt the term 'tonic state of accommodation' to describe the phenomenon of night myopia.

Mellerio (1966) reviewed the literature concerning the myopic shift which occurs at low illuminations and concluded that three factors were responsible for night myopia. He felt that the Purkinje shift coupled with the chromatic aberration of the eye, accounted for about 0.4 D of night myopia whilst the increase in spherical aberration due to pupillary dilation was responsible for up to 1 D of the refractive change. He felt, however that accommodation was the largest component of night myopia introducing up to 1.5 D of myopia.

The development of the subjective Badal laser optometer (Hennessy and Leibowitz, 1970; 1972; Inglestam and Ragnarsson, 1972) provided researchers in the period since the early seventies with a simple reliable technique by which to measure accommodation under darkroom conditions (see Section 1.6D pps. 59-60). The most extensive was that of Leibowitz and Owens (1978) who reported a mean value of +1.52 D (s.d. = 0.77 D, range = -0.50 to +4.00) for a group of 220 college-age observers. The majority of studies employing the technique have found a mean value of TA, for a young population, of around 1.5 D (Leibowitz and Owens, 1975a; Leibowitz and Owens, 1975b; Owens and Leibowitz, 1976; Miller, 1978a; 1978b; Mershon and Amerson, 1980; Owens and Leibowitz, 1980; Heron et al., 1981; Epstein et al., 1981; Maddock et al., 1981; Miller et al., 1983; Smith, 1983; Hogan and Gilmartin, 1984a).

Other workers have adopted different techniques to assess TA. Simonelli (1983) employed a polarised vernier optometer (see section 1.6A pps. 56-57) to measure TA in 301 subjects and found a mean value of 0.71 D (s.d. = 0.53 D). More recently Johnson *et al.* (1984) measured TA in 50 subjects using an infra-red optometer and found a mean value of 1.10 D (s.d. = 1.06 D). They note that this mean value is significantly lower than that reported by Leibowitz and Owens (1978) for 220 subjects using the laser optometer. In an accompanying paper Post *et al.* (1984) compared TA values obtained by laser optometry and infra-red optometry and concluded that the laser optometer may influence estimates of TA (see section 2.2 pps. 80-93).

1.5B - Empty-field, instrument and small-pupil myopia.

Accommodation has also been shown to adopt an intermediate resting position in conditions other than darkness. Whiteside (1952) found that when subjects viewed a bright featureless environment, such as a cloudless sky or fog they showed 0.5 to 2.0 D of myopia, a finding confirmed by Heath (1956b). Westheimer (1957) and Heath (1962) both demonstrated that the level accommodation recorded under empty-field conditions was equivalent to that found under darkroom conditions. Leibowitz and Owens (1975a) compared values of dark focus in 30 subjects with empty-field myopia and found a correlation coefficient of 0.68.

It is well established that subjects tend to overaccommodate when viewing through an optical instrument (Baker, 1966; Schober *et al.*, 1970; Richards, 1976; Richards *et al.*, 1980; Ditchburn, 1980). Instrument myopia appears to be derived from an interaction between the subject's perception of the proximity of the instrument and the small exit pupils of the instrument (Schober *et al.*, 1970). Miller *et al.* (1984) found that subjects viewing through a phoropter with 2mm artificial pupils produced an increase in accommodative lag and lead. This is consistent with the findings of other workers who have demonstrated that a reduction in pupil size causes the accommodative response to approach its intermediate resting position (Ripps *et al.*, 1962; Hennessy *et al.*, 1976; Ward and Charman, 1985; 1987). Leibowitz and Owens (1975b) compared values of dark focus in 30 subjects with instrument myopia and found a correlation coefficient of 0.68.

1.5C - The long-term stability of tonic accommodation

Several studies have demonstrated the long-term stability of TA. Miller (1978a) could find no apparent diurnal or cyclic variations in TA in 21 subjects who were examined over a 2-3 week period. Mershon and Amershon (1980) obtained two sets of measurements of TA for 39 subjects. Nineteen subjects performed the second test in the same experimental session and the other 20 participated in a second session a week later. They found an average change of 0.3 D between the two tests and correlation coefficients of 0.91 for the subjects tested twice in the same session and 0.81 for those retested a week later. Heron *et al.* (1981) assessed diurnal TA variations in one subject and also examined variations in TA over a two week period in a further subject and found the measured values to be consistent. In addition they performed a test-retest study on 30 subjects over a period of between 3 and 23 weeks (mean time between sessions = 12 weeks) and found a correlation coefficient of 0.69 ($p < 0.05$). Miller et al. (1983) measured TA for 10 subjects over a 3 hour period and found no significant change during this time although they found that females ($N = 5$) tended to show greater variation than males. Similarly, Krumholz *et al.* (1986) found nonsystematic variations of TA in five subjects measured over a 8 to 13 hour period. Owens and Higgins (1983) monitored TA for 1 year in 5 subjects and found that the largest individual difference in mean values between measurement periods was 0.66 D, the average difference being 0.21 D.

It is important to note that most of the aforementioned studies have employed laser optometry to measure TA. Since this is a subjective technique, variations in a subject's performance may influence the value of TA obtained. Post *et al.* (1984), however, used an infra-red optometer to measure TA in 47 subjects and found test-retest correlation coefficients for session separations of a few minutes, 1 day, 1 week and 2 weeks, of

0.98, 0.72, 0.75 and 0.76, respectively.

It may be concluded, from the above studies, that the level of stability diminishes with increasing time between retest sessions. It is apparent, however, that the tonic resting position of accommodation is relatively stable and is, therefore, an appropriate parameter for the study of the accommodative mechanism.

1.5D - Accommodative hysteresis and adaptation of tonic accommodation

Although the previous section has reported the long-term stability of TA, there is a growing body of evidence which suggests that a period of sustained fixation may produce changes in a subject's tonic resting position. Ebenholtz (1983) measured TA in 12 subjects using a laser optometer. Subjects participated in three experimental sessions wherein, following initial measurement of TA, they would view monocularly a fixation target placed at their far point (FP), near point (NP) or tonic resting position by means of a Badal optical system, for 8 minutes. TA was measured immediately following the task and two further measurements made 8 and 16 minutes after cessation of the task. Ebenholtz (1983) found that NP fixation produced a mean increase in TA of 0.34 D ($t = 4.25$, d.f. = 11, $p < 0.01$). Conversely, FP fixation elicited a mean decrease in TA of -0.21 D ($t = 4.20$, d.f. = 11, $p < 0.01$). Fixation at the resting position produced a nonsignificant increase in TA of 0.06 D. Assuming the regression of TA towards pre-task levels to be exponential, Ebenholtz calculated that the effects would dissipate in 72 minutes for FP fixation whereas the NP effects would require 10.26 hours and commented that a non-linearity existed in these results. The NP target was, on average, 5.12 D proximal to the subject's TA position, whereas the FP target was, on average, 0.98 D beyond the resting position. Hence it might have been expected that the NP effect would be five times that of the FP effect. Ebenholtz regarded this, along with the difference in FP and NP decay times, to be evidence for the existence of two sub-systems for the control of accommodation.

More recently Ebenholtz and Zander (1987) repeated the above experiment examining pre- and post task measures of FP and NP, in addition to TA. He found that NP shifted outward by 0.37 D and inward by 0.62 D after 8 minutes FP and NP fixation respectively. No significant changes in FP were recorded, however, for any experimental condition.

Baker *et al.* (1983) employed a dynamic infra-red optometer to monitor TA in darkness for 20 seconds following 5 seconds of fixation at 0, -1, -2 and -3 D. They found that a stable resting state was reached 1 to 3 seconds after the lights were extinguished. They poposed the existence of a zone of 'inactive accommodation', of about 1 D, within which accommodation was relatively stable in darkness, rather than a single resting position. Following fixation proximal to the 'rest zone', accommodation drifted towards the near edge of the zone. Conversely, fixation beyond the rest zone resulted in accommodation drifting towards the far edge of the zone. For stimulus levels within the rest zone there was little change in accommodation when the lights were extinguished.

Schor *et al.* (1984) also used infra-red optometry to examine the effects of periods of monocular fixation on TA, which they termed 'adaptation of TA'. For short-term adaptation (15 to 120 seconds) to stimuli 4 D nearer and 1.5 D further than the subject's initial resting position, they were unable to demonstrate consistent after-effects that were correlated with the adapting stimulus. Thirty minutes monocular adaptation to a -6 D stimulus, however, produced a significant mean increase in TA of 0.5 D in 9 subjects ($t = 2.46$, d.f. = 8, $p < 0.025$). It is interesting to note that Schor *et al.* (1984) recorded post-task TA as the accommodative state 45 seconds after the stimulus offset to allow for all transient (non-tonic) responses to decay. They cite the study of Krishnan and Stark (1975) who showed that the accommodative response decays in 2 to 15 seconds, a range of values consistent with the more recent findings of Baker *et al.* (1983). It may be more appropriate, however, to measure TA immediately after the stimulus offset and over a period of time as this may yield valuable information concerning the mechanisms underlying adaptation of TA.

Ebenholtz (1985) studied the effect of NP and FP fixation for 8 minutes in 17 subjects. This was repeated for between 3 and 6 sessions at each task location and pre- and post-task TA values measured using a laser optometer. He found strong individual differences with respect to susceptibility to accommodative hysteresis. In addition, the magnitude of hysteresis produced within a given individual on one occasion relative to another varied inversely with the pre-task TA. Ebenholtz also found that, for the FP condition, the magnitude of the hysteresis effect was related to the dioptric distance between the FP and the pre-task TA. There was no such relationship for the NP condition and supporting previous evidence for the existence of two sub-systems for the control of accommodation (Ebenholtz, 1983).

Hogan and Gilmartin (1985) examined the effect of a 15 minute interactive task at 2.75, 1.00 and 0.33m on TA and tonic vergence (TV) in 27 subjects. For the far and intermediate tasks, they found post-task changes in both TA and TV to be biased towards the task position and proportional to the dioptric distance between the task and the subject's pre-task resting position. For the near task, however, the positive shifts in TA and TV were reduced significantly when the difference between the task location and initial TA and TV positions was greater than 1.5 D and 3.5 degrees respectively. Hogan and Gilmartin proposed that TA and TV may be reference points of the accommodative and vergence systems and that the attenuation of positive accommodative hysteresis effects may be mediated by the beta-inhibitory sympathetic input to the ciliary muscle.

Pigion and Miller (1985) measured TA and accommodative responses to a near (30cm) and far (6m) targets in 20 young males. Measurements were made before and after a 1 hour session during which subjects either read monoculary at near or far or remained in darkness and listened to a tape recording. No significant changes in near or far target accommodative response were produced by any of the tasks. The near task and darkroom condition induced significant mean increases in TA (0.27 D and 0.47 D respectively) but the far task had no significant influence on TA.

Schor *et al.* (1986) suggested that the method by which the accommodation loop is opened, following a period of sustained fixation, will alter the level of adaptation occuring. They investigated TA after-effects under three experimental conditions: Maxwellian view (pin-hole pupil), empty-field and darkness. After fixating a -3 D stimulus for 2 minutes the TA regressed to baseline levels after a few seconds in darkness. For the Maxwellian view and empty-field conditions, however, a period of several minutes were required for TA to reach pre-task levels. Furthermore, if allowed to regress in darkness, accommodation would return to its adapted state when Maxwellian view conditions were reinstated. Thus, rather than decaying more rapidly in darkness, tonic adaptation was effectively masked by darkness.

Wolfe and O'Connell (1987) compared the adaptation of TA under darkroom and bright empty-field conditions in 21 subjects using a vernier optometer. They found that the adaptation of TA was significantly greater for the empty-field condition than for the darkroom condition (difference = 0.43, $t = 2.24$, $p < 0.05$). These differences in adaptation were, however, due entirely to a subset of subjects ($N = 5$) showed much larger TA after-effects (> 2.5 D) for the empty-field condition. Wolfe and O'Connell term these subjects 'superadaptors'. Wolfe and O'Connell also found that pre-task TA values measured under empty-field conditions were significantly higher than those measured under darkroom conditions.

Tan and O'Leary (1986) studied the effect of 5 minute and 1 hour monocular reading task at 0 D and 3 D on TA using a laser optometer. They found that, for the briefer task, TA shifted towards the task position and returned slowly towards the pre-stimulus level during the 15 minute post-task measurement period. For the longer task TA showed a sustained shift towards the task position during the subsequent 6 hour measurement period. Tan and O'Leary suggest that a subject's TA is determined by the accommodation that has been exerted prior to the measurement period.

Tan (1986) used laser optometry to examine the influence of stimulus vergence and task duration on accommodative hysteresis. The mean initial TA was found to be 1.71 D and 1 minute monocular fixation of reduced Snellen letters at 2, 3 and 4 D produced mean post-task TA values of 1.70 D, 1.97 D and 2.14 D respectively. Increasing the task duration from 1 minute to 5 minutes produced a significant increase in the magnitude of the hysteresis effect. Tan also found that the magnitude of the hysteresis effect was proportional to the dioptric difference between the stimulus level and the subject's initial TA. It should be noted, however, that each subject performed the task at only one stimulus vergence. The experimental design could have been improved by, adopting a within-subject design, *i.e.* recording the hysteresis effects for each subject for all task locations so that the relative contributions of inter-subject and intra-subject variations to the results could be examined.

Fisher *et al.* (1987a) examined interocular differences in TA and the consensuality of accommodative hysteresis in 12 emmetropic subjects using a Hartinger optometer. They assessed the effect of monocular fixation of reduced Snellen letters for 8 minutes at the subject's near point (within a near point limit of 6 D). They found no significant difference in TA between the two eyes and that a control condition of viewing a green homogenous oscilloscope screen at 50 cm produced no significant change in TA. Near point fixation, however, produced significant increases in TA and the change in TA in the fixating eye was equivalent for that in the non-fixating eye.

In a recent report Owens and Wolf-Kelly (1987) employed a polarised vernier optometer (Simonelli, 1980) and a subjective vernier alignment device to assess the effect of one hour of reading at 20 cm on TA and TV in 28 college students. They found that both TA and TV increased significantly by 0.60 D and 11.4 cm respectively following the reading period but that the increases in the two tonic states were uncorrelated. Owens and Wolf-Kelly conclude that the TA and TV are determined by different mechanisms, although pre-task TA and TV values were significantly correlated. They also present data for 24 additional subjects on whom TV was not measured increasing the sample on whom TA was measured to 52. They found that the largest increases in TA occured in subjects with low initial values of TA and TV.

Wolf *et al.* (1987) assessed the effect of a 45 minute binocular reading task at 20cm for 22 normal subjects using a haploscope-optometer. They found TA and TV increased significantly by 0.35 D and 0.38 meter angles respectively and that both tonic components decayed to baseline levels within three minutes.

It may be concluded, therefore, that a period of sustained fixation or reading may produce changes in both TA and TV although it is likely that adaptation of the two systems is determined by independent mechanisms (Kotulak and Schor, 1986; Owens and Wolf-Kelly, 1987). The adaptation of TA will be a primary area of interest in this thesis and the intended areas for research are discussed in section 1.8 (pps. 72-75).

1.6 - THE MEASUREMENT OF ACCOMMODATION

1.6A - Objective and subjective optometers

Various subjective and objective techniques have been employed in the measurement of accommodation. Since changes of accommodation are, essentially, alterations in the refractive state of the eye, certain of the measurement techniques have been recently applied to routine ophthalmic refraction, e.g. infra-red optometry. Conversely, certain workers have relied on established refractive techniques to study accommodation, e.g. retinoscopy (e.g. Mohindra, 1975).

An estimate of the refractive state of the eye can be made by either measuring the vergence of the light that leaves the eye, as in retinoscopy, or by adjusting the vergence of the light that enters the eye until a clear image of the target is formed on the subject's retina. Many early optometers were based on the latter of these principles, an example being the Thorner optometer (Duke-Elder, 1970) which was used by Törnqvist (1966; 1967). A further example of this type of optometer is the stigmatoscope where a spot of light is imaged on the retina of the subject. The instrument is adjusted until the subject reports that the diameter of the spot is reduced to a minimum. The source will then be positioned at the point in space conjugate with the subject's retina. This design of optometer has been used by such workers as Morgan (1944b) and Wolf *et al.* (1987).

A disadvantage of the above instruments is that they rely on the experimenter or subject judging the exact point at which the target is correctly focused. The accuracy of the optometer may, however, be greatly increased by incorporating the principle of displacement by parallax, as in Fincham's coincidence optometer (Fincham, 1937). In this instrument, when the target is not in a position which is conjugate with the subject's retina, the retinal image is displaced from the axis. The image is viewed through a set of prisms which divides the field into two and reverses one half. When the image is out of alignment the two halves are displaced in opposite directions and correct alignment results in an unbroken line being formed. The Hartinger optometer (Carl Zeiss Jena) utilizes similar design principles to that of Fincham (1937) and has been used in the study of TA and accommodative hysteresis by Fisher *et al.* (1987a). A further modification was made by Simonelli (1980) in the design of his polarised vernier optometer. The subject has to judge the vernier alignment of two perpendicularly orientated polarised bars. Simonelli demonstrated that measurements of far-point and TA may be made using this instrument and suggests that the instrument is an economical and effective alternative to the laser optometer.

1.6B - Infra-red optometry

The primary problem with the aforementioned optometers is that they employ targets which are visible to the subject. As the vergence of the light from the target is altered so too is the stimulus to accommodation. The presence of a bright target may also influence the pupil size of the subject thereby further altering their accommodative state (Hennessy *et al.*, 1976; Ward and Charman, 1985). This problem may be overcome if the target is made invisible to the subject by introducing filters which only transmit infra-red radiation.

Collins (1937) constructed an infra-red optometer utilizing the retinoscopic principle and used a photoelectric cell as the detector of movement. Chin and Horn (1956) employed an infra-red retinoscope to investigate night myopia. The infra-red light reflected from the subject's fundus was converted to visible light by an infra-red converter placed before the experimenter's eye. Campbell and Robson (1959) developed an infra-red optometer based on the Scheiner disc principle and claimed accuracy of 0.1 D. The temporal resolution of the apparatus enabled Campbell *et al.*, (1959) to assess micro-fluctuations in the accommodative response. Several designs of infra-red optometer have been published subsequently (e.g. Cornsweet and Crane, 1970; Charman and Heron, 1975; Lovasik, 1983), many of which are based on the design of Campbell and Robson (1959).

Infra-red optometry has the advantage of being objective hence the effect of psychological influences on accommodation could be assessed (Kruger 1980; Malmstrom *et al.*, 1980). The technique also facilitates rapid and continuous measurement, enabling researchers to study temporal aspects of the accommodative response (Campbell *et al.*, 1959; Campbell and Westheimer, 1960; Shirachi *et al.*, 1978; Charman and Heron, 1979; Tucker and Charman, 1979; Denieul, 1982; Kotulak and Schor, 1986)

Recently the principles of infra-red measurement have been applied to automated objective refractors such as the Canon Autoref R-1. The currently available instruments employ one of the following basic principles: grating focus principle, retinoscopy or Scheiner disc principle (Henson, 1983). This advance in technology has presented researchers with highly sophisticated optometers for experimental use. Johnson and his co-workers used a modified Ophthalmetron (Bausch and Lomb), an instrument based on the retinoscopic principle, to assess short- and long-term fluctuations in TA (Johnson *et al.*, 1984; Post *et al.*, 1984). Furthermore, the Canon Autoref R-1, an autorefractor which engages the grating focus principle, has been employed to assess variations in the accommodative response with refractive error (McBrien and Millodot, 1986a; 1987) and to investigate the influence of various ophthalmic drugs on accommodation (Ward and Charman, 1986). A full description of the Autoref R-1 is given in Section 2.1B (pps. 75-80).

1.6C - Purkinje image photography

A further objective method which has been used in the study of accommodation is purkinje image photography (Fincham, 1937; Otero, 1951; Campbell, 1957; Whiteside, 1957). The technique involves photographing the 3rd Purkinje image which is formed by the anterior surface of the lens, the refractive surface which undergoes the greatest change in radius of curvature during accommodation (Fincham, 1937; Fisher, 1969b). This requires a bright source which may produce sufficient glare so as to interfere with the subject's perception of the accommodative stimulus. The technique may only be used to monitor changes in accommodation since it cannot determine the total refractive state of the eye. Furthermore, time-consuming analysis of the photographs is necessary before the magnitude of the change in accommodation may be assessed.

1.6D - Laser optometry

Many studies of accommodation have been conducted using the Badal Helium-Neon (He-Ne) laser optometer (Hennessy and Leibowitz, 1970; 1972; Inglestam and Ragnarsson, 1972). Divergent laser light is collimated and reflected from the matt surface of a slowly rotating cylindrical drum. The apparent velocity of the speckles seen by an observer is a function of the dioptric difference between the plane of stationarity of the drum and the point in space conjugate with the observer's retina (Charman, 1974). Since the perception of the speckle pattern is a consequence of interference at the retina, it is always in focus and hence subjective estimates of blur are not required. The laser optometer is, therefore, unique since changes in the refractive state of the eye result in the observer perceiving changes in the motion of the speckle pattern but not its spatial structure.

In order to ensure that the pattern has no effect on the existing accommodative state, short presentations are used (Hennessy and Leibowitz, 1972). The majority of previous studies have used exposure times of 500 msec but recently Hogan and Gilmartin (1984b) have suggested that an exposure time of 300 msec be adopted in order to minimize the variability of results. In a subsequent paper, Kothe *et al.* (1987) measured TA for 10 laser exposure durations ranging from 100 to 1000ms in 10 subjects. They found that in 3 subjects speckle exposure time had no influence on the measured TA value. In the remaining subjects, however, increasing the exposure time resulted in a monotonic decrease in TA (N = 3), a monotonic increase in TA (N = 1) or non-monotonic trends (N = 3).

Laser optometry has been employed in a large number of studies of TA and accommodation stimulus/response studies since it's introduction (e.g. Leibowitz and Owens, 1978; Charman and Tucker, 1977). The technique has the advantage of being independent of pupil size and there is little restraint on the head position of the subject. The technique has the disadvantage, however, of being subjective, hence the results obtained are dependent on the accuracy of the observations made by the subject. In addition, recent research has demonstrated that the observational demands of the laser optometer may influence the accommodative state of the observer (Post *et al.*, 1984; Post *et al.*, 1985).

1.6E - Summary

Previous workers have employed a variety of techniques in the study of accommodation. A major consideration in the choice of instrument for the project was the speed with which measurements could be taken. A further requirement was that the instrument was objective in order to avoid subject-optometer interactions (Post *et al.*, 1984; Post *et al.*, 1985). For these reasons it was decided to employ infra-red measurement techniques. Further methodological considerations are discussed in section 2.1 (pps. 75-80).

1.7 - ACCOMMODATION AND THE DEVELOPMENT OF MYOPIA.

This section is intended to provide a brief review of the role of near-work and accommodation in the development of myopia. A full treatise of the vast amount of literature concerning the aetiology of myopia is, however, beyond the scope of this thesis but extensive reviews may be found elsewhere (e.g. Borish, 1970; McBrien and Barnes, 1984)

1.7A - Genetic factors and refractive error

Steiger (1913) suggested that the majority of refractive errors may be explained by normal variation in the refractive components of the eye, *viz.* corneal power, anterior chamber depth, lens power and axial length. The distribution of refractive error, however, is distinguished by the predominance of emmetropia (e.g. Stenstrom, 1946) and free association of the ocular components would lead to much less emmetropia than is found in the normal population. There would appear, therefore, to be a co-ordinating mechanism whereby a relative abundance of emmetropic or near-emmetropic eyes are produced (Sorsby *et al.*, 1957).

Sorsby *et al.* (1957) found that nearly all eyes with refractions within the range of -4 to +6 D had values for the individual components within the range found in emmetropia. They used the term *"correlation ametropia"* to describe these eyes since it was felt that a failure in the correlating mechanism had led to the ametropia rather than one individual component. For ametropic eyes outside of this range, Sorsby and his co-workers found that one component, usually axial length, fell outside of the emmetropic range and adopted the term *"component ametropia"* to describe this group.

Sorsby *et al.* (1962) measured refraction and ocular components in 78 uniovular twins, 40 binovular twins and 48 unrelated pairs. They found that uniovular twins show a marked concordance for refraction and its individual components whereas binovular twins showed no such concordance. This led Sorsby and his co-workers to propose that refraction is genetically determined. Sorsby (1967) concluded: "The traditional emphasis on environmental factors as productive of refractive errors finds no support in the detailed studies of today".

1.7B - Near-work and myopia

Ramazzini (1713) was the first worker to suggest that sustained near vision produces "weakness of vision" and myopia, however, Cohn (1886) is generally credited as being the founder of the theory that near-work causes myopia. Numerous subsequent workers have reported a relationship between the development of myopia and the amount of near-work undertaken [see Borish (1970) for review]. Occupations which require a relatively high level of accommodation and convergence tend to show a higher incidence of myopia than those where prolonged periods of near vision are not required. Furthermore, various workers report a correlation between the number of years spent at school and college and myopia (e.g. Young, 1967). Other workers (e.g. Nadell *et al.*, 1956), however, have found no relationship between the time spent reading and myopia. Many researchers, notably Francis Young, have sought to establish the role of environmental influences in the development of myopia by experiments on monkeys and selected populations.

Young (1967) observed that adult monkeys reared in laboratories show 25-30% myopia, whereas those reared in open-field situations show practically no myopia. Furthermore Rose *et al.* (1974) compared the refraction of 12 street cats with that of 11 caged cats. They found that 87.5% of the street cats were hyperopic (mean Rx = +1.14 D) whilst the cats who had been caged for between 8 and 14 months showed a mean refraction of -0.62 D, 68.2% being myopic.

Young (1961) placed nine monkeys, aged between 4 and 6 years, in restraining chairs and restricted their visual environment to 50 cm by means of white hoods. He found that after eleven months approximately 70% of animals demonstrated myopic shifts in refraction greater than 0.50 D and over half showed changes greater than 1.50 D. Young (1965) reported that the progression of myopia induced by a restricted visual environment could be arrested by the daily instillation of atropine. This led Young to propose that accommodation played a significant role in the development of myopia (see section 1.7C).

Young *et al.* (1969) studied eskimo families and found very little myopia among the older generations, but some 65% myopia among the younger. They attributed the difference to the imposition of compulsory education for the younger generation. Since heredity influences were constant for the population, Young and his co-workers proposed that environmental factors played a significant role in myopia development. Further studies of selected populations suggest that myopia is a correlated with near-work (Alsbirk, 1979; Richler and Bear, 1980). Richler and Bear (1980) examined 957 patients aged 5 years and above in 3 isolated communities in western Newfoundland and found that refraction was significantly correlated with the amount of near-work carried out by the subjects.

1.7C - The mechanisms associated with environmentally induced myopia

Although it would appear that there is a relationship between the amount of near-work undertaken and the development of myopia, the mechanism is subject to debate. Some workers assumed that it was the accommodation associated with near-work that led to the development of myopia, mediated by tonus changes in the ciliary body and an increase in lens power (e.g. Sato, 1957). Young (1965; 1975) also believed that accommodation was responsible and proposed that myopia developed in two stages (Young, 1975). The first stage was due to a temporary increase in lens thickness due to an inability to relax accommodation fully. This was followed several months to a year later by an increase in the depth of the vitreous chamber. Young suggested that accommodation produced an increase in vitreous chamber pressure which when sustained would result in an increase in vitreous chamber depth. He implanted pressure transducers in the anterior chamber and vitreous of monkeys and found that near-point accommodation produced increases in vitreous pressure of the order of 6-7 mmHg, accompanied by a decrease in anterior chamber pressure.

Bedrossian (1966) investigated the effect of daily instillation of atropine into one eye of young myopes using the other eye as the control. He found a 0.50 D reduction in myopia in the cyclopleged eye after one year, whereas the untreated eye progressed in the myopic direction by -0.63 D, thus supporting the proposal that accommodation was an important factor in the development of myopia. Oakley and Young (1975) treated 226 myopic children with a +1.50 D bifocal reading addition. They found that these children showed negligible myopia progression (-0.03 D per year) while a control group showed an annual progression of -0.50 D. Bedrossian concluded that accommodation, and not convergence, was the cause of myopia. It is interesting to note, however, that similar results were obtained by Luedde (1932) but were interpreted oppositely, i.e. he proposed that excessive convergence is responsible for the development of myopia.

Subsequent studies have found varying degrees of success in the control of myopia using bifocals and cycloplegics (e.g. Curtin, 1970; Gimbel, 1970; Brodstein *et al.*, 1984). Raviola and Wiesel (1985) offer an explanation for this variation in success. They demonstrated that myopia develops in macaque monkeys when their lids are surgically fused for one year immediately following birth. Interestingly they found that the instillation of atropine arrested the progression of myopia in the species *Macaca arctoides*. Conversely, atropine did not influence the progression of lid-suture myopia in the species *Macaca mulatta*. They suggest that the variation of the effect of atropine on the lid-suture myopia in these two closely related species may parallel the varying effectivity of bifocals and cycloplegia in the control of myopia in humans.

Further evidence for the the role of accommodation in the development of myopia has been provided by studies of various aspects of accommodative function in different refractive groups, principally tonic accommodation (TA). Van Alphen (1961) suggested that individuals with high levels of ciliary tone would be hyperopic, whereas low levels of cillary tone would be conducive to the development of myopia (see section 1.7D pps. 68-69). Charman (1982) also suggested that there might be a relationship between TA and refractive error by applying the model of Toates (1972). Charman proposed that hyperopes would have high values of TA and that this was associated with a strong sympathetic innervation to the ciliary muscle, consistent with the model of Van Alphen (1961). Conversely, Charman predicted that myopes would have lower values of TA and a weak sympathetic ciliary input. Garner (1983) also predicted that myopes would reduced values of TA but that this was associated with increased sympathetic innervation.

Various workers have investigated the relationship between TA and refractive error but most studies have produced somewhat conflicting results. The most extensive study (N = 301) was that of Simonelli (1983) who found no clear relationship between TA and refractive error and similarly tenuous trends have been found in most other studies (Carreras, 1951; Irving, 1957; Gawron, 1981; Heron *et al.*, 1981; Hogan and Gilmartin, 1983; Smith, 1983; Ramsdale, 1985). Maddock *et al.* (1981) were the first workers whose results suggest a relationship between TA and refraction, myopes having the lowest values of TA and hyperopes the highest. A recent report (McBrien and Millodot, 1987) also suggests that hyperopes (mean TA = 1.33 D) have higher values of TA than emmetropes (mean TA = 0.89 D). McBrien and Millodot divided their myopic subjects into two groups depending on their age of onset; early-onset myopes whose myopia developed prior to 13 years of age and late-onset myopes who developed myopia after the age of 15. They found that early-onset myopes (mean TA = 0.92 D) had similar values of TA to emmetropes, whilst late-onset myopes showed significantly lower values of TA than both groups (mean TA = 0.49 D). McBrien and Millodot propose that this difference between the two myopic groups is evidence for the two myopic groups having a different aetiology.

Additional interest in accommodation has been provoked by the finding that a period of sustained fixation at distance or near can produce significant changes in TA (see section 1.5D pps. 50-55). Ebenholtz (1983) proposed that these changes which he termed accommodative hysteresis, may be a precursor to induced myopia. Furthermore, preliminary reports suggest that certain refractive groups may be more susceptible to accommodative hysteresis than others (Fisher *et al.*, 1987b; McBrien, 1987)

Further studies have demonstrated other accommodative differences between refractive groups. McBrien and Millodot (1986a) found that myopes show increased accommodative lag compared to hyperopes and emmetropes, and suggest that this is consistent with myopes having lower values of TA. Fledelius (1981) reported that myopes had a higher amplitude of accommodation than hyperopes and emmetropes and suggested that this was a possible cause of environmental myopia. Similarly, Maddock *et al.* (1981) observed that low myopes had higher amplitudes of accommodation than emmetropes and high myopes.

McBrien and Millodot (1986b) found significant differences in amplitude of accommodation between refractive groups, late-onset myopes having the largest amplitude of accommodation followed by early-onset myopes, emmetropes and hyperopes. McBrien and Millodot suggest that these differences are due to variations in autonomic innervation of the ciliary muscle. Citing Cogan (1937) they suggest that the increased amplitude of accommodation found in late-onset myopes is consistent with subjects having reduced sympathetic innervation to the ciliary muscle. Conversely, Gilmartin *et al.* (1984) found that blocking sympathetic innervation to the ciliary muscle with timolol maleate (0.5%) produced no effect on the amplitude of accommodation. In an extensive study Mäntyjärvi (1987) measured the amplitude of accommodation in 150 hyperopes and 150 myopes aged between 7 and 16 years. He found no difference between the two refractive groups and concluded that amplitude of accommodation does not predict the development of myopia in school children.

Other workers have proposed that the convergence associated with near vision is responsible for the development of myopia (Jackson, 1931; Luedde, 1932). Donders (1864) and Linder (1944) both observed that the incidence of myopia among watchmakers was lower than might be expected in view of their high level of near-work. Donders (1864) suggested that this phenomenon was due the use of a monocular loupe which reduces the convergence requirements of the task, but may, of course, also lower the accommodative demand. Luedde (1932) claimed that monocular cycloplegia inhibited the development of myopia by dissociating the eyes at near thereby reducing convergence demand. Similar findings led Bedrossian (1966), however, to suggest that accommodation played the major role in myopia development.

Recently Greene (1980) proposed that the elongation of the posterior portion of the globe could result from the action of the extraocular muscles, notably the superior and inferior oblique muscles. He stated that the extraocular muscles could exert forces on the globe 250 times that of the ciliary muscle and hence the intraocular pressure (IOP) changes induced by vergence are larger and transmitted directly to the sclera. Clement (personal communication) believes, however, that Greene's calculation of the force exerted by the extraocular muscles is an overestimate. Furthermore, Mohan *et al.* (1977) demonstrated that the myopia induced in rabbits by raising temperature and IOP (Maurice and Mushin, 1966; Tokoro, 1970) was dependent on extraocular tension. The development of myopia was found to increase following resection of the four recti, while free tenotomy of the muscles resulted in a reduction of myopia development.

In conclusion, evidence has been presented for both accommodation and convergence in the development of myopia. Most workers propose that the refractive changes are mediated by increases in intraocular or vitreous pressure produced by either the intraocular or extraocular muscles. A research programme is currently underway within the department to evaluate the interaction of accommodation and vergence in various refractive groups (see Rosenfield and Gilmartin, 1987a; 1987b).

1.7D - Emmetropization and the work of Van Alphen

The predominance of emmetropia in the normal population (e.g. Stenstrom, 1946) has led certain workers to suggest the presence of a central co-ordinating mechanism or an emmetropization process (Straub, 1909; Van Alphen, 1961; Sorsby, 1967), the most comprehensive account being that of Van Alphen (1961).

Van Alphen (1961) carried out a detailed statistical analysis of the biometric data of Stenstrom (1946) and found 10 significant intercorrelations between refractive components. Further analysis led to the identification of three independent factors, each of which contributed to the development of emmetropia. Factor *"S"* (or size factor) was shown to be relevant to corneal curvature and axial length and would predict that larger eyes would have flatter corneae. Factor *"P"* (or stretch factor) was shown to be relevant to axial length, anterior chamber depth and lens power and would predict that larger eyes would have flatter lenses and deeper anterior chambers. Van Alphen proposed that the development of ametropia was due to a third variable *"R"* (or adjustment factor) which represented the resistance offered by the ciliary muscle-choroid layer. He considered the ciliary muscle-choroid layer to behave as a continuous elasto-musculous sheet of smooth muscle surrounding the eye, a proposal supported by a later study (Van Alphen, 1986).

Van Alphen (1961) assumed that the growth of the eye was determined by genetic factors and the stretch by the intraocular pressure (Coulombre and Coulombre, 1956). He postulated that the tonus of the ciliary muscle-choroid layer limited the stretch of the sclera by counteracting part of the intraocular pressure. He assumed that the macula and brain act to feedback information to the Edinger Westphal nucleus, concerning the degree of stretch and adjust its activity accordingly. The stretch of the sclera would, therefore, be under cortical and subcortical control and mediated by tonus changes of the ciliary muscle. Van Alphen proposed that any disruption of this feedback loop would interfere with emmetropization. He observed that emmetropia is rarely achieved in cases of corneal opacities, high astigmatism, congenital nystagmus or mental deficiency (Rabin *et al.*, 1981). Furthermore recent animal work has shown that the disruption of the normal visual environment results in the development of myopia (Wiesel and Raviola, 1977; Wallman and Turkel, 1978; Raviola and Wiesel, 1985) supporting the proposal that emmetropization is a vision-dependent process.

Van Alphen (1961) also noted that the Edinger-Westphal nucleus received most of its afferent connections from the reticular formations. He proposed, therefore, that stress, emotion or extreme autonomic endowment could interfere with the emmetropization mechanism and that the stress associated with studying for exams was responsible for the development of "school myopia". He suggested that such learning situations can involve substantial levels of stress and anxiety which may trigger myopic changes. He observed, however, that near vision situations of a leisurely nature, such as needlework, were not associated with the development of myopia. Van Alphen also reported some evidence for psychological differences between different refractive groups and suggested that such differences may facilitate the development of ametropia, a proposal which has been studied by subsequent workers (Young, 1967; Young *et al.*, 1975; Baldwin, 1981; Gawron, 1981; 1983).

In a further study Van Alphen (1986) partly denuded 32 enucleated human eyes by removing the sclera behind, in front of, or about the equator. He found that inflation of the eyes to 14 mmHg produced axial, rather than radial, expansion of the eye. The expansion was shown to emanate from ciliary muscle stretch, providing further support for the concept of ciliary muscle tonus influencing increases in axial length by effecting net pressure on the sclera via modifications of choroidal tensions.

1.7E - Discussion of theories of refractive error development

This brief review of the literature has examined the three principal theories of refractive error development, *viz.*, The biological-statistical theory, the use-abuse theory and the theory of emmetropization and it would appear that there is convincing evidence for all three theories. It is clear from twins studies that the dimensions of the ocular components are determned predominantly by genetic factors (Sorsby *et al.*, 1962) but a change in the amount of near-work undertaken by a selected population can result in a substantial increase in the incidence of myopia (Young *et al.*, 1969). It is likely, therefore, that the eventual refractive outcome will be a consequence of subtle interaction between genetic predisposition and the nature of the visual environment. If we assume that the development of myopia can be influenced by a subject's visual environment the question remains as to the mechanism of such refractive changes.

Certain authors have proposed that accommodation is the causative factor of myopia (Young, 1975) although clinical and experimental evidence is equivocal (Raviola and Wiesel, 1985). Alternatively, other workers have suggested that convergence is responsible for the axial elongation of the globe in myopia (Greene, 1980). Furthermore, it is important to acknowledge that accommodation and convergence are synkinetically linked and anomalies of this relationship may contribute to the development of myopia (Rosenfield and Gilmartin, 1987b). Intraocular pressure may also play an important role in refractive development (Coulombre and Coulombre, 1956) although the mechanism and the influence of accommodation and ciliary muscle tonus are still open to debate (Van Alphen, 1961; 1986; Young, 1975).

Further controversy exists concerning the role of ciliary muscle tonus and tonic accommodation in refractive development. Van Alphen (1961) proposed that a reduction in ciliary tonus will result in the development of myopia. Conversely, Ebenholtz (1983) suggested that a near- vision task-induced increase in TA may be a precursor to induced myopia. This thesis is concerned principally with the study of TA and the adaptation of

TA. The aims of the project are detailed in the final section of this chapter.

1.8 - INTRODUCTION TO EXPERIMENTAL WORK

The results of the studies reported in section 1.5 (pps. 46-55) provide incontravertible evidence that in the absence of adequate visual stimuli accommodation adopts an intermediate resting position (TA). In addition, variations in TA exist within the population and a period of sustained vision at a fixed distance will produce changes in TA, termed adaptation of TA or accommodative hysteresis. It is clear, however, that several aspects of the adaptation of TA need to be investigated further.

1.8A - The role of sympathetic innnervation of the ciliary muscle in the adaptation of TA

It is well established that the ciliary muscle receives a small inhibitory sympathetic input (see Gilmartin (1986) for review) yet the role of sympathetic innervation in accommodation is unclear. Previous research suggests that the time-course of sympathetic activity is significantly slower than that of parasympathetic activity (Törnqvist, 1967; Hurwitz *et al.*, 1972a) and that the influence of the sympathetic input increases with concurrent background parasympathetic activity. This would indicate that the fuction of the sympathetic nervous system is more relevant to tasks requiring sustained accommodation for near rather than those tasks which require a low or rapid change in accommodative response. This led Gilmartin and Hogan (1985a) to suggest that the sympathetic input to the ciliary muscle may serve to attenuate the myopic shifts in TA. It may prove fruitful, therefore, to investigate the contribution of the sympathetic input in the adaptation of TA.

1.8B - The time course of the adaptation of TA

Previous research has produced conflicting estimates of the duration of tonic after-effects of sustained near vision. Ebenholtz (1983) assumed the regression of TA towards pre-task levels to be exponential and calculated that the effects of an 8 minute task at the near-point would require 10.26 hours to dissipate. Wolf *et al.* (1987) found, however, that TA and TV decayed to baseline levels within three minutes following a 45 minute binocular reading task at 20cm. Schor *et al.* (1986) showed that TA regressed to baseline levels after a few seconds in darkness, after fixating a -3 D stimulus for 2 minutes. For the Maxwellian view and empty-field conditions, however, a period of several minutes were required for TA to reach pre-task levels.

It is clear that the variety of experimental designs adopted by previous researchers have produced a disparity in estimates of the time-course and decay of the adaptation of TA. It would be preferable, therefore, to employ an objective optometer in order to avoid possible contamination of results due to optometer/observer interactions (Post *et al.*, 1984; Post *et al.*, 1985).

1.8C - The contribution of cognitive demand to adaptation of TA

It is likely that the vergence of the task is the primary determinant of post-task TA values. Previous research has shown, however, that the imposition of mental effort/cognitive demand can produce significant changes in TA (Kruger, 1980; Malmstrom *et al.*, 1980; Post *et al.*, 1985). Furthermore, Pigion and Miller (1985) found that when 20 subjects listened to a tape recording in the dark for 1 hour the mean value of TA increased significantly by 0.47 D while a near reading task only produced an increase of 0.27 D. It is possible, therefore, that the cognitive demand of the task may play a role in the adaptation of TA.

1.8D - Are myopes more susceptible to adaptation of TA?

The evidence for environmental influences in the development of myopia were discussed in section 1.7 (pps. 61-71). McBrien and Millodot (1986a) postulated that, if accommodation plays a role in the development of myopia, fundamental differences would exist in the accommodative responses of the various refractive groups. Ebenholtz (1983) suggested that accommodative hysteresis may be a precursor to induced myopia, i.e. myopia of environmental origin. If Ebenholtz's hypothesis is valid it would be expected that 'induced' myopes are more susceptible to adaptation of TA than emmetropes. Preliminary reports suggest that some myopic groups may be more susceptible to accommodative hysteresis than others (Fisher *et al.*, 1987b; McBrien, 1987). It would be appropriate, therefore, to investigate further TA and the adaptation of TA in emmetropes and subjects whose myopia is likely to have been influenced by environmental factors.

1.8E -Methodological considerations in the adaptation of TA.

The majority of previous workers have employed laser optometry in the study of TA and the adaptation of TA. It is possible, however, that the interactive nature of the laser optometer, or indeed other subjective optometers, may influence pre- and post-task measures of TA (Post *et al.*, 1984; Post *et al.*, 1985). A primary methodological consideration of the project was, therefore, the development of objective methods of accommodation measurement. The following chapter describes the development of a central methodology and the evaluation of an objective infra-red optometer.

CHAPTER 2

THE DEVELOPMENT OF A CENTRAL METHODOLOGY

2.1 - MEASUREMENT OF ACCOMMODATION

2.1A - Infra-red optometry

The various techniques by which the accommodative response may be measured has been discussed in the previous chapter (see section 1.6 pps. 56-60). An early consideration was the technique to be employed for the project. Infra-red measurement was chosen as the appropriate technique since it has certain advantages over other methods: first it is objective requiring no manipulation or judgement on the part of the subject. Second it is rapid and able to produce a series of values within a short time period.

Infra-red optometers may, however, be time consuming to construct, calibrate and bring into active service. It was decided, therefore, to employ a commercially available infra-red optometer, namely the Canon Autoref R-1 (see Fig. 2.1), which is an instrument designed essentially for consulting-room use.

2.1B - The Canon Autoref R-1

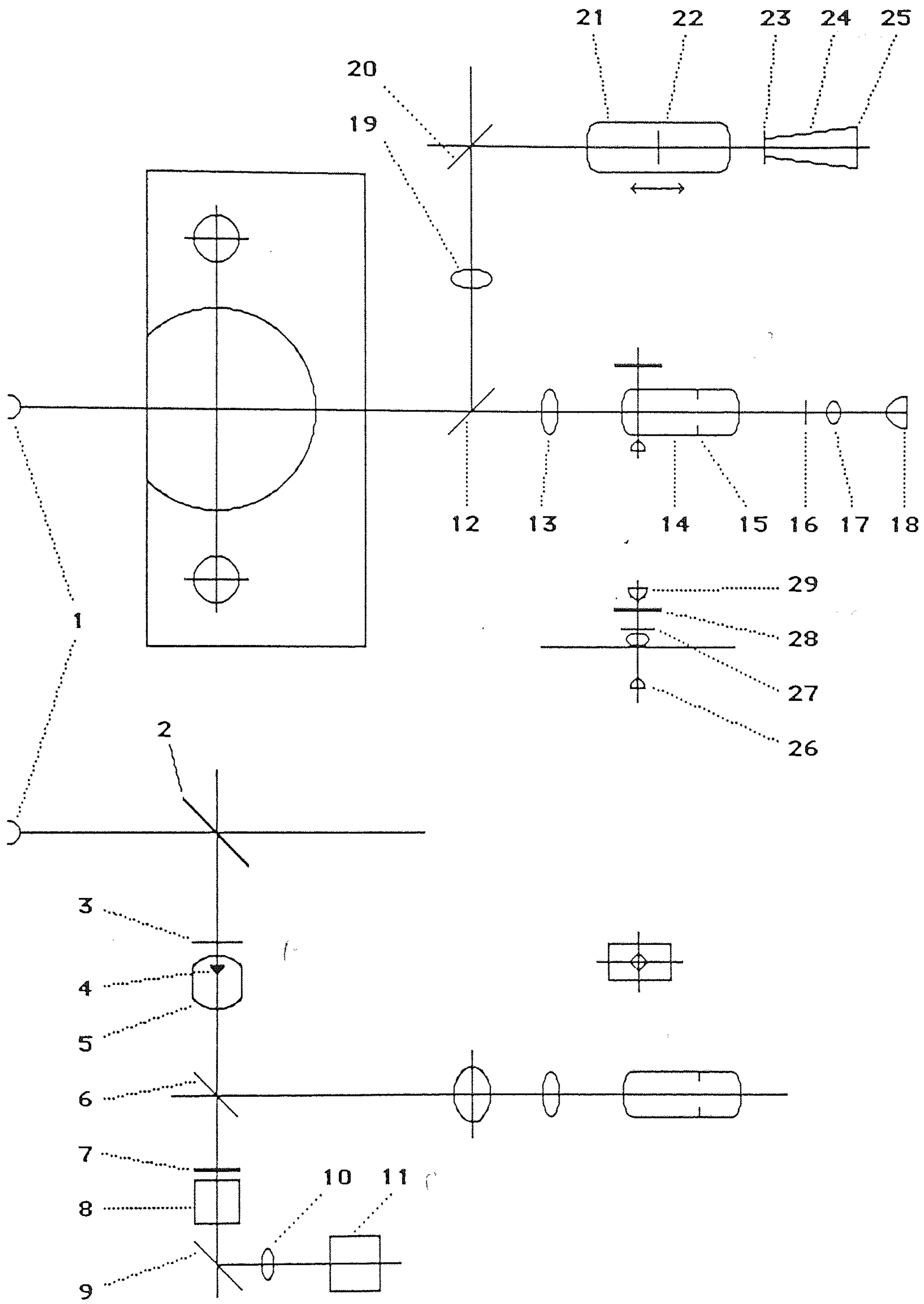
The Canon Autoref R-1 (Canon Europa) is an objective infra-red autorefractor that uses the grating focus principle (Matsumura *et al.*, 1983). The instrument has similar technical specifications to other instruments, such as the Dioptron Nova, but is unique in that it allows the subject an unrestricted binocular field of view by means of a semi-silvered mirror: instrument myopia is thus reduced (Schober *et al.*, 1970; Hennessy, 1975). It can produce a complete record of an eyes refractive state at approximately one-second intervals, the measurement procedure taking 0.2 seconds. It incorporates a power range

FIG. 2.1. - The Canon Autoref R-1 in use.

of ±15.0 D sphere and ±7.00 D cylinder in steps of 0.12 D. The axis is measured in 1° steps and vertex distances of 12mm and 0mm are available such that the refractive findings may be referenced to the spectacle plane or the cornea. The instrument requires a minimum pupil diameter of 2.9mm for measurement purposes.

McBrien and Millodot (1985) have described, in some detail, the operating principles of the Autoref R-1. The optical system may be divided into seven different light paths: A: eye front illumination; B: eye front observation; C: projection optics; D: photoreception; E: encoder optics; F: alignment ring projection; G: internal fixation lamp optics.

The lights L_1 L_2 (4) (see Fig. 2.2) are filtered for infra-red illumination of the subject's eye by filters (3) and the infra-red light reflected back to form an image on the photosensitive screen of the TV camera. The corneal-reflected images (Purkinje I) are used for adjustment of working distance and alignment. Lightpath C forms an image of an infra-red illuminated projection chart on the subject's retina. The light reflected from this retinal image passes back through the pupil and is reflected by mirrors (2), (6) and (12). The light is then transmitted by relay lens (19) and moving lens (21) to the photoreception chart (23) and detected by photodiodes (28). The reflected light detected by the photodiodes is electronically processed to produce a measured value. The maximum signal for detection by the photodiodes is attained when the projection chart is in optimum focus on the retina. This is achieved by movable lenses in the projection and photoreception systems. The lens movement is monitored by light path E where infra-red light from diode (26) passes through a scale unit (27) and slit (28) for detection by the photodiode (29). The scale unit, which is mounted on top of the projection and photoreception units, moves a certain amount for measurement purposes. The transmitted light detected by photodiode (29) is electronically processed to produce the measured value for display. The instrument determines the best focus of the chart in three meridians, each separated by 60 degrees and computes a sphero-cylindrical refractive finding by extrapolating the results to a sine^2 curve. The whole procedure is



KEY: 1. subject's eye; 2. infra-red reflecting mirror; 3. infra-red filters; 4. eye front illuminating lamps; 5. objective lens; 6. infra-red reflecting mirror; 7. infra-red filter; 8. infra-red reflecting mirror; 9. full reflecting mirror; 10. TV lens; 11. TV camera; 12 holed mirror; 13. relay lens; 14. moving lens; 15. aperture diaphragm; 16. projection chart; 17. condenser lens; 18. infra-red illuminating diode; 19. relay lens; 20. mirror; 21. moving lens; 22. slit; 23. photoreception chart; 24. photoreception rod; 25. photodiodes; 26. infra-red illuminating diode; 27. scale; 28. slit; 29. photodiode.

FIG. 2.2. - Optical layout of the Canon Autoref R-1 (redrawn from McBrien and Millodot, 1985)

completed in 0.2 seconds for each measurement. If the instrument is not aligned properly or the subject blink during the measurement procedure the instrument will be unable to complete the above measurement procedure and will produce an error reading on the screen and printer. An attempt was made to interface the R-1 to a microcomputer but this has, as yet, been unsuccessful.

Light path F projects an illuminated ring on the monitor screen for alignment purposes. Light path G produces a blurred (vergence at the subject's eye = +15 D) red target for projection on a black screen placed 20cm from the subject's eye, for use with hyperopic subjects.

Two studies have assessed the clinical potential of the Autoref R-1 (Berman *et al.*, 1984; McBrien and Millodot, 1985). Berman *et al.* (1984) compared the R-1 with static distance retinoscopy and another autorefractor , the Dioptron II, which also employs the grating principle. They found that for a sample of 75 subjects (150 eyes) the R-1 gave results which were 0.13 D mean sphere less negative than retinoscopy but concluded the results were comparable with all three techniques. McBrien and Millodot (1985) compared the results obtained from 93 subjects (186 eyes) with those obtained by subjective refraction. They found that the R-1 gave results which were slightly more negative than subjective refraction (0.39 D best sphere) but compared favourably with previous studies on other such instruments (e.g Wood *et al.*, 1984). They also assessed the reliability of the instrument by repeating the measurements on 50 eyes and found a correlation coefficient of 0.999 for best sphere. They concluded that the Autoref R-1 has a commendable degree of repeatability.

The Autoref R-1 has been employed by various research workers. Millodot and Thibault (1985) used the instrument to assess variations in astigmatism with accommodation and Ward and Charman (1986) were able to investigate the effects of various ophthalmic drugs. More recently McBrien and Millodot (1986a; 1987) have assessed various aspects of accommodative function in different refractive groups using the R-1. It was concluded, therefore, that the R-1 would be an appropriate instrument to employ for the project. The Autoref R-1 has certain features which make it exceptionally attractive as a research tool:

1. Alignment is relatively easy and subject fixation can be monitored by means of an infra-red video monitor.
2. Pupil size may be monitored accurately since a x8 image is produced on the video monitor.
3. The semi-silvered mirror allows the subject an open binocular view, this was measured using a tangent scale and found to subtend 18 degrees vertically and 50 degrees horizontally. Hence, the experimenter is able to present any accommodative stimuli he wishes.
4. The instrument is portable.

The instrument does have the disadvantage, however, of being unable to take readings through spectacle lenses. Hence when accommodative measurements are made on corrected ametropes they need to be corrected by means of soft lenses.

2.2 - COMPARISON OF OBJECTIVE AND SUBJECTIVE MEASUREMENT OF TONIC ACCOMMODATION.

2.2B - Introduction

An early consideration of the project was to compare measurements of accommodation taken with the R-1 with those obtained by other techniques. It was decided to undertake the comparison under darkroom conditions i.e. measurement of TA for two reasons. First, it would avoid interactions between the target and the optometer which may arise from measuring accommodation for a given stimulus. Secondly, using a large sample it would be possible to measure a range of accommodative values since TA shows large intersubject variation (e.g. Leibowitz and Owens, 1978; Hogan and Gilmartin, 1984a). The techniques compared were laser optometry, infra-red optometry and near retinoscopy.

Laser optometry.

Most studies concerning TA have been conducted using the Badal Helium-Neon (He-Ne) Laser optometer (Hennessy and Leibowitz, 1972). Divergent laser light is collimated and reflected from the matt surface of a slowly rotating cylindrical drum. The apparent velocity of the speckles seen by an observer is a function of the dioptric difference between the plane of stationarity of the drum and the point in space conjugate with the observer's retina (Charman, 1974). Since the perception of the speckle pattern is a consequence of interference at the retina, it is always in focus and hence subjective estimates of blur are not required. In order to ensure that the pattern has no effect on the existing accommodative state, short presentations are used (Hennessy and Leibowitz, 1972). The majority of previous studies have used exposure times of 500 msec but recently Hogan and Gilmartin (1984b) have suggested that an exposure time of 300 msec be used in order to minimize the variability of results. Furthermore, Kothe *et al.* (1987) have shown that laser speckle exposure times may be a contaminant of TA measures. Leibowitz and Owens (1978) measured TA for 220 college-age observers and found a mean value of 1.52 D with a standard deviation of 0.77 D and a range of values between -0.50 and 4.00 D.

Infra-red Optometry.

Infra-red optometers have also been used in the study of accommodation (Campbell and Robson, 1959; Campbell *et al.*, 1959; Charman and Heron, 1979; Johnson *et al.*, 1984; Schor *et al.*, 1986). The technique has the advantage of being objective and also facilitates rapid and continuous measurement. Campbell *et al.*, (1959) used infra-red techniques to measure accommodation in empty-field conditions and more recently

Johnson *et al.* (1984) have used infra-red recording to assess fluctuations in TA. Johnson and his co-workers found a mean value for TA of 1.10 D (s.d. = 1.06 D, range = - 1.00 to 4.00 D) for a group of 50 subjects, aged 18-31 years. Recently the principles of infra-red measurement have been applied to automated objective refractors such as the Canon Autoref R-1.

Near Retinoscopy.

Mohindra (1975) has developed a technique referred to as 'near retinoscopy' whereby a subject views a retinoscope beam monocularly at 50 cm while retinoscopy is performed in a darkened room by the experimenter. Owens *et al.* (1980) have shown that under such conditions subjects' adopt an intermediate resting position of accommodation. Although this position (mean = +0.70 D) did not correspond to their mean TA position (+1.50 D), Owens and his co-workers have shown that these two accommodative states are well correlated. Furthermore, the study proposed that the retinoscope beam does not influence accommodation. It has also been shown that near retinoscopy results correlate well with distance subjective refraction in adults (Mohindra, 1977a) and with cycloplegic refraction in children (Mohindra, 1977b) and hence has potential value in refracting infants without the use of cyclopegics.

Previous literature has shown differences in TA distributions for different measurement techniques (Owens *et al.*, 1980; Post *et al.*, 1984), yet no study has compared results for the same subjects for all three aforementioned methods. The primary aim of this first study was to assess whether results obtained by the subjective laser optometer correlate with objective readings from an infra-red optometer, i.e. the Autoref R-1. A previous study (Post *et al.*, 1984) had found a poor agreement between infra-red and laser techniques but it was felt that this warranted further investigation. The second aim was to assess the value of near retinoscopy as a reliable way of predicting TA.

2.2B - Method

Twenty-five subjects participated in the study, 9 women and 16 men, all of whom were optometry students aged between 19 and 28 (mean age = 21.5 years). All subjects had refractive errors between -0.25 and +1.00 DS best sphere (with not more than 0.50 dioptres of astigmatism), as determined by distance subjective refraction, and were able to achieve uncorrected visual acuities of 6/5 or better. Although subjects did not wear their appropriate refractive corrections during the experiments, all values recorded during the study have been adjusted to account for this factor.

Measurements of TA were obtained for the left eye only, under darkroom conditions. The laser optometer used was controlled by an Apple IIe microcomputer in conjunction with a CIL PC1 6000 interface unit (Gilmartin *et al.*,1984). The subject was given an auditory cue prior to the presentation of the speckle pattern. The duration of the interval between cue and speckle onset was randomized between 1 and 5 sec and an exposure time of 300 msec was employed (Hogan and Gilmartin, 1984b). Subjects were, initially, instructed to use a bracketing technique in order to determine the position at which no speckle motion could be discerned. The experimenter was able to monitor continuously the observer's performance by means of a digital read-out on a video screen. When three of the positions chosen by the observer varied by less than 0.25 D of each other the experimenter would then check the TA position by using a double staircase method of presentation (Heron *et al.*, 1981; Miller *et al.*, 1983). Four readings were taken in this manner; the whole procedure taking approximately 15-20 min.

Infra-red measurements of TA were made using a Canon Autoref R-1. Subjects were positioned in front of the optometer and instructed to look directly ahead while the instrument was aligned with reference to an infra-red video monitor and folowing this the room lights were extinguished. Any further adjustments were carried out with the brightness of the monitor reduced to a minimum. During this procedure the subject was unable to perceive any light coming from the monitor. Ten readings were taken after a period of 20-30 seconds in darkness (Baker *et al.*, 1983). Each of these sphero-cylinder results was converted to a mean-sphere value. The mean and standard deviation of the 10 mean-sphere results was calculated for each subject.

Near retinoscopy was performed as described by Mohindra (1975), all values being determined by the same experimenter. Subjects' were instructed to fixate the retinoscope beam with their right eye occluded. The 'neutral-reflex' end-point result was modified by -2.00 D thus compensating for the experimenters' working distance of 50cm; the whole procedure took several minutes. Mohindra (1975) adopts 'tonal adjustments' of +0.75 D when converting near retinoscopy findings to results comparable with distance refraction. It should be noted that such adjustments of Mohindra (1975) are not employed in determining TA values from near retinoscopy.

It is feasible that the laser optometer (or indeed the infra-red optometer) may influence the accommodative state of the subject, as suggested by Post *et al.*, (1984). In order to investigate this possibility the experimental procedure was repeated on ten cyclopleged observers, the instillation procedure being as follows. Following the instillation of 0.4% oxybuprocaine HCl (benoxinate) to inhibit reflex blinking and lacrimation each subject was given two instillations of 1.0% tropicamide separated by a period of 10 min. Maximum cycloplegia and mydriasis was achieved after 25 min and sustained for a further 20-30 min (Ward and Charman, 1986). Furthermore, 200 repeated measurements were made over a 5-min period on a further 10 cyclopleged subjects under darkroom conditions using the infra-red optometer. This was done in order to determine whether the intra-subject variations in infra-red estimates of TA were due to fluctuations in accommodation or head and eye movements.

2.2C - Results

The mean values of TA obtained from each instrument is given in Table 2.1. Positive values of TA indicate myopic resting positions; negative values indicate hyperopic resting positions. In addition graphs were plotted of infra-red TA values against laser TA values (Fig. 2.3) and near retinoscopy (NR) values against laser TA values (Fig. 2.4).

TABLE 2.1. Mean levels of tonic accommodation as measured by laser optometry, infra-red optometry and near retinoscopy for 25 subjects. Laser results do not include a correction for chromatic aberration.

	TONIC ACCOMMODATION (D)		
	LASER OPTOMETER	INFRA-RED OPTOMETER	NEAR RETINOSCOPY
MEAN	+1.10	+1.15	+1.07
S.D.	0.74	0.82	0.45
RANGE	-0.06 to +3.43	-0.13 to +4.03	+0.37 to +2.00

It can be seen from Table 2.1 that there is little difference between the mean infra-red (IR) value and the mean laser value. Repetition of the procedure with the 10 cyclopleged observers gave mean readings for each instrument that differed by 0.07 D (IR mean = 0.25 D, laser mean = 0.18 D). Thus, it can be seen that the cycloplegia does not significantly alter the difference between the mean values. It was also found that tropicamide produced a change in TA (cycloplegic refraction) distribution, significantly reducing the variation of recorded values (IR s.d. = 0.20 D, laser s.d. = 0.26 D), thus supporting previous studies (Gilmartin and Hogan, 1985b).

The data recorded for each subject under cycloplegia using the infra-red optometer, over a 5 min period, is given in appendix I.3 (pp. 209). Inspection of the data revealed that the standard deviations are of the order of 0.10 D or less whereas the standard deviations obtained for uncyclopleged observers ranged between 0.05 and 0.55 D. It was therefore assumed that errors due to head and eye movements are minimal.

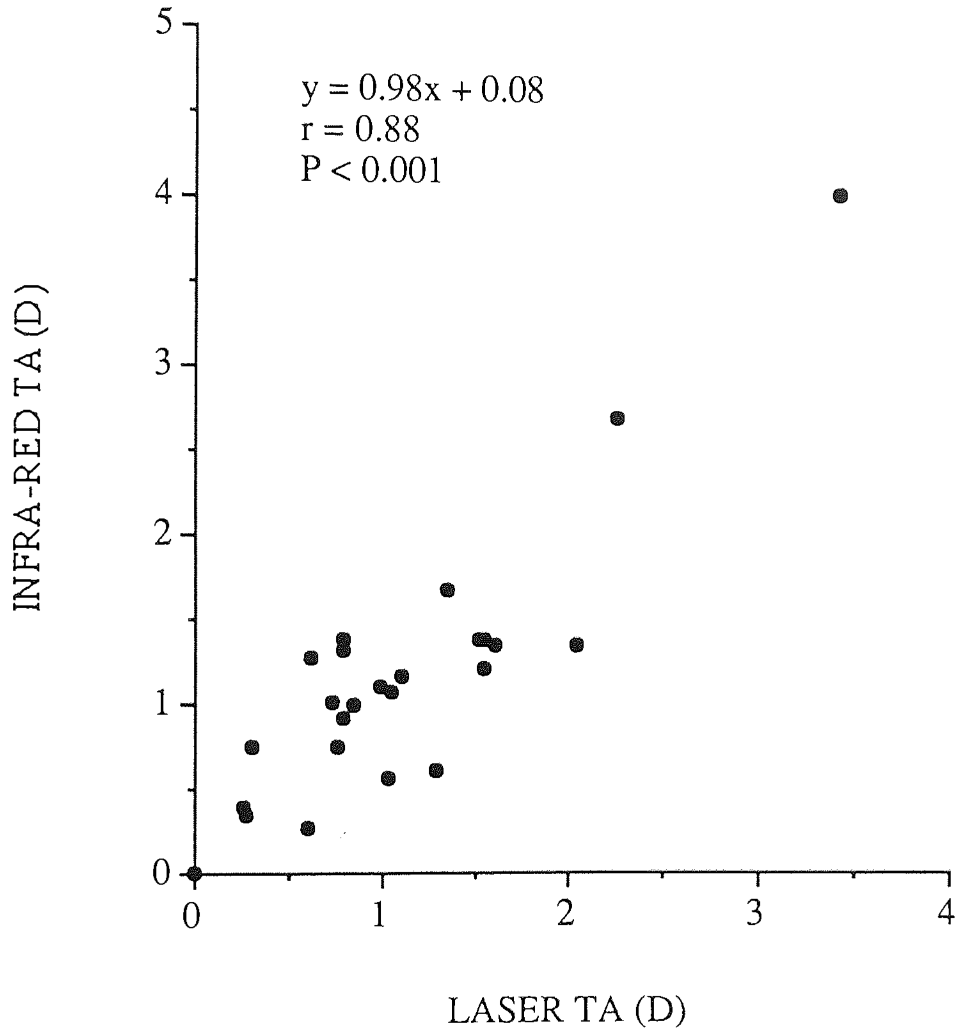


FIG. 2.3. The relationship between tonic accommodation (TA) measured with the infra-red optometer and the laser optometer for 25 subjects. Laser measures do not include a correction for longitudinal chromatic aberration.

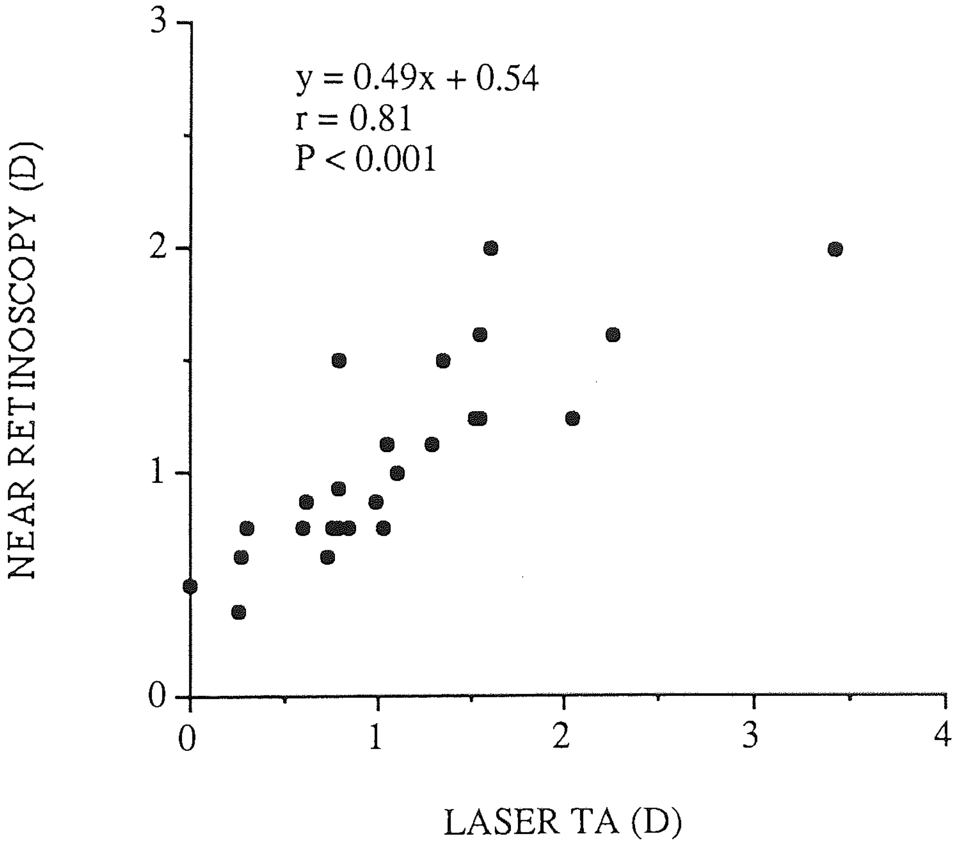


FIG. 2.4. The relationship between tonic accommodation (TA) measured with near retinoscopy and laser optometry for 25 subjects. Laser measures do not include a correction for longitudinal chromatic aberration.

An assessment of the short-term variability of TA can be made by examining the standard deviations, for each subject, of the 10 readings taken with the infra-red optometer. Fig. 2.5 illustrates the standard deviation of TA against TA and it can be seen that the magnitude of the fluctuations of TA is directly proportional to the value of TA, supporting the results of Johnson *et al.* (1984) and Kotulak and Schor (1986).

2.2D - Discussion

The mean TA for the 25 subjects participating in this study was found to be +1.10 D as measured with the laser optometer at 633 mm. This is in close agreement with the results of previous studies employing this technique, the most extensive (N = 220) being that of Leibowitz and Owens (1978) who found a mean resting position of +1.52 D (s.d. = 0.77 D, range = -0.50 to +4.00 D) which incorporates a correction factor of 0.33 D. Although most authors (e.g Leibowitz and Owens, 1975; 1978; Heron *et al.*, 1981) apply a chromatic aberration correction factor of 0.33 D (for 555nm), citing Bedford and Wyszecki (1957), a recent study by Gilmartin and Hogan (1985c) has suggested that the correction factor should be around 0.60 D (for 578nm). The mean TA as measured with the commercial infra-red (IR) optometer is 1.15 D, which agrees well with the value of 1.10 D found by Johnson *et al.* (1984). Furthermore, the good correlation between IR and laser methods found in this study indicate that, if correction factors are not applied, no substantial differences in estimates of TA would occur between the two methods. A source of error, however, may be the temporal variability of TA. Johnson *et al.* (1984) showed that infra-red estimates of TA can vary by up to 1 dioptre during 10 sec of measurement, a period comparable with the duration of the IR measurement in this experiment. In contrast, laser optometer measurements were taken for up to 20 min using a double-staircase method, a psychophysical technique which, due to the number of observations made, will tend to attenuate fluctuations in TA.

A comparison of the mean TA values (Table 2.1) reveals an insignificant difference between the IR optometer and the laser optometer. The results obtained under

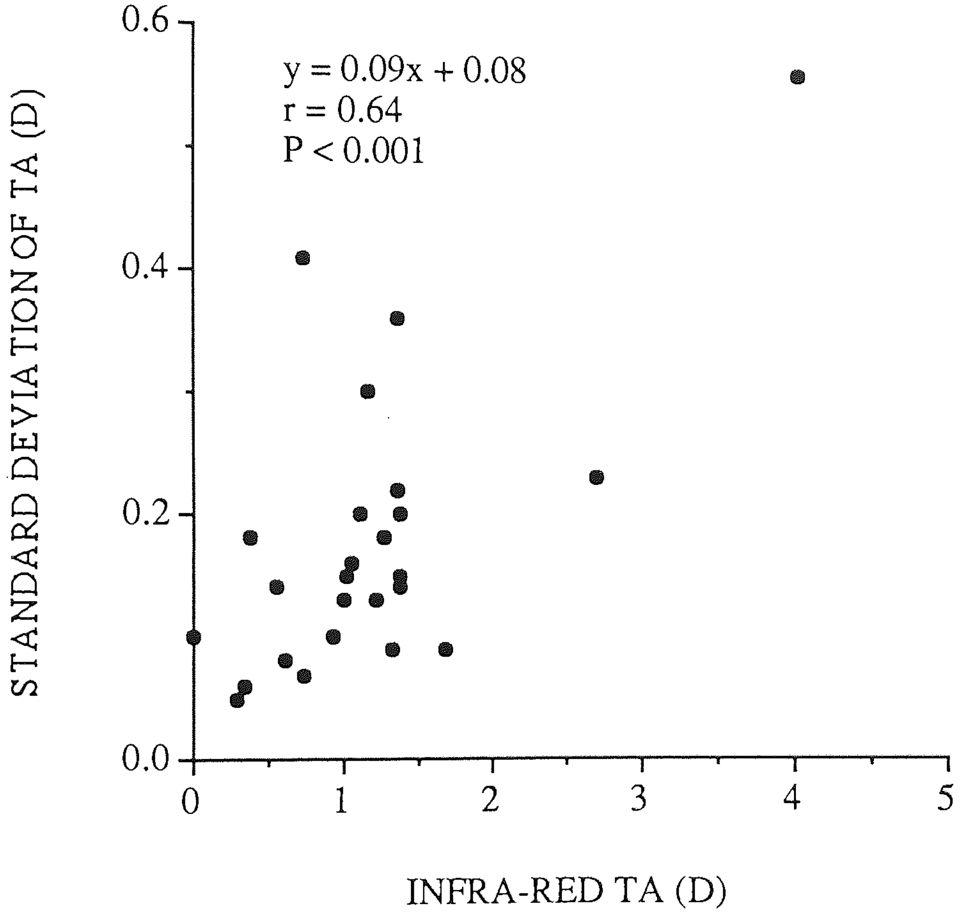


FIG. 2.5. The relationship between standard deviation of tonic accommodation (TA) and tonic accommodation measured by infra-red optometry for 25 subjects.

cycloplegia confirm that this relationship is not due to any induced changes in the existing accommodative state. A previous study (Post *et al.*, 1984) found poor agreement between laser and IR measurements of TA. Furthermore the study showed that, for approximately a third of the subjects, judgement of laser speckle motion produced a significant increase in TA. Post and his co-workers suggest that these results are due to the cognitive demand associated with judgement of speckle pattern movement in the laser optometer since Kruger (1980) demonstrated that the imposition of cognitive demand may produce an increase in the accommodative response. These results may, alternatively, be explained by the exposure times adopted for the laser optometer. Although Post *et al.* (1984) do not state the shutter speed used in their study, it is not unreasonable to assume that they followed the precedent of Hennessy and Leibowitz (1970) and adopted a time of 500 msec. However, various workers have investigated the accommodative reaction times (e.g Stark *et al.*, 1965; Tucker and Charman, 1979), the mean of the reported values being of the order of 358 msec (see Hogan and Gilmartin, 1984b), somewhat less than the 500 msec shutter speed used by most workers. It is therefore feasible that, if an accommodative response is possible during the 500 msec interval, visibility of the rotating surface of the drum may act as an accommodative stimulus and thus alter the subjects accommodative state. Since the surface of the drum is closer to the subject than the plane of stationarity an attempt to focus on its surface would produce an increase in accommodation and hence a higher recorded value of TA. In order to diminish the opportunity for a change to occur in the subjects accommodative state, an exposure time of 300 msec was used in this study (Hogan and Gilmartin, 1984b). In a further study Kothe *et al.* (1987) measured TA in 10 subjects using ten exposure times between 100 and 1000ms. They found that in 3 subjects exposure time had no influence on the measured TA value. In the remaining subjects, however, an increase in exposure time resulted in a monotonic decrease in TA in three subjects, a monotonic increase in TA in one subject and non-monotonic trends in three subjects. Kothe and her co-workers conclude that laser speckle exposure time is a possible contaminant of laser estimates of TA.

Before the aspect of correction factors is addressed, the method of calibration of each instrument should be examined. The laser optometer was calibrated by accurate linear measurement of the distance from Badal lens to the plane of stationarity of the rotating drum. However, since a He-Ne laser was used with a wavelength of 633nm, a chromatic aberration correction factor must be applied in order to convert results to the reference wavelength selected (usually 578 nm). As already noted, the majority of previous workers (e.g Hennessy, 1975; Heron *et al.*,1981) have applied a correction factor of 0.33 D (for 555 nm) to the laser optometer. Gilmartin and Hogan (1985c) have, however, measured TA using lasers of various wavelengths and suggested that a correction factor of 0.60 D (for 578 nm) be used. Applying this value to the data from this study would give a mean TA value of 1.70 D for the laser optometer.

Although only a limited amount of information could be ascertained concerning the calibration of the Canon Autoref R-1, it is understood that the instrument was calibrated empirically to produce results comparable with distance subjective refraction, such that measurement of an emmetrope viewing a distant target will yield a result of plano. Researchers have consistently demonstrated, however, that during accurate distance fixation the eye is accommodating by 0.50-0.70 D (e.g. Charman and Tucker, 1978), a phenomenon referred to as 'accommodative lead' (Morgan, 1944b). Hence any measurement taken with such an instrument should be adjusted by the appropriate amount in order to give an absolute measure of a subject's accommodative state. Therefore the mean TA as measured by this instrument should be of the order of 1.65-1.85 D.

With respect to the near retinoscopy (NR) data, a mean value of 1.07 D was found. This value is more myopic than the mean value (0.70 D) found by Owens *et al.*, (1980). The discrepancy may be due to the fact that all of the subjects taking part in the present study were accurately refracted immediately prior to the experiment, whereas Owens and his co-workers only state that their subjects (N = 11) wore their current optical correction.

Inspection of the graph of NR against laser TA (Fig. 2.4) shows a good correlation, but, as the slope of the regression line is only 0.49, near retinoscopy gives an estimate of TA which is of limited accuracy. Therefore one might conclude that the presence of the retinoscopy beam influences the accommodative state of the subject. Owens and Leibowitz (1975) have shown that a very small monocular fixation light does not constitute an adequate accommodative stimulus: further, Owens *et al.* (1980) demonstrated that the presence of a stationary retinoscope beam positioned at various distances did not influence TA. However, during near retinoscopy the retinoscope beam is moving, which may enhance its effect on accommodation, and in addition the retinoscopist is positioned adjacent to the beam. It is possible, therefore, that proximal accommodation may bias TA towards the position of the observer, who is 50cm from the subject. The mean value for NR is, however, 1.07 D and thus other factors must be involved.

Charman (1975) has demonstrated that the majority of the visible light reflected from a subject's retina is from the red end of the spectrum, thus making retinoscopy results more hyperopic. Charman suggests that this error is less than 0.25 D, using the data of Wald and Griffin (1947) and Bedford and Wyszecki (1957) for the chromatic aberration of the eye. However, as indicated earlier, Gilmartin and Hogan (1985c) have suggested that the chromatic aberration of the eye may be greater than previously reported and hence the correction factor which should be applied to the retinoscopy results may be greater than that suggested by Charman (1975), thereby producing more myopic NR results. It should also be noted that the retinoscope reflex is reflected from the anterior retinal surface making the results relatively hyperopic compared with subjective refraction (Glickstein and Millodot, 1970). Despite the aforementioned factors it is still possible to obtain a reasonable estimate of TA by mathematical adjustment of the NR results (Hope and Rubin, 1984). Using the results of the present study, the following equations can be derived to estimate laser TA values at 633nm and IR TA values from

NR results:

$$\text{laser TA} = 2.04\,(\text{NR}) - 1.00$$

$$\text{IR TA} = 2.00\,(\text{NR}) - 1.00$$

This study has certain implications for previous and future research in this area. First, the infra-red optometer has been shown to produce results comparable with the laser optometer for TA measurements, when correction factors are not incorporated. Also, the excellent correlation between laser and infra-red estimates of TA found in this study compared with the poor agreement found by Post *et al.* (1984) adds further evidence that an exposure time of 300 msec should be adopted when using the laser optometer to avoid interactive effects. Finally, the reliability, and more importantly, the speed with which measurements may be taken using infra-red techniques augurs well for future research.

2.3 - INFRA-RED SOURCES AND RETINAL TARGET ECCENTRICITY

2.3A - Introduction

One of the features the Autoref R-1 which should be investigated is the possible influence of the infra-red sources described in section 2.1B (pps. 75-80). These sources are invisible under normal room illumination but under darkroom conditions, as employed in section 2.2, the sources are visible to the subject as two dim red lights. By positioning an appropriate tangent scale it was found that these sources were imaged 20 degrees either side of the optical axis of the instrument. It was decided, therefore, to investigate whether targets of such retinal eccentricity could influence the accommodative response.

Whiteside (1957) used thin concentric circles of various sizes to investigate the effect of target eccentricity on the accommodative response. Using only one subject and one stimulus vergence (optical infinity), he found that targets greater than 4 degrees or more from the fovea had no effect on accommodation.

Hennessy and Leibowitz (1971) investigated the effect of peripheral targets on accommodation using a subjective laser optometer. Subjects monocularly fixated a defocussed spot of light at six metres while a circular aperture of constant angular subtense was placed at various distances. They found that as the aperture was moved closer to the subject small increases in accommodative response were observed. In addition the influence of the aperture on the accommodative response was greater for a 1 degree aperture than for a 4 degree aperture.

Semmlow and Tinor (1978) investigated the influence of retinal target eccentrity on accommodative convergence and found that while off-foveal images can generate accommodative vergence movements, the amplitude of the response diminishes substantially with increasing eccentricity. They found that for targets six degrees from fixation, the maximum eccentricity employed, the accommodative convergence was approximately 30% of that found for central targets.

Ciuffreda and Kenyon (1983) cite the data of Phillips (1974) who showed that stimuli greater than ten degrees from the fovea had no influence on accommodation. It is also interesting to note that Otto and Saffra (1974) found that the accommodative response was reduced or even absent in individuals with central scotomas due to pathological conditions.

It can be seen, therefore, that although previous studies have demonstrated that an increase in retinal target eccentricity is accompanied by a decrease in the accuracy of the accommodative response, no systematic results exist whereby the influence of the infra-red sources on the R-1 could be estimated. It was decided, therefore, to conduct a more thorough investigation of the relationship between retinal target eccentricity and the accommodative response.

2.3B - Method

All measurements of accommodation were made using the Canon Autoref R-1. A Badal optical system was adopted in order to limit the influence of proximal clues. Subjects viewed monocularly a uniform white field (luminance = 35 cd/m^2), through a +7.00 dioptre badal lens, which was produced by placing a back illuminated opaque screen beyond the focal point of the lens (see Fig. 2.6). The field of view was restricted to 25 degrees by an aperture placed 10cm from the eye. Targets consisted of six black cards each having a central circular aperture. The angular subtenses of these apertures were 1, 2, 4, 6, 10, and 20 degrees and could be positioned such that the aperture was at the centre of the subject's field of view such that the subject would perceive a white circle against a black background. Targets were presented in a randomised order at five dioptric distances, namely 0, 1, 2, 3 and 4 dioptres, giving a total of thirty stimuli. For each stimulus the subject was instructed to fixate the centre of the circle. The retinal eccentricity of the stimuli were, therefore, 0.5, 1, 2, 3, 5 and 10 degrees. Previous research has demonstrated the importance of subject instruction on the measured accommodative response (Owens, 1980; Ciuffreda and Hokoda, 1985). It was decided, therefore, to instruct all subjects "to exert the same amount of effort that they would use while reading a book" when viewing the target. Following a period of ten seconds to allow the subject's accommodation to reach the appropriate level for a given stimulus, ten continuous readings were taken. The mean of those ten values was computed and this taken to represent the accommodative response for that stimulus. If a subject reported fatigue or discomfort at any time during the experiment he or she was allowed a rest period, although the experiment only usually lasted around 25 minutes.

Seven visually normal subjects participated in the study, 6 men and 1 woman, all of whom were aged between 20 and 25 (mean age = 21.5 years). All subjects had refractive errors between -0.25 and +0.50DS best sphere with not more than 0.25 D of

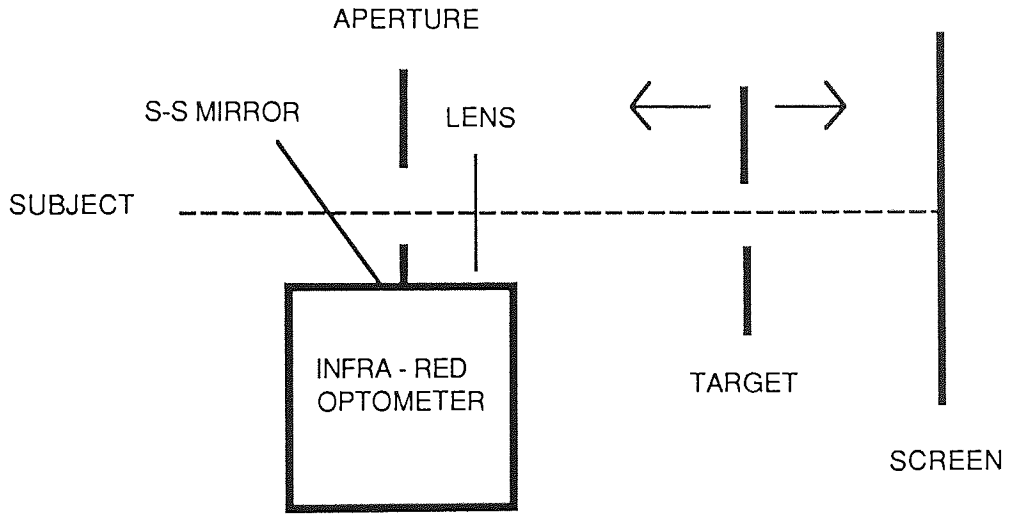


FIG. 2.6. Schematic diagram of experimental apparatus, side view.

astigmatism. No refractive corrections were worn during the experiment and all readings were taken from the left eye.

2.3C - Results

The mean accommodative response to each of the thirty stimuli was calculated for the seven subjects. These were plotted as six stimulus/response curves, one for each retinal target eccentricity (see fig. 2.7). It can be seen that the accommodative response is most accurate for central retinal stimuli. An increase in the retinal eccentricity of the target is accompanied by a decrease in accommodative responsiveness and a flattening of the stimulus/response curve. The relationship between retinal eccentricity and accommodative response may be examined further by calculating the magnitude of the slope (m) of these stimulus/response curves using the method of least squares and plotting these values in terms of retinal eccentricity (see fig. 2.8). For this procedure the results for the 0 dioptre stimuli were ignored, due to presence of the well established "lead of accommodation" (Morgan, 1944b).

2.3D - Discussion

The findings of the present study, whilst showing similar trends to those of previous workers, exhibit some contradictory results. Whiteside (1957) found that targets greater than 4 degrees from the fovea had no influence on accommodation. Results from the present study would suggest that a 5 degree target may still have a significant effect on accommodation, the slope of the stimulus/response curve being 0.55. This may be partially explained by Whiteside's small sample size. An alternative reason for these differences may be the targets used, when considered in terms of their spatial frequency content. Whiteside's targets consisted of thin concentric circles which may have had a limited spatial frequency spectrum. The stimuli used in the present study, however, had one high contrast border and hence may be richer in lower spatial frequencies which may drive accommodation more effectively for eccentric targets.

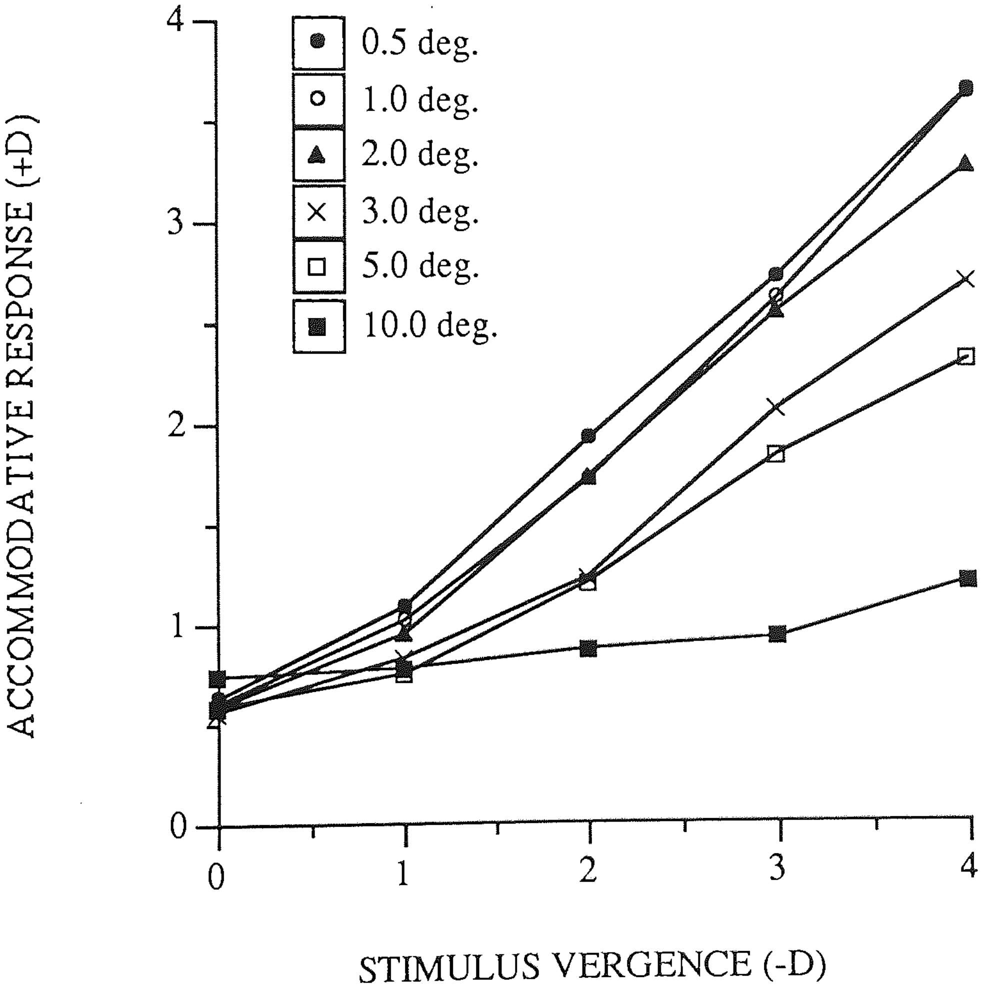


FIG. 2.7. Mean accommodative stimulus/response functions for seven subjects for each retinal target eccentricity. Standard errors of the mean are omitted for clarity but were of the order of 0.1 to 0.3 D.

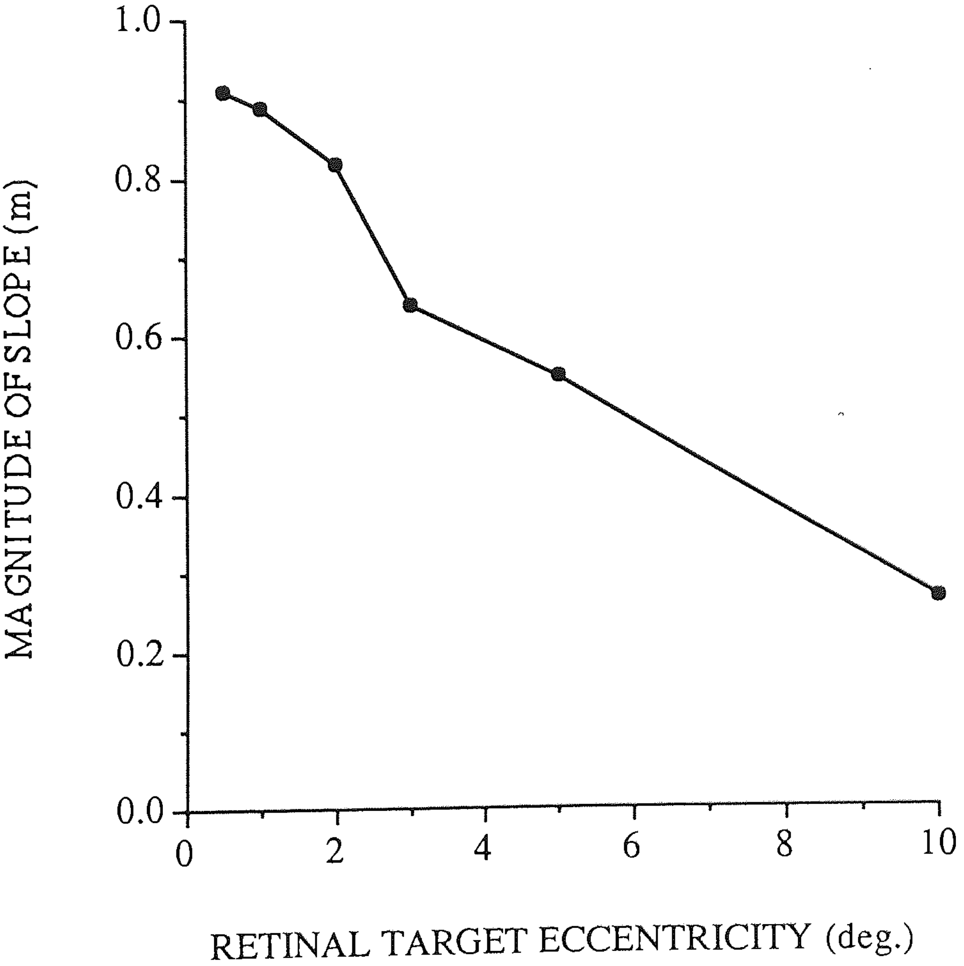


FIG. 2.8. Magnitude of the slope, m, of the accommodation stimulus function (stimulus range -1 to -4 D) as a function of retinal target eccentricity.

Previous workers have suggested that the accuracy of the accommodative response is related to a subjects visual acuity (e.g. Heath, 1956a). In addition Whiteside (1957) remarked that his plot of accommodative response versus retinal eccentricity was similar to a graph of visual acuity versus retinal eccentricity. Recently Charman (1986) has considered the various factors associated with the accuracy of the accommodative response and concludes that the slope (m) of the linear portion of the stimulus/response function is linearly related to the minimum angle of resolution (MAR) achievable by the observer under the observation conditions. Using some basic assumptions and incorporating the constant C Charman derives the equation:

$$|\mathbf{m}| = \mathbf{1 - C(MAR)}$$

Charman (1986) compares various experimental data with this prediction and concludes that the data from the majority of studies predicts a value for C of ~0.1 to 0.5 min^{-1}. The data from the present study were treated in a similar fashion, that is the values of |m| plotted against values of MAR for each retinal eccentricity (Fig. 2.9). The values of MAR were taken from the data of Wertheim (1891) and yield a value of 0.17 min^{-1} for C, which is within the range reported by Charman (1986).

In summary, this study has demonstrated that the accuracy of the accommodative response decreases with increasing retinal target eccentricity. It was not possible, for methodological reasons, to use targets of equivalent eccentricity to the infra-red sources on the R-1. It may be assumed, however, from the results of this study and from those of previous workers that stimuli 20 degrees from fixation should have no influence on accommodation, even under open-loop conditions. Furthermore previous research has demonstrated that small point sources of light are very poor stimuli for accommodation (Owens and Leibowitz, 1975).

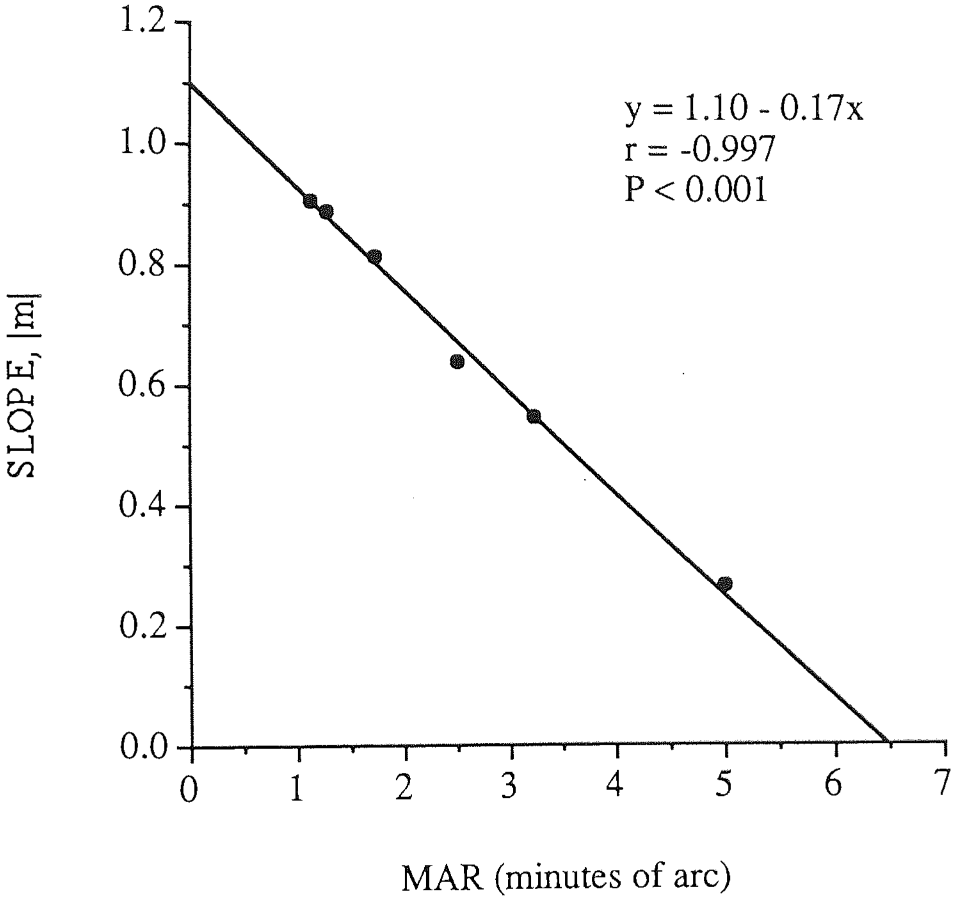


FIG. 2.9 - Effect of increased **MAR** produced by increased retinal target eccentricity on the slope, **m**, of the accommodation stimulus/response function. The values of **m** are derived from the mean values of accommodative response for seven subjects for eccentricities of 0.5, 1, 2, 3, 5, 10 degrees. The values for **MAR** are taken from Wertheim (1980).

2.4 - CALIBRATION FACTORS FOR THE AUTOREF R-1

2.4A - Introduction

The question of calibration factors was discussed in Section 2.2D (pps. 88-93). It was assumed that the Autoref R-1 has been calibrated empirically to produce results comparable with distance subjective refraction. Researchers have consistently demonstrated, however, that during accurate distance fixation the eye is accommodating by 0.50-0.70 D (e.g Charman and Tucker, 1978), a phenomenon referred to as 'accommodative lead' (Morgan, 1944b). Hence in order to obtain an 'absolute' value for accommodation the reading taken from the R-1 would need to be adjusted for this factor. It was decided, therefore, to calibrate the instrument empirically by applying classical accommodation theory. It is generally accepted that the intersection of the accommodation stimulus/response function with the unit-ratio line represents the tonic resting state of accommodation (Toates, 1970; Johnson, 1976). Thus, if a target is placed close to a subject's TA position it should evoke a very accurate response. The difference between the value produced by the R-1 and the stimulus vergence, for a target close to a subject's TA position should, therefore, represent the calibration factor for the instrument.

2.4B - Method

One emmetropic male volunteer aged 23 years participated in the study. The accommodative response was measured for a target placed 50cm from the subject. The vergence of the stimuli was varied by placing various 60mm lenses 13cm from the subject such that the stimulus vergences produced at the cornea of the subject were -0.53, -1.12, -1.92, -2.66, -3.23 and -4.03 D. The introduction of such lenses between the subject and target will result in changes in magnification which may produce concurrent changes in the spatial frequency content of the stimulus. It is well established that the accommodative response is dependent on the spatial frequency spectrum of the observed object (e.g. Charman and Tucker, 1977; Owens, 1980), therefore a target whose spatial frequency spectrum was unaffected by changes in magnification was chosen, namely a high contrast, black and white, starburst pattern. Ten readings were taken at each stimulus vergence following a period of ten seconds to allow the subject's accommodation to reach the appropriate steady-state level for that stimulus. The mean of those ten values was computed and this taken to represent the accommodative response. In addition the subject's TA was measured on two occasions using the method described in section 2.2B (pps. 83-84) and the mean of these two values taken as the subjects TA.

2.4C - Results

The mean values of accommodative response are given in Table 2.2. Since it was known that the R-1 was set to give results for a back vertex distance of 12 mm results were adjusted mathematically for a back vertex distance of 0mm. In addition values of the accommodative steady-state error are given. A stimulus/response function was then plotted as shown in Fig. 2.10 and a typical curve produced. The subject's TA was measured as +1.59 D and +1.21 D, the mean of these two values being +1.40 D.

TABLE 2.2 - Mean values of accommodative response and steady-state error for each stimulus vergence. All values given are in dioptres and figures in brackets represent standard deviations.

STIMULUS VERGENCE	ACCOMMODATIVE RESPONSE (BVD 12 MM)	ACCOMMODATIVE RESPONSE (BVD 0 MM)	STEADY-STATE ERROR
-0.53	+0.83 (0.07)	+0.83	+0.30
-1.12	+1.04 (0.07)	+1.03	-0.09
-1.92	+1.77 (0.09)	+1.73	-0.19
-2.66	+2.47 (0.10)	+2.39	-0.27
-3.23	+3.16 (0.17)	+3.04	-0.19
-4.03	+4.14 (0.16)	+3.94	-0.08

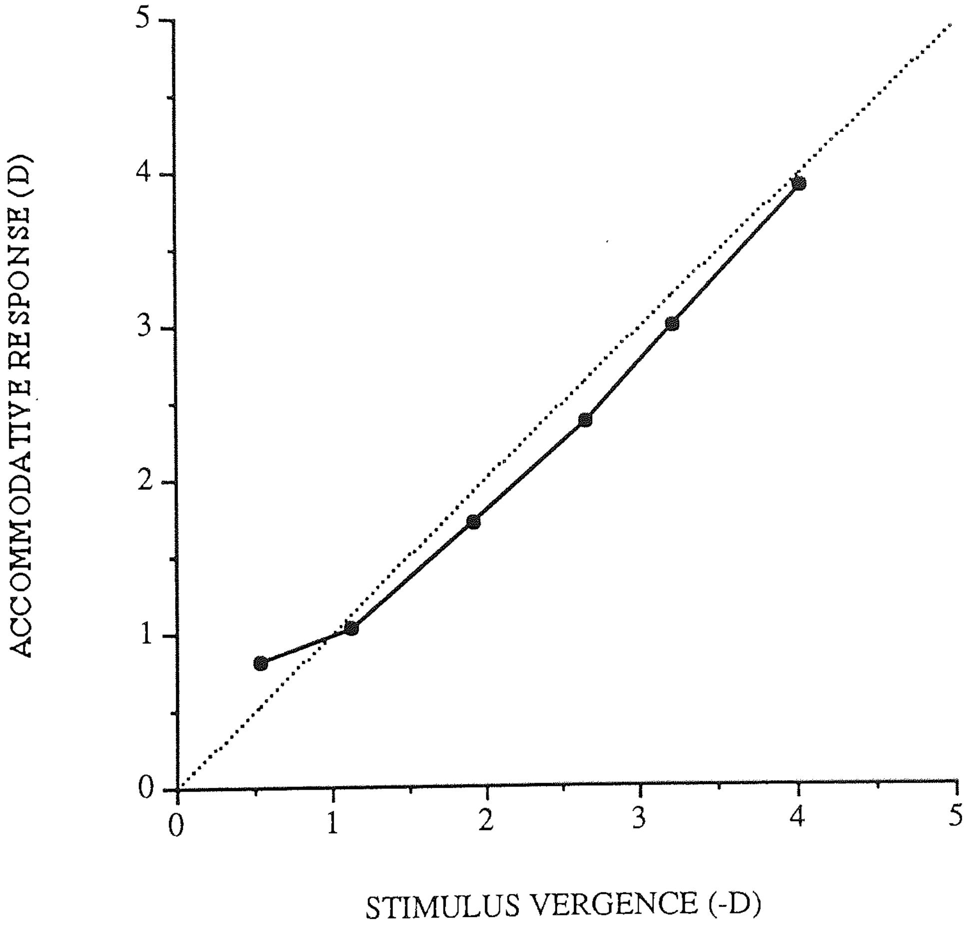


FIG. 2.10. - Accommodative response as a function of stimulus vergence for a starburst target presented for six stimulus vergences.

2.4D - Discussion

It can be seen from Table 2.2 and Fig. 2.10 that the accommodative reponse exceeds the stimulus vergence for the lowest stimulus vergence (-0.53 D), representing the lead of accommodation (Morgan, 1944b). For all other stimulus locations the response is lower than the stimulus vergence. As mentioned previously, it is generally accepted that the accommodation stimulus/response function crosses the unit ratio line at the resting position or TA value. The TA value of the subject participating in the present study was found to be 1.40 D but inspection of Fig. 2.10 reveals that for a stimulus vergence of -1.40 D the accommodative response would be 1.25 D. Hence the curve produced in this study would need to be shifted vertically by +0.15 D.

An alternative method of calibration is that employed by Baker *et al.* (1983) in the calibration of their infra-red optometer. They presented targets at 2, 3 and 4 D and assumed that their subject would be accommodating accurately at such vergences. If this applied to the data from the present study it and the mean steady-state error calculated for the stimuli between -1.92 and -4.03 D a value of -0.19 D is obtained, hence a calibration factor of +0.19 D would be required. It should be noted, however, that this method assumes that the accommodative lag is zero.

In summary, it was found that both calibration methods produce similar results. All values of accommodation reported in the following chapters are therefore referenced to the corneal plane (corrected for a b.v.d. of 0mm) and have been adjusted by +0.20 D. It is interesting to note that Ward (1987) adopted a different calibration technique whereby infra-red estimates of distance refraction were compared with those obtained with a calibrated laser optometer. He found that a correction factor of +0.60 D was required for the R-1. It is uncertain, however, whether the discrepancy between Ward's value and that found in the present study is due to the methodology employed or due to variations between the individual instruments.

It should be stressed that the adoption of the calibration factor is of limited importance to this project since all of the experiments described in the following chapters are concerned with pharmacologically, psychologically and task induced changes in the accommodative response or variations between refractive groups as opposed to 'absolute' values of accommodation.

The results of the study reported in section 2.2 have been published in *Ophthalmic and Physiological Optics*, see Appendix X.1. The results of the study reported have been published in *Advances in Diagnostic Visual Optics*, edited by Fiorentini A, Guyton DL and Siegel IM, see Appendix X.8 and the *American Journal of Optometry and Physiological Optics* see Appendix X.12.

CHAPTER 3

THE ROLE OF SYMPATHETIC INNERVATION IN THE ADAPTATION OF TONIC ACCOMMODATION

3.1 - INTRODUCTION

It is well established that a period of sustained fixation can produce significant changes in a subject's tonic resting position (see section 1.5D pps. 50-55). Ebenholtz (1983) demonstrated that 8 minutes of monocular fixation (N = 12) at the far point (FP) produced a mean decrease in tonic accommodation (TA) of -0.21 D whereas a similar period of near point (NP) fixation produced a mean increase in TA of 0.34 D. He noted, however, that the the NP target was, on average, 0.98 D beyond the subject's resting position, whilst the NP target was 5.12 D closer than the subject's TA. Hence it might have been expected that the effect of NP fixation would be some five times that of the FP target. Ebenholtz suggested that this was evidence for the existence of two sub-sytems for the control of accommodation. This led Gilmartin and Hogan (1985a) to suggest that the inhibitory sympathetic input to the ciliary muscle may serve to attenuate task induced increases in TA. It was felt that this proposal warranted further investigation.

The autonomic control of accommodation is primarily due to parasympathetic innervation of the ciliary muscle. Previous research suggests, however, that the ciliary muscle also receives sympathetic innervation mediated by the action of noradrenaline on inhibitory beta receptors (see review by Gilmartin, 1986 and section 1.3 pps. 30-41). Research suggests that the nature of the sympathetic input to the ciliary muscle may be summarised as follows:

1. The input is inhibitory in nature and is mediated by inhibitory beta adrenergic receptors, predominantly of the $beta_2$ sub-type (Lograno and Reibaldi, 1986; Wax and Molinoff,1987).
2. The input is small in magnitude relative to the predominant parasympathetic input.
3. The latency of sympathetic activity is significantly slower than that of parasympathetic activity (Törnqvist, 1967).
4. Inhibitory sympathetic activity is augmented by increased levels of background parasympathetic tone (Tornqvist, 1966; 1967; Hurwitz *et al.*, 1972a).

This would suggest that the role of the sympathetic input is more suited to visual tasks requiring sustained accommodation for near rather than to those tasks requiring a low or rapid change in accommodative response.

Gilmartin and his co-workers have recently employed laser optometry to study the effects of various pharmacological agents on TA (Gilmartin *et al.*, 1984; Gilmartin and Hogan, 1985b). They found that the non-selective beta-receptor antagonist timolol maleate induces increases in TA of between +0.6 D and +1.2 D which are directly proportional to the pre-drug level of TA (Gilmartin *et al.*, 1984). This finding supports the proposal that the influence of the sympathetic nervous system is proportional to the background parasympathetic activity since the distribution of TA has been shown to be predominantly a consequence of parasympathetic tone (Gilmartin and Hogan, 1985b). In a further study Gilmartin and Hogan (1985b) showed that the non-selective beta-receptor agonist isoprenaline sulphate induces hyperopic shifts that are independent of the pre-drug TA, thus demonstrating that the influence of agonist action is unrelated to the existing level of sympathetic activity (see Fig. 3.1).

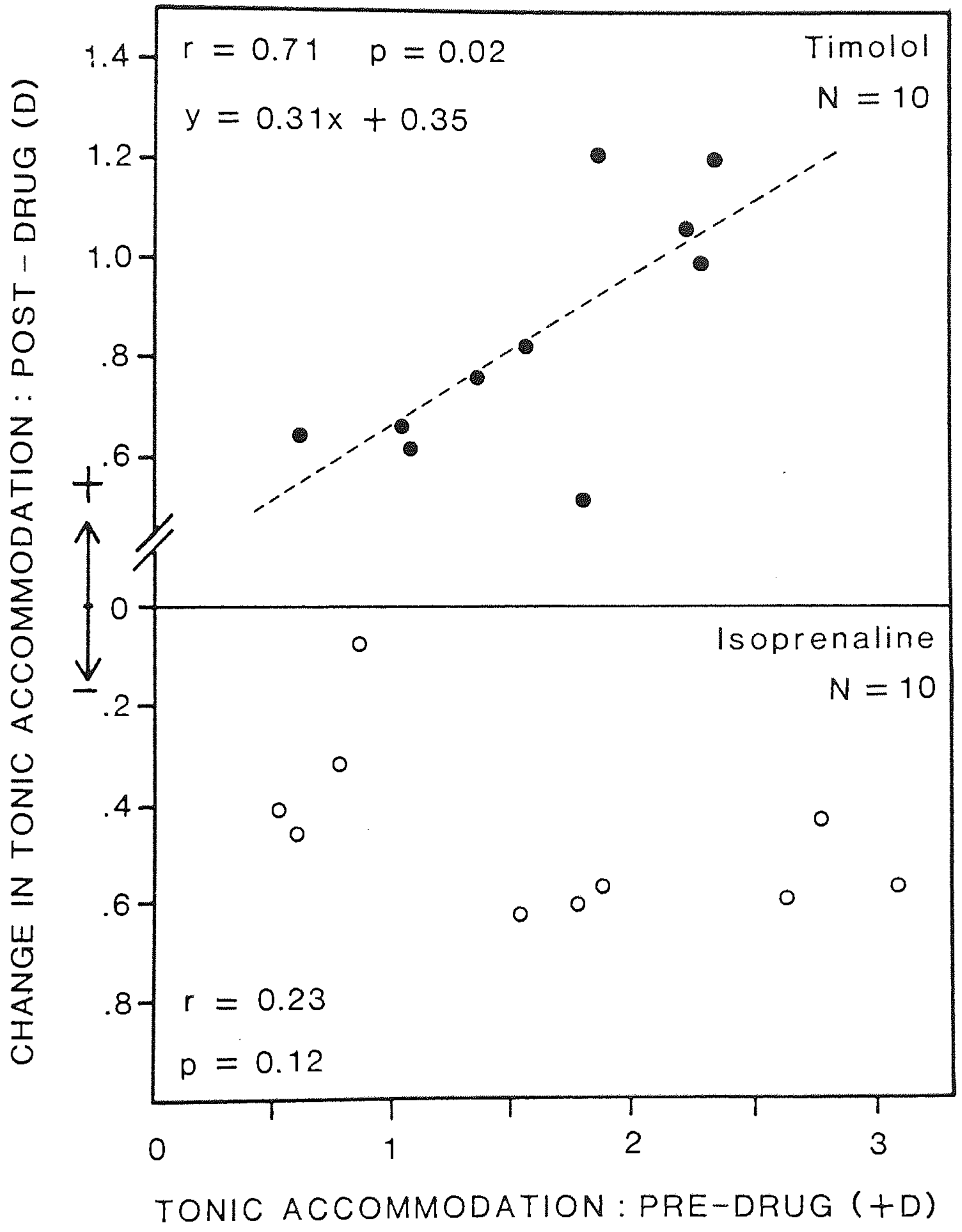


FIG. 3.1. - The relationship between pre-drug level of tonic accommodation (TA) and the dioptric change in TA induced by topical instillation of timolol maleate, 0.5% (37.5 minutes post-drug) and isoprenaline sulphate, 3% (22.2 minutes post-drug). Data is taken from Gilmartin *et al* (1984) and Gilmartin and Hogan (1985).

The aim of this study was to investigate whether the increase in ciliary muscle parasympathetic activity associated with a change in accommodative demand from -0.3 D to -5.0 D is accompanied by an inhibitory sympathetic input. Monitoring autonomic control of accommodation during a visual task presents considerable methodological difficulty. It was felt, however, that information concerning ciliary muscle innervation during the task could be deduced from the changes in accommodative state that occur when the accommodative loop is opened. It was assumed, therefore, that the nature of the innervation to the ciliary muscle during the task would determine the locus or pattern of regression of accommodation towards the pre-task TA position.

Pilot studies indicated that when using an objective infra-red optometer, *viz*. the Canon R-1 autorefractor, under the conditions of the present study, post-task shifts in TA dissipate within a 90 second period. The relative contribution of the parasympathetic and sympathetic nervous systems to the control of accommodation during and immediately after the task can be assessed by examining the influence of blocking the sympathetic system with timolol maleate on the time-course and magnitude of these post-task shifts. Post-task TA shifts which are vulnerable to the effects of beta-antagonism will provide evidence for the operation of dual innervation during the task. It might be predicted that attenuation of an inhibitory sympathetic component would produce a relative myopic shift in post-task TA together with a modified time course.

3.2 - METHOD

Fifteen male emmetropic subjects aged between 19 and 22 years (mean = 20.8) participated in the study. All subjects had refractive errors between plano and +0.50 best sphere (mean = +0.12 D) and not more than 0.25 dioptres of astigmatism. All subjects could achieve distance 6/5 visual acuity. All accommodation measurements were made on the left eye only using the Canon R-1 autorefractor. Subjects participated in six experimental sessions each of which lasted approximately 50 minutes. Each session was separated by a period of at least 4 days and comprised a combination of 1 of 2 drug conditions (timolol maleate 0.5%; normal saline) with one of three task conditions (far, -0.3 D; near, -5.0 D; and a darkroom condition). In the darkroom condition the 10 minute task period was replaced by a 10 minute period in the dark to allow for any myopic shifts in tonic accommodation (TA) that might have occurred independent of the task (Gilmartin *et al.*, 1984; Gilmartin and Hogan 1985b).

All experimental sessions commenced with an initial 10 minute period in darkness to limit the effect of pre-task influences on the initial TA measurement. After this "wash-out" period 10 TA readings were taken every minute for 5 minutes and later averaged to give a pre-task estimate of TA. This was followed by two instillations of the drug (timolol or saline) separated by a period of 10 minutes. Both experimenter and subject were unaware of which agent had been used. The instillations were made using a precision micro-pipette such that each instillation comprised 25 µl of drug (therefore total amount per eye = 50 µl). Ten minutes after the second instillation the subject performed the 10 minute task. While viewing through the semi-silvered mirror of the infra-red optometer subjects were required to add together a series of black numbers on a white background (90% contrast) which were equivalent to Snellen 6/9 for the far task and N6 for the near task. This task was employed so that active accommodation was required for the duration of the task and furthermore provided a specific level of mental effort. The accommodative response was measured at one minute intervals during the task. Following the task, the room lights were extinguished and TA was immediately measured at approximately 1 second intervals over a 90 second period. 5 seconds was allowed following extinction of the room lights for slight re-alignment of the instrument.

In order to monitor the well known ocular hypotensive effects of timolol, IOP was measured at the beginning and end of the experimental session using a Digilab Pneuma-Tonometer (Model 30D, Cambridge, MA. 02139). This required the instillation of 2 drops of the topical anaesthetic benoxinate (0.4%).

3.3 - RESULTS

The mean pre-task TA for each task condition was not significantly different for timolol and saline trials (see Table 3.1). The overall group mean of 0.85 D is slightly less than that of 1.10 D previously reported for a group of 50 subjects using an infra-red optometer (Post *et al.*, 1984) and the mean value found in section 2.2 (pps. 80-93).

TABLE 3.1 - Mean pre-task tonic accommodation (TA) for the group of 15 subjects and for each experimental condition. The mean change in intraocular pressure (IOP) in mm Hg is also shown for the whole group and for each experimental condition. Figures in brackets represent standard deviations.

	PRE-TASK TA (+D)		CHANGE IN IOP (mmHg)	
	SALINE	**TIMOLOL**	**SALINE**	**TIMOLOL**
FAR	0.84 (0.51)	0.79 (0.43)	-0.3 (0.6)	-4.1 (1.1)
NEAR	0.82 (0.52)	0.88 (0.48)	+0.2 (0.8)	-4.0 (1.1)
DARK	0.88 (0.44)	0.87 (0.38)	+0.2 (0.6)	-4.2 (0.7)

The far task (stimulus vergence = -0.3 D) produced a mean accommodative response for the group of 0.62 D (sd = 0.18) for both the timolol and saline trials. The near task (stimulus vergence = -5.0 D) produced mean accommodative responses of 4.31 D (sd = 0.22) and 4.55 D (sd = 0.25) for saline and timolol trials respectively.

The post-task data were summarised using the following procedure: after taking account of each subject's refractive error, the mean-sphere was determined for each of the 90-second data points and means and standard deviations were then calculated for the nine sets of 10 data points that were symmetrically placed about the 10, 20, 30.........90 second points; the respective pre-task level of TA was subtracted from each of these mean values and graphs of mean post-task shift in TA was plotted against time for each experimental condition. The post-task TA regression patterns demonstrate marked inter-subject variations, consistent with previous studies (Schor *et al.*, 1984; Ebenholtz, 1983; 1985). Fig. 3.2 illustrates, however, an individual example of the principal effects found for the grouped data.

Mean post-task regression patterns for the whole experimental group are shown in Fig. 3.3 for each task condition and for both timolol and saline trials. For the saline trial a rapid regression of TA towards pre-task levels occurs within the first 10 seconds following the near task. Darkroom control levels are reached in 20 to 30 seconds. The far task induced no significant shift in post-task TA and pre-task levels were reached within 10 seconds. The darkroom control data varied little over the 90 second period.

It can be seen that, for the near task, beta-receptor antagonism induces an increase in the post-task shift in TA of around +0.30 D for the initial 50 second period. This modification of near regression pattern is not statistically significant (see below). It may be concluded, however, that the post-task change in TA for near is due to a combination of parasympathetic and inhibitory sympathetic ciliary muscle innervation. It may be concluded, therefore, that dual innervation of the ciliary muscle occurs during the near task.

The mean difference between timolol far and near regression patterns occurring over the the 50 second period is an indication of the degree of sympathetic inhibition associated with the near task. If the mean difference is plotted as a function of pre-task TA a significant correlation is found. Fig. 3.4 illustrates that mean differences were negative

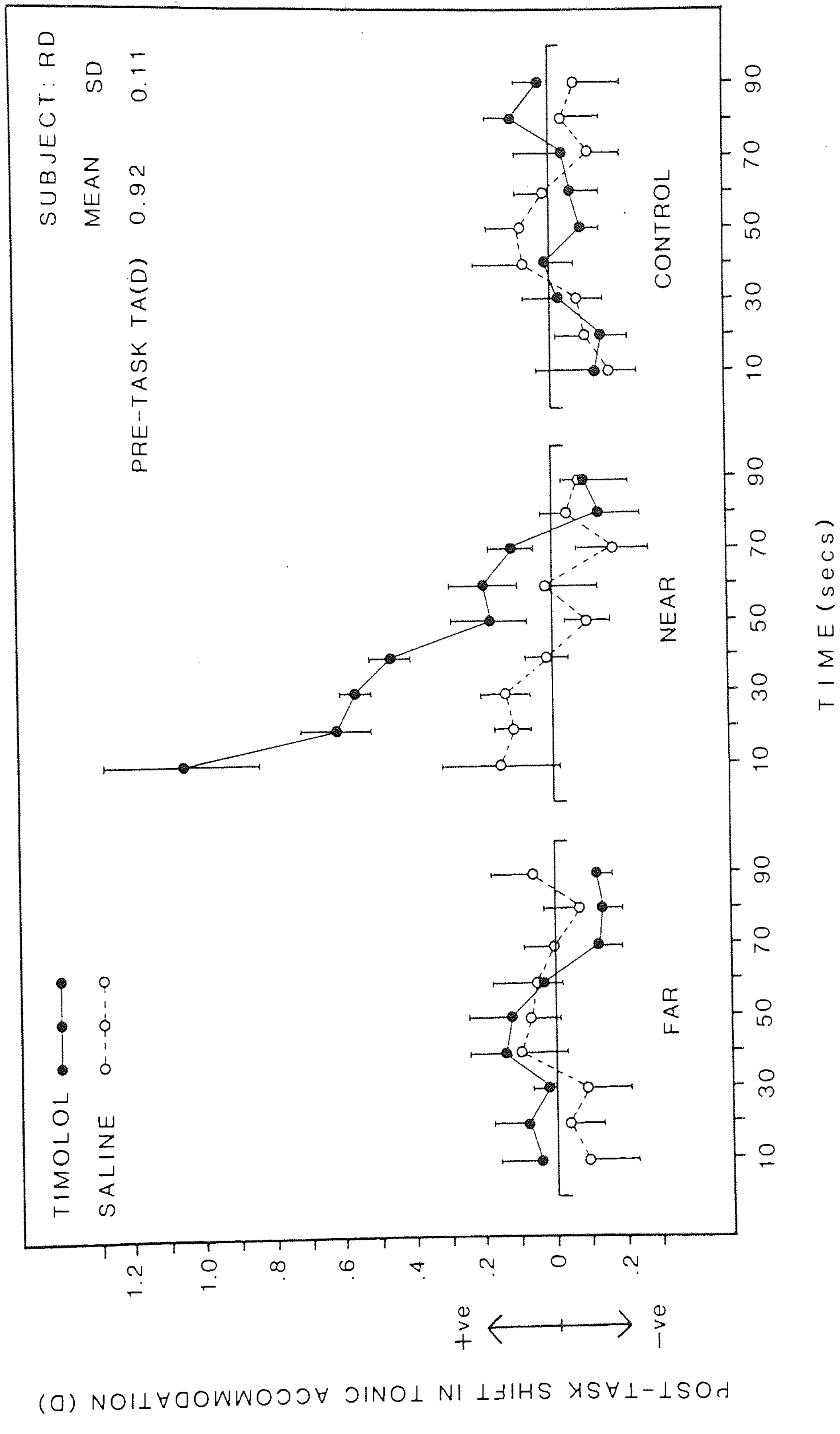


FIG. 3.2. - Post-task dioptric shift in tonic accommodation (TA) against time with respect to each experimental condition for subject R.D. Errors bars represent 1 s.d. The mean pre-task level of TA was calculated from the 6 experimental trials.

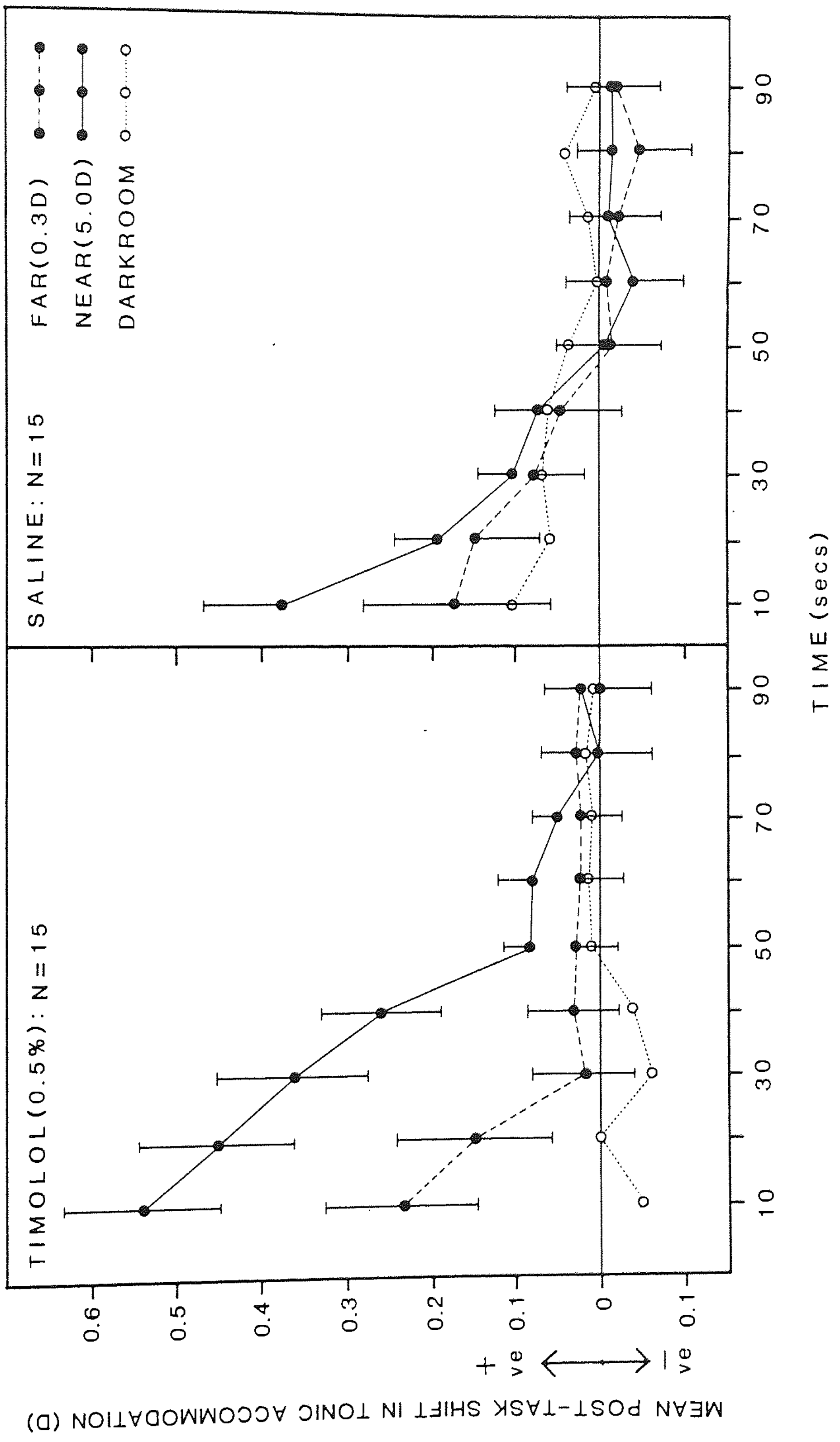


FIG. 3.3. - Mean post-task dioptric shift in tonic accommodation (TA) against time for the whole group and for each experimental condition. Errors bars (representing ±1 s.e.m.) were consistently the order of 0.05 D for all darkroom control conditions and have been omitted for clarity.

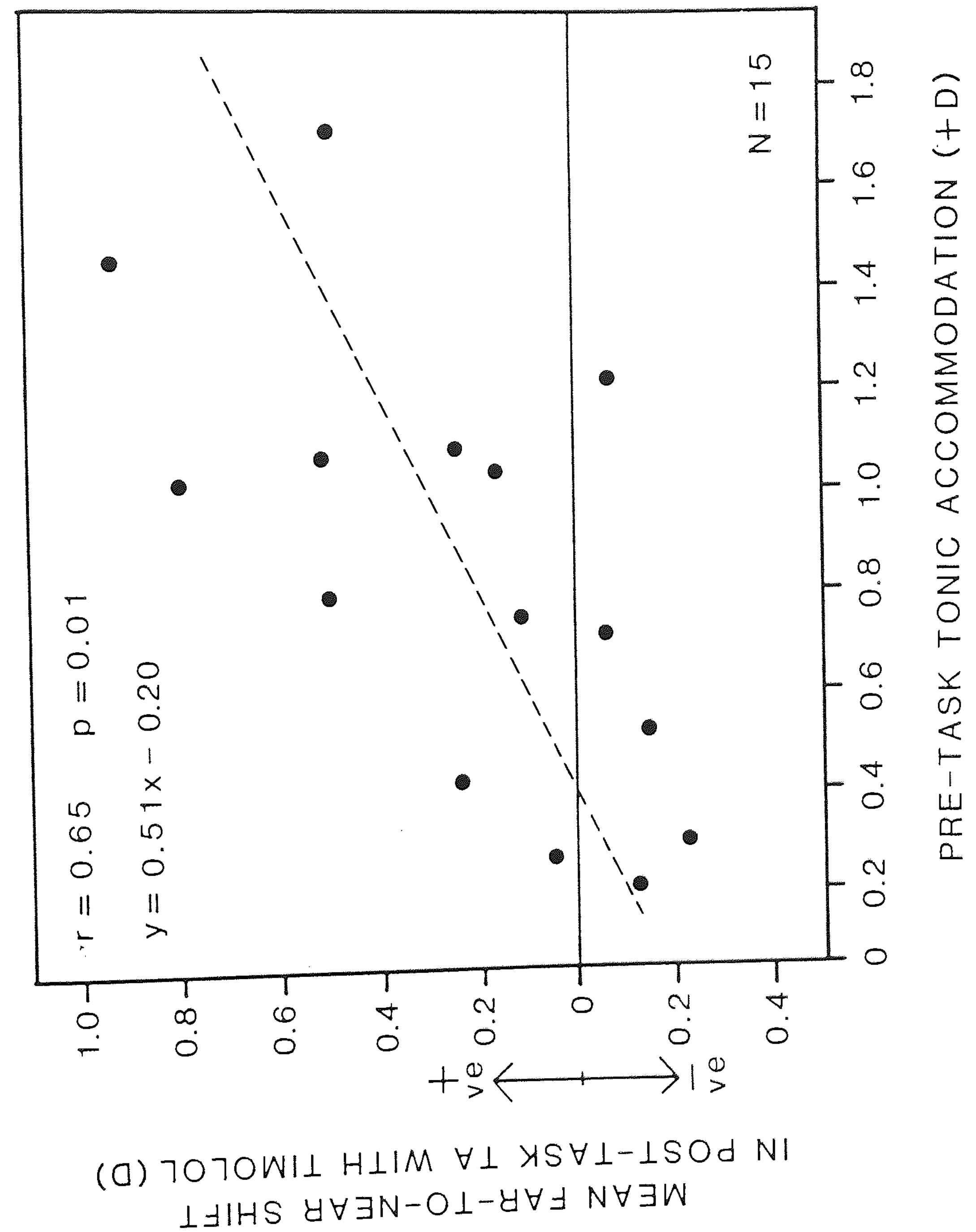


FIG. 3.4. - The mean dioptric difference between each subjects' far -and near-timolol regression patterns for the first 50 second post-task period plotted against respective pre-task tonic accommodation levels.

or slightly positive for pre-task TA levels less than 0.75 D but predominantly positive for pre-task TA values greater than 0.75 D. This division separated the 15 subjects into two groups: one comprising 7 subjects with pre-task TA ≤ 0.75 D (mean TA = 0.45 D) and the other comprising 8 subjects with pre-task TA > 0.75 D (mean TA =1.17 D).

The regression patterns for the lower pre-task TA group showed no significant differences between timolol and saline trials for any of the task conditions (see Fig. 3.5). For the higher pre-task TA group, however, there was a marked positive shift in the near regression pattern produced by timolol (see Fig. 3.6). The shift was significant at the 3% level and is of the order of 0.50 D when compared to both the far task and to the equivalent saline trial for the lower TA group. The interaction between drug effect and task effect was significant at the 4% level.

The saline trial regression patterns provide further evidence for inhibitory activity at near. Fig. 3.7 illustrates data for both far and near tasks for the high and low TA groups. It can be seen that the mean post-task shifts in TA for near are similar for the two groups for the initial 20 seconds, however, after this point the higher TA group show a negative component. It is possible that this component is due to the sympathetic inhibition identified by the timolol trial data. It would then follow that the pattern for the lower TA group is derived solely from the parasympathetic system, whereas the pattern for the higher TA group is derived from the combination of both parasympathetic and inhibitory sympathetic systems. Fig. 3.7 also compares the saline regression patterns for the far task and the higher TA group again tend to have a more negative response pattern than the lower group. This negative shift was not, however, modified by timolol (see Fig. 3.6).

Table 1 demonstrates the efficacy of timolol as an ocular hypotensive agent. The reductions in IOP did not correlate with any of the changes in accommodative state induced by timolol.

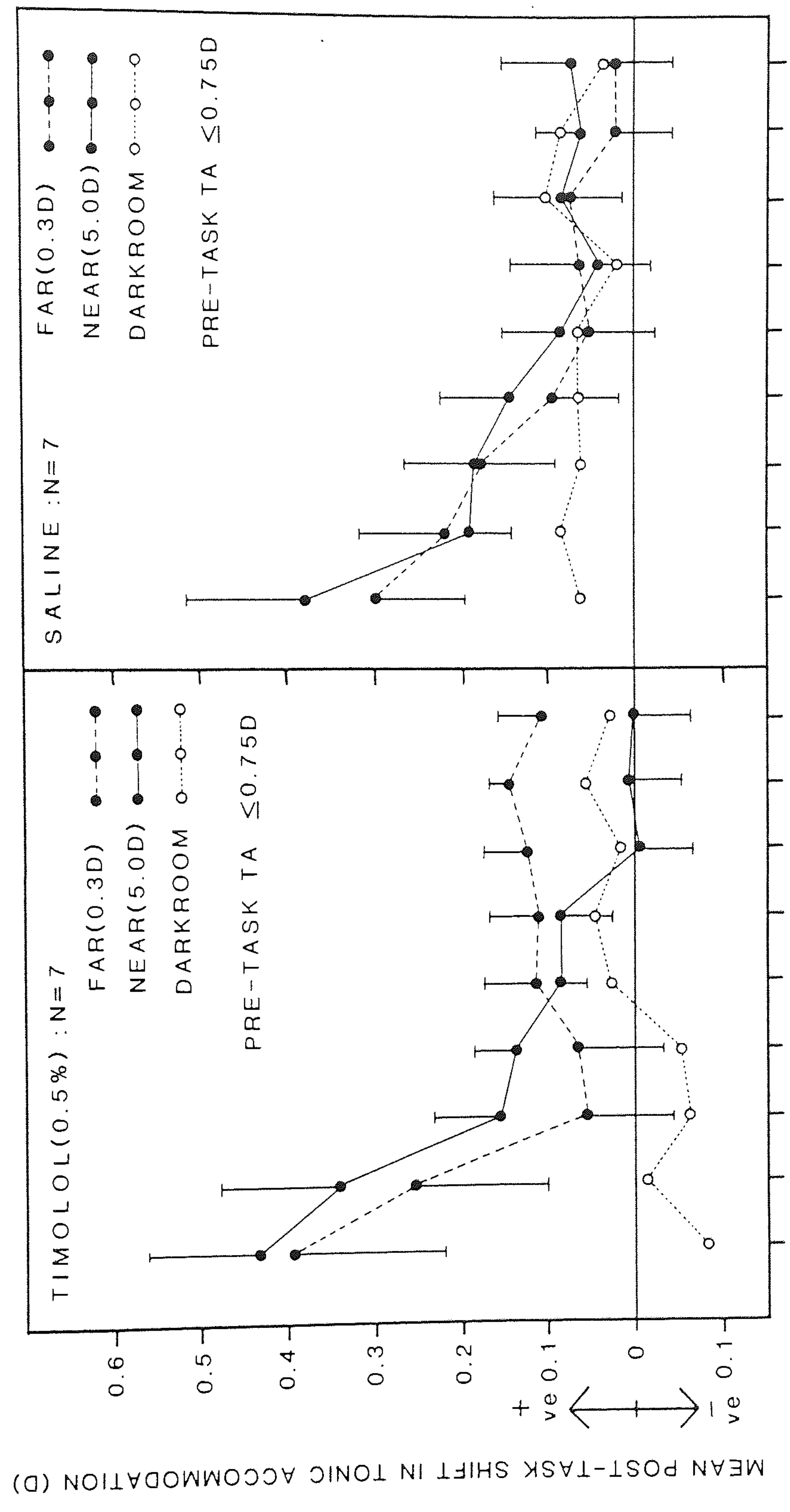


FIG. 3.5. - Mean post-task dioptric shift in tonic accommodation (TA) against time for each experimental condition and for the group of 7 subjects having pre-task TA levels ≤ 0.75 D. Error bars represent one standard error of the mean.

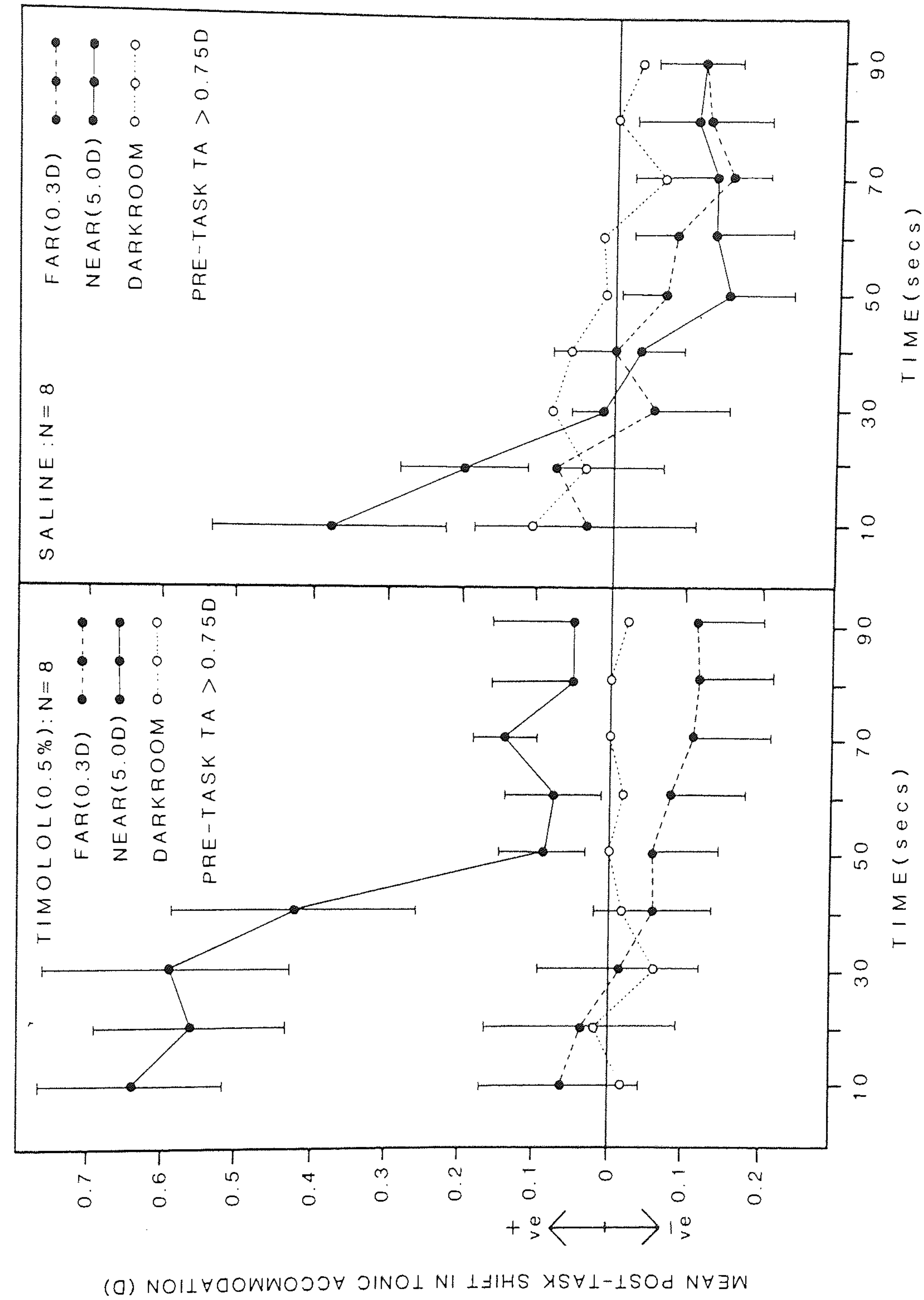


FIG. 3.6 - Mean post-task dioptric shift in tonic accommodation (TA) against time for each experimental condition and for the group of 8 subjects having pre-task TA levels > 0.75 D. Error bars represent one standard error of the mean.

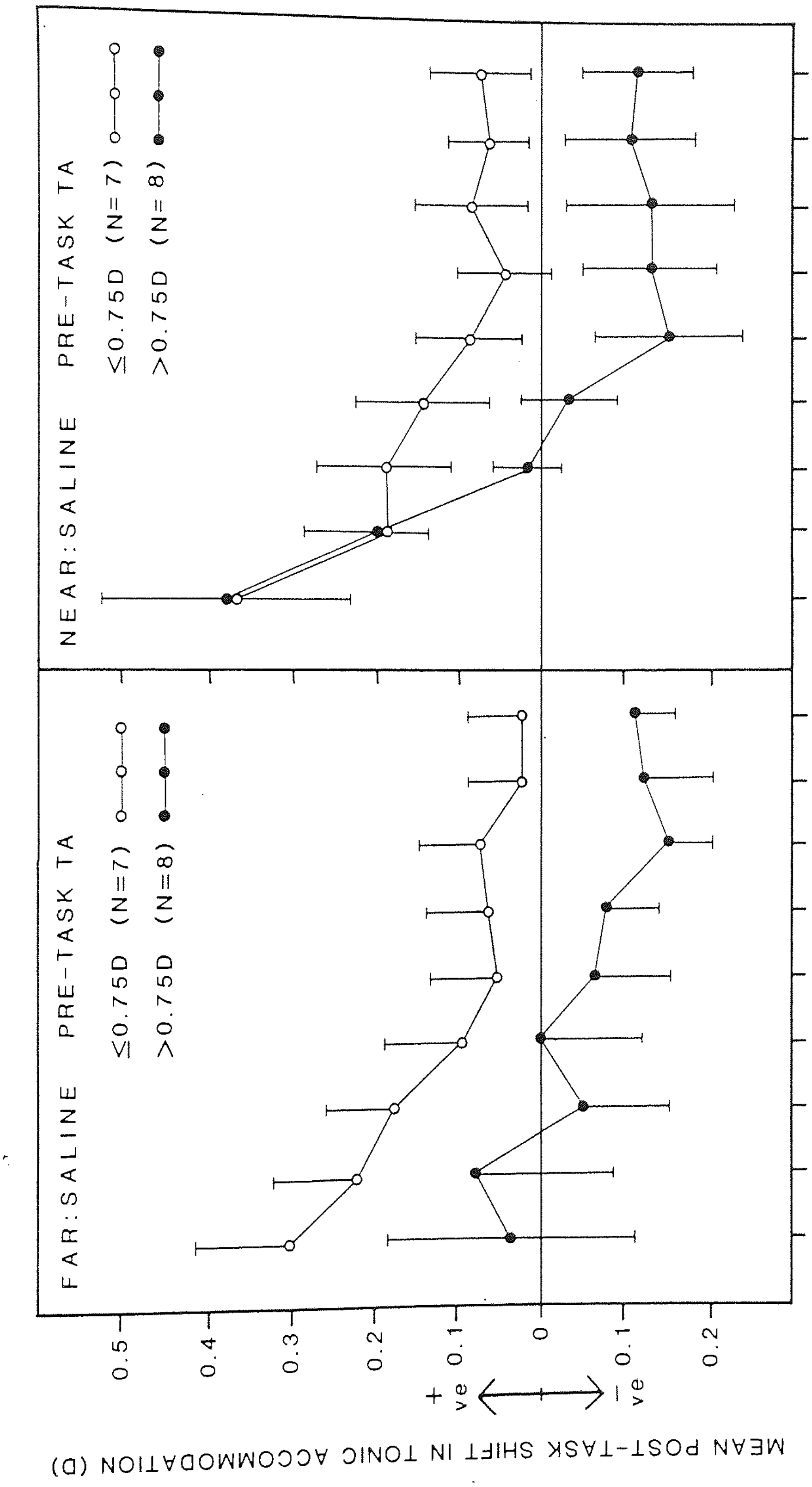


FIG. 3.7. - Mean post-task dioptric shift in tonic accommodation (TA) against time for the saline condition. Data is illustrated for far and near tasks only and compares regression patterns for the group of 8 subjects having pre-task TA levels > 0.75 D with the group of 7 subjects having pre-task TA levels ≤ 0.75D. Error bars represent one standard error of the mean.

3.3A - Statistical Analyses

Four- factor analyses of variance [i.e. drug, task (far vs. near), time and subject] were carried out on the post-task shifts in TA illustrated in Fig. 3.3, 3.5 and 3.6). F-ratios for main treatment effects and second-order interactions were computed using denominators that took account of the interactive effects with respect to subjects. For example, F-ratios for drug effects would be calculated by dividing the mean square for drug by the mean square for the drug/subject interaction (Willemsen, 1974). Analyses for all 15 subjects over the full 90 second period only indicated significant effects for time ($F = 12.97$; $p < 0.001$; df = 8, 504) and subjects ($F = 26.79$; $p < 0.001$; df = 14, 504). It is clear, however, from the graphical representation of the data that the group of 8 subjects having higher pre-task TA levels are more susceptible to drug and task effects and furthermore that the effects occur mainly over the initial 50 seconds. Taking this into account, analyses for the higher TA group show significant effects for drug ($F = 7.21$; $p = 0.033$; df = 1, 140), task ($F = 8.24$; $p = 0.023$; df = 1, 140), time ($F = 4.84$; $p = 0.004$; df = 4, 140) and subject ($F = 16.96$; $p < 0.001$; df = 7, 140). Drug/task interactions and task/time interactions were also significant ($F = 6.25$; $p = 0.04$; df = 1, 140 and $F = 5.08$; $p = 0.003$; df = 4, 140 respectively). For the lower TA group only time ($F = 6.51$; $p = 0.001$; df = 4, 120) and subject ($F = 38.13$; $p < 0.001$; df = 6, 120) factors were significant.

3.4 - DISCUSSION

The results of the present study clearly demonstrate that beta receptor antagonism significantly modifies the pattern of regression of TA towards the initial values following a near vision task. The influence of timolol is limited, however, to individuals with pre-task TA levels greater than 0.75 D. Beta receptor antagonism failed to modify regression patterns for the far task or for the darkrooom control. This demonstrates that sympathetic innervation of the ciliary muscle is manifest when substantial levels of parasympathetic activity are required.

An extensive range of exogenous stimuli can contribute to parasympathetic activity and all subjects demonstrated similar levels of accommodative response for the near-task. It is unlikely that sympathetic activity is derived from the same source since only certain subjects were shown to be susceptible to beta antagonism. The data illustrated in Fig. 3.4 suggests that an inhibitory sympathetic facility is derived from an endogenous souce i.e. TA, and that this facility increases with increasing levels of pre-task TA. Furthermore, Fig. 3.6 indicates that this inhibitory facility is augmented by relatively high levels of concurrent parasympathetic activity.

It should be noted that timolol had little effect on TA for the darkroom control condition. This disagrees with a previous study (Gilmartin *et al.*, 1984) which demonstrated that timolol induces an average myopic shift of +0.85 D in TA. An important methodological difference between the studies is that Gilmartin and co-workers employed a subjective laser optometer whereas the present study utilised infra-red optometry.

In order to be consistent with the results of the present study the laser optometer study would have to satisfy several conditions. First, that all subjects had relatively high pre-drug tonic levels; this was the case as all had tonic values greater than +0.65 D and the group mean was also high at +1.66 D. Second, that the myopic shifts found would be positively correlated with pre-drug tonic accommodation; this relationship was also demonstrated (see Fig. 3.1). Finally, laser optometry would have to instigate a significant level of accommodation response. A recent study (Post *et al.*, 1985) demonstrated that the observational demands of the laser optometer can influence TA. It was concluded that "effort to see" laser speckle motion can significantly effect TA measures.

The present study demonstrates that sympathetic innervation of the ciliary muscle is only manifest during near-vision when the mean accommodative response was 4.43 D. It is improbable that laser techniques would stimulate accommodation to levels approaching this value. It is feasible, however, that the short laser speckle presentation time adopted by Gilmartin *et al.* (1984) would enhance parasympathetic activity sufficiently to augment sympathetic inhibition.

The vergence system will, like accommodation, demonstrate adaptive changes following a sustained visual task. Krishnan and Stark (1977) suggest that under "open-loop" conditions, vergence regression patterns have time courses of around 16 seconds. It is possible, therefore, that some interference occurs with accommodation regression patterns. It is unlikely however that the infuence of such interference is significant since it is well established that accommodation and vergence are not correlated and regress independantly under darkroom conditions (Fincham, 1962; Owens and Leibowitz, 1980; Kotulak and Schor, 1986; Owens and Wolf-Kelly, 1987). Furthermore Gilmartin *et al.* (1984) demonstrated that timolol has no significant effect on tonic vergence.

It is also possible that the synkinetic link between accommodation and vergence will be altered by beta-adrenergic antagonism, resulting in an altered AC/A ratio. If dual innervation contributes to the accommodative response, then elimination of sympathetic inhibition with timolol will reduce the parasympathetic input required to maintain the same level of accommodative response. A concomitant reduction in accommodative convergence will occur as demonstrated in studies by Stephens (1985) and Rosenfield and Gilmartin (1987a). Fincham and Walton (1957) proposed that the accommodative response at near is determined by the vergence requirements of the stimulus. It may be more relevant, therefore to consider the effect of beta-adrenergic antagonism on convergence accommodation.

Ebenholtz (1983) suggested that excessive tonic adaptation (or accommodative "hysteresis") may be a precursor for induced myopia. Furthermore, Gilmartin and

Hogan (1985a) suggested that the sympathetic input to the ciliary muscle may serve to attenuate myopic shifts in TA. The results of the present study would predict that individuals with low levels of TA would be more susceptible to accommodative hysteresis since they do not have access to an inhibitory sympathetic facility. A further prediction is that induced myopes would have lower values of TA than emmetropes (see chapter 5 pps. 141-149).

It is interesting to speculate as to the effect of the application of timolol over an extended period, as in chronic simple glaucoma, on a subject's refractive state. To date, no consistent changes in accommodative or refractive state have been reported although, of course, the majority of patients receiving treatment for glaucoma would be post-presbyopic. Van Buskirk (1980) used data from the U.S. National Registry, and reports 547 cases of adverse effects associated with topical timolol therapy. Visual disturbance was indicated in 52 of the reports, 7 of which noted myopia of between 1.5 and 3.0 D. Van Buskirk (1980) reported that the myopia reversed on discontinuation of the drug.

A further study suggests that long-term timolol therapy can result in myopic shifts in refraction (Lutjen-Drecoll and Kaufman, 1986a; 1986b). Cynomologus monkeys were treated twice daily in one eye with timolol (180μl) or epinephrine (540-600μl) for around a 6 month period. The timolol treated animals (N = 6) were found to be significantly more myopic, by approximately 2.0 D, than the epinephrine treated (N = 2) or the control animals (N = 11). Lutjen-Drecoll and Kaufman suggest that the increase in myopia could be mediated solely by ciliary muscle beta-adrenergic blockade but could also be consistent with pathophysiological changes in the trabecular meshwork and ciliary muscle.

The present study suggests that the properties of autonomic control of accommodation prevailing during sustained near-vision influence the degree of tonic adaptation that takes place. The proposal that excessive tonic adaptation may act as a precursor to induced myopia is at present conjecture. Certain aspects of the adptation process, however, require further investigation. Previous research has demonstrated that the imposition of mental effort can influence accommodation (Kruger, 1980; Malmstrom *et al.*, 1980; Post *et al.*, 1985; Gawron *et al.*, 1985). It is possible, therefore, that the mental effort associated with a sustained visual task is a component of tonic adaptation. Furthermore, there is a marked discrepancy between the lack of effect of timolol on darkroom control data in the present study and the positive shift of +0.85 D found by Gilmartin *et al.* (1984) using the laser optometer. It is feasible that the mental effort associated with laser speckle judgement enhances the influence of sympathetic innervation on TA. The following chapter, therefore, examines the relationship between ciliary muscle innervation and mental effort.

The results of this study have been published in *Clinical Vision Sciences*, see Appendix X.6.

CHAPTER 4

MENTAL EFFORT, TONIC ACCOMMODATION AND CILIARY MUSCLE INNERVATION

4.1 - INTRODUCTION

The influence of psychological factors on the accommodative response has been investigated by several previous workers (see section 1.3E pps. 36-39). Specific attention has been directed by some investigators towards the relationship between cognitive demand and the accommodative response (Kruger, 1980; Malmstrom *et al.*, 1980; Malmstrom and Randle, 1984; Post *et al.*, 1985; Gawron *et al.*, 1985). The existing experimental evidence appears, however, to be contradictory. Kruger (1980) found that when 20 subjects changed from passive reading of a series of two-digit numbers at 40 cm to adding the numbers the level of accommodation increased by a mean of 0.28 D. Conversely, Malmstrom *et al.* (1980) demonstrated that a written backward-counting task could induce hyperopic shifts of 0.25-0.75 D from a 3 D target stimulus. Malmstrom and his co-workers could not demonstrate significant shifts for a 0 D stimulus (optical infinity) nor under "open-loop" conditions (analogous to empty-field).

In the absence of an adequate visual stimulus, such as being in a darkroom or an empty-field, accommodation adopts an intermediate resting position (Leibowitz and Owens, 1978). This myopic shift may be appropriately described as "tonic accommodation" (TA) although the terms "dark-focus" or "resting-focus" are also frequently used. A recent study by Post *et al.* (1985) showed that a mental arithmetic task could produce significant changes in TA although large differences existed between subjects, an observation previously made by Malmstrom *et al.* (1980). No investigation has been made, however, into the relationship between such cognitive induced shifts in TA and the initial resting state of the subject.

There is now considerable evidence that the ciliary muscle receives a small inhibitory input from the sympathetic nervous system and that this input is mediated by inhibitory beta receptors (see section 1.3 pps. 30-41), although the evidence for a predominant parasympathetic control of accommodation is unequivocal. Malmstrom *et al.* (1980) have suggested that cognitive induced shifts in accommodation may be caused by changes in the autonomic balance due to psychological stress. This theory is examined further by Birnbaum (1985) who suggests that mental activity may produce an increase in sympathetic input to the ciliary muscle thereby producing a hyperopic shift in accommodation.

This study utilizes the relative stability of TA (see section 1.5C pps. 49-50) to investigate:

(i) the magnitude and direction of changes in accommodative response induced by tasks requiring high and low levels of mental effort.

(ii) the relationship between cognitive induced shifts in TA and pre-task TA levels.

(iii) the role of sympathetic innervation of the ciliary muscle with respect to cognitive induced shifts in TA.

The latter aspect may be examined by the topical use of the non-selective beta receptor antagonist timolol maleate. Previous laser optometer studies have shown that such a technique is an effective method of blocking sympathetic innervation of the ciliary muscle (Gilmartin *et al.*, 1984; Gilmartin and Hogan, 1985b). A further important methodological feature of the present study is the measurement of TA using an objective infra-red optometer. Several previous studies have assessed psychologically induced variations in TA using the subjective laser optometer (e.g. Miller and Lebeau, 1982). Post *et al.* (1985) have shown, however, that the observational demands of the laser optometer may influence estimates of TA.

4.2 - METHOD

Subjects took part in two experimental sessions and the group consisted of 20 male volunteers, all of whom were aged between 19 and 30 (mean age = 20.4 years). Subjects had refractive errors between -0.25 and +0.62 dioptres best sphere (with less than 0.50 dioptres of astigmatism) which were determined by distance subjective refraction prior to the experiment. All subjects could achieve uncorrected visual acuities of 6/5 or better in both eyes and had normal binocular vision. Refractive corrections were not worn during the experiment but each individuals results were corrected for his refractive error. Measurements of accommodation were made using the Canon R-1 autorefractor. All readings in this study were taken monocularly from the left eye.

A double-blind protocol was employed between timolol maleate (0.5%) and normal saline and is summarised in Fig. 4.1. Subjects were placed in total darkness for 10 minutes prior to any data being recorded in order to reduce the effect of any pre-experimental influences on tonic accommodation (Ebenholtz, 1983; Schor *et al.*, 1984). Following this "wash-out" period a series of ten measurements of TA were made every minute for five minutes thus producing 50 readings which were later averaged (TA1). The baseline series of measurements was followed by two instillations of the drug separated by ten minutes (at T = 15 min and T = 25 min). The instillations were made using a precision micro-pipette such that each instillation comprised 25 µl drops of drug (i.e. total amount per eye = 50µl).

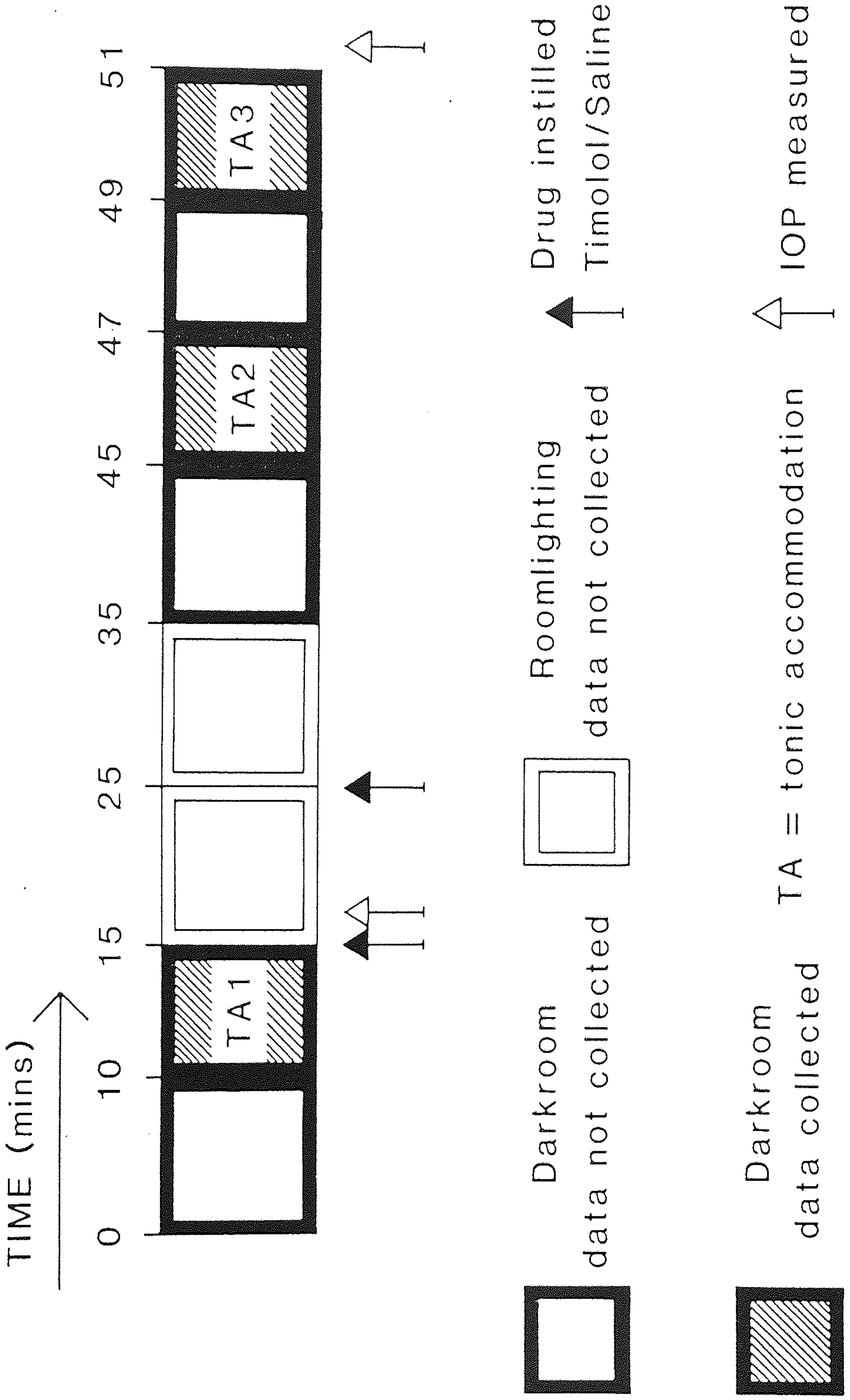


FIG. 4.1. - Schematic diagram of the experimental procedure.

Twenty minutes after the initial drug instillation the subject was placed in total darkness for a further ten minutes to minimise extraneous influences on TA. This was followed by two further sets of measurements of TA both consisting of two minutes of continuous infra-red optometer readings (each yielding some 100 TA estimates). The first set of measurements (TA2) was taken while the subject was listening to a tape of popular music through a set of stereo headphones. The purpose of the music was to mentally relax the subject as much as possible. After a further two minutes the music was terminated and the subject was verbally presented with a three figure number and was instructed to count backwards in sevens while the final set of TA readings were taken (TA3). The backwards counting task was chosen for its high degree of difficulty and has been previously employed by Post *et al.* (1985). The subject was previously instructed to count to himself and to keep his head and eyes still. Subjects were also informed that they would be asked to tell the experimenter the number they had reached after the two minute measurment period. These instructions encouraged consistent task performance and counting speeds could be later examined.

Intraocular pressures were measured at the beginning and end of each experimental session, using a Perkins hand-held tonometer, in order to monitor the well known ocular hypotensive effects of timolol. Two drops per eye of 0.4% Benoxinate were used to produce topical anaesthesia. The timolol and saline trials were separated by 2 days to 4 weeks (mean separation = 11 days).

The two minute measurement periods employed are longer than those used by previous workers. The extended sampling time was adopted for two reasons. First, in order that the influence of short term variations in TA may be reduced (Johnson *et al.*, 1984) and secondly so that the latency and time course of any cognitive induced shifts in TA could be examined.

4.3 - RESULTS

The mean tonic accommodation (TA) values for each experimental condition are given in Table 4.1. It can be seen that the mean post drug TA (TA2) is very similar to the initial TA value (TA1) showing that neither saline nor timolol has a significant effect on TA prior to the task. The difference between these two values (TA2 - TA1) is designated drug induced shift (D.I.S.); similiarly the difference between TA2 and TA3 will be referred to as the cognitive induced shift (C.I.S.). Mean values for counting task speeds, initial intraocular pressure (IOP) and change in IOP during the experiment are also shown in Table 4.1. Initial TA measures for the saline and timolol trials were compared and found to be well correlated ($r = .85$, $p < .001$) indicating that TA is reasonably stable over an extended period of time. The three mean TA values (TA1, TA2 and TA3) for each trial are shown in histogram form in Fig. 4.2.

TABLE 4.1. - Mean tonic accommodation values for each experimental condition. Mean values for the drug induced shift (D.I.S.) and and the cognitive induced shift (C.I.S.) are also shown. Mean values for counting speed (per 2 min session), initial intraocular pressure (IOP) and change in IOP are also given. Figures in brackets represent standard deviations.

MEAN	SALINE		TIMOLOL	
TA1 (D)	1.00	(0.57)	1.02	(0.49)
TA2 (D)	1.00	(0.54)	0.98	(0.46)
TA3 (D)	1.14	(0.56)	1.19	(0.55)
D.I.S. (D)	0.00	(0.13)	-0.03	(0.16)
C.I.S. (D)	0.15	(0.33)	0.21	(0.35)
COUNTING SPEED	210	(65)	221	(55)
INITIAL IOP (mmHg)	13.2	(1.54)	13.8	(1.96)
Δ IOP (mmHg)	-0.2	(0.98)	-2.5	(1.30)

Table 4.1 shows that cognitive induced shifts in TA were very similar for both saline and

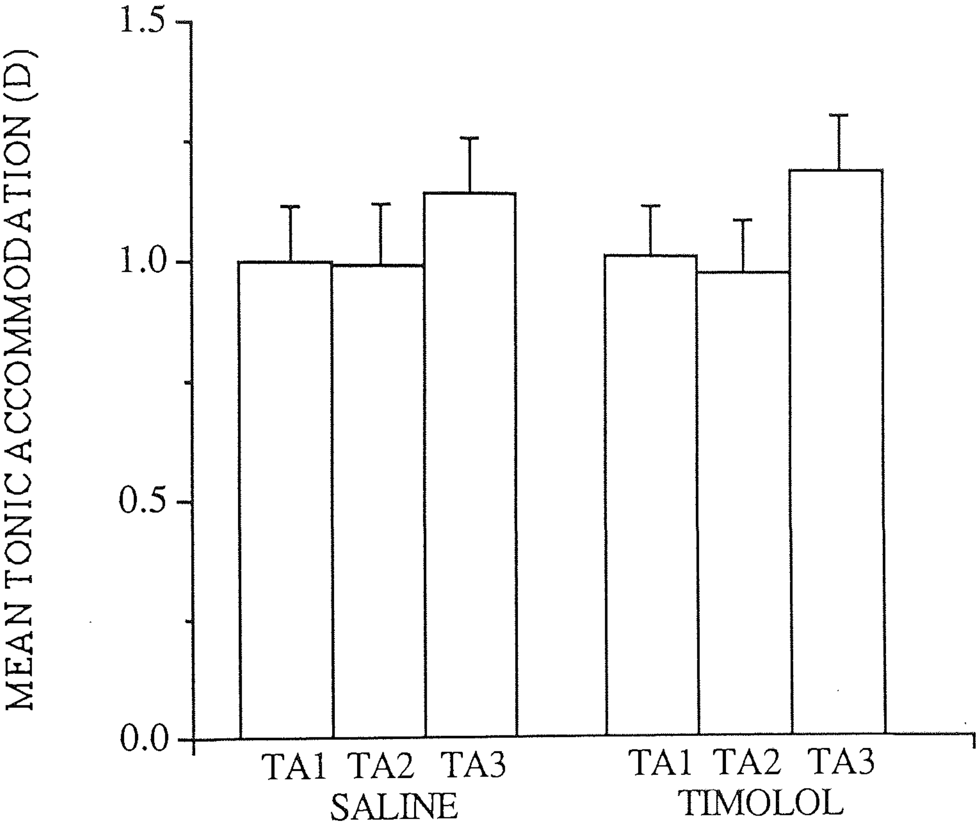


FIG. 4.2. - Mean TA values for each experimental condition. TA1, initial TA; TA2, post-drug TA ; TA3, post-drug TA + counting task.

timolol (saline mean = .15D, timolol mean = .21D, t = 1.25, p = .22). If the cognitive induced shift for the timolol trial is plotted against that for the saline trial (Fig. 4.3) a good correlation is found (r = .79, p < .001). In view of the non-significant effect of sympathetic blockade this can be taken as a measure of the reproducibility of the data.

The relationship between initial TA and cognitive induced shifts in TA found in the saline trial is illustrated in Fig. 4.4. Statistical analysis reveals poor correlation (r = -.19, p = .59), and indeed no clear relationship is apparent. A similarly unimpressive relationship was found between counting speed and cognitive induced TA shift (r = .09, p = .71). Inspection of the mean data for those subjects showing positive cognitive induced shifts in TA greater than 0.2 D (N = 8) revealed that the change in resting state was immediate, some 80% of the mean shift occurring in the first 10 seconds of the measurement period.

4.4 - DISCUSSION

It would appear from Fig. 4.2 that no clear relationship exists between a subject's initial TA and the accommodative shift induced by cognitive demand. As variations in TA across the population have been shown to be due to variations in parasympathetic ciliary muscle innervation (Gilmartin and Hogan, 1985b) and as previous investigations have suggested that subjects with higher levels of TA are more susceptible to psychologically induced accommodative changes (Miller, 1978b) it might have been expected that subjects with higher initial TA values would exhibit greater cognitive induced shifts. Miller and LeBeau (1982) found that the presence of stress caused TA to increase and suggest that such an effect is essentially cholinergic and the results of the present study would support this hypothesis.

It would be useful at this point to consider certain aspects of ciliary muscle innervation. The control of ciliary smooth muscle contraction and relaxation is predominantly

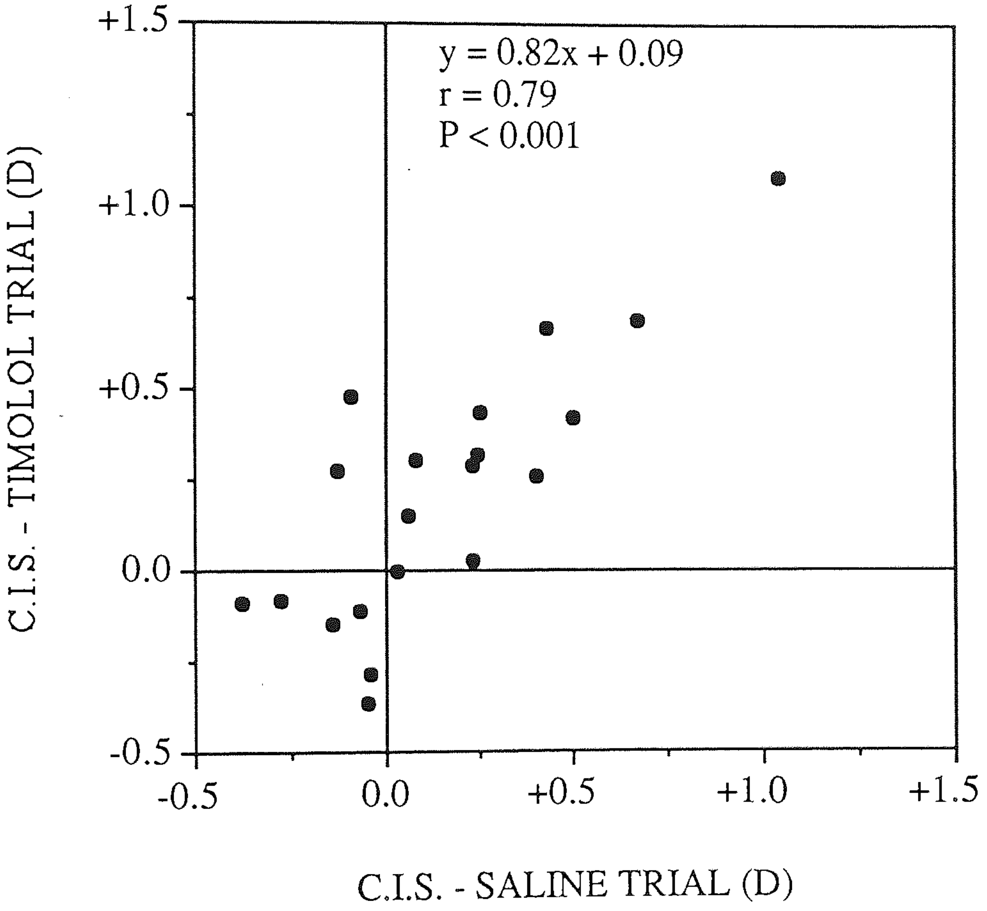


FIG. 4.3. - The relationship between cognitive induced shifts in TA (C.I.S.) for the saline and timolol trials.

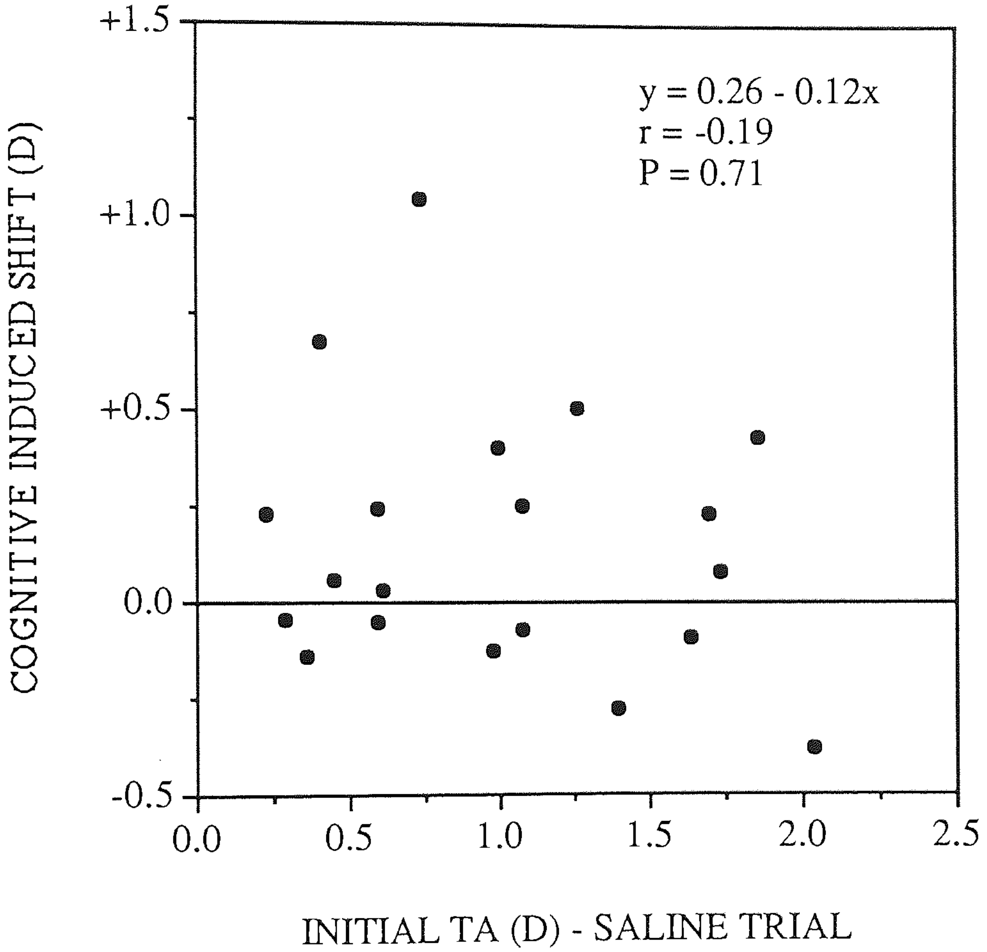


FIG. 4.4. - The relationship between initial TA and cognitive induced shifts in TA for the saline trial.

cholinergic (parasympathetic) and the (adrenergic) sympathetic input appears to be much smaller. Physiological and pharmacological studies have shown that, at low levels of accommodation, neither sympathetic excitation nor inhibition has any significant effect on the accommodative response (Törnqvist, 1967; Hurwitz *et al.*, 1972a; Gilmartin, 1986). Hurwitz et al. (1972a) used electrical stimulation of the midbrain to induce positive accommodation in monkeys. They studied the effects of stimulating and blocking the ciliary muscle with subconjunctival injections of isoproterenol and propranolol respectively. They found that the inhibitory effects of their beta-stimulating drug were only significant for accommodation levels greater than 4 dioptres. It would appear, therefore, that for the sympathetic system to have any effect on accommodation there must exist a significant background parasympathetic smooth muscle tone.

It is traditionally assumed that the effect of stress on the general autonomic nervous system is an enhanced sympathetic response. The accommodative changes found in this study, however, suggest an increase in parasympathetic innervation. Miller and LeBeau (1982) propose that this effect may be accounted for by Porge's "two-component model of attention" which suggests that both sympathetic and parasympathetic excitation may occur (Porges, 1976). The results of the present study may be explained by the nature of the physiological response to stress which suggests that both sympathetic and parasympathetic excitation may occur (see section 1.3E pps. 36-39). If dual excitation occurs, what would be the expected effect on TA? For low TA values the sympathetic effect would be neglible and hence a parasympathetic induced shift would be produced. For medium values of TA a similar shift would be observed, perhaps enhanced by the higher parasympathetic resting tone. For relatively high TA values a different effect might occur; the same increase in parasympathetic tone may be present but the myopic shift might be attenuated by a significant sympathetic input thus producing a reduced mean change in TA. This theory may be tested by dividing the 20 subjects up into three approximately equal groups (low, medium and high TA) based on the initial TA value from the saline trial. The distribution of the three groups is given in Table 4.2. The mean cognitive induced TA shifts are shown in Fig. 4.5 for each of these three groups. For the saline trial the mean myopic shift is significantly lower for the high TA group. If this is the effect of sympathetic attenuation then adrenergic blockade should enhance the shift for this group and this effect is shown in Fig. 4.5. This sympathetic attenuation may be observed further by plotting the difference in cognitive induced TA shifts (timolol trial minus saline trial) against initial TA (see Fig.4.6) and a reasonable correlation was found.

TABLE 4.2 - Mean and standard deviation tonic accommodation values for the three groups (high, medium and low TA) based on the pre-task TA value (TA1) for the saline trial

GROUP	LOW	MEDIUM	HIGH
SIZE	7	7	6
MEAN (D)	0.41	0.96	1.72
S.D. (D)	0.13	0.20	0.20

One discrepancy between this study and previous work which should be examined is the effect of timolol on TA. Previous studies utilising laser optometry found that the timolol produced significant myopic shifts in TA of the order of 0.85D 45 minutes after instillation (Gilmartin *et al.*, 1984). As can be seen from Fig. 4.2 no significant shift was found in this study, a finding consistent with the results reported in the previous chapter. Figs. 4.5 and 4.6 provide some evidence for sympathetic innervation to the ciliary muscle and demonstrate that this input may attenuate parasympathetically mediated cognitive induced shifts in TA. It would appear, however, that this inhibitory facility is restricted to those individuals with relatively high levels of TA, thus supporting the results of chapter 3.

It remains unclear as to why certain subjects demonstrate significant shifts in TA while others remain unaffected, although the initial TA level may influence the amount of shift produced. As previously mentioned, no correlation was found between counting speed

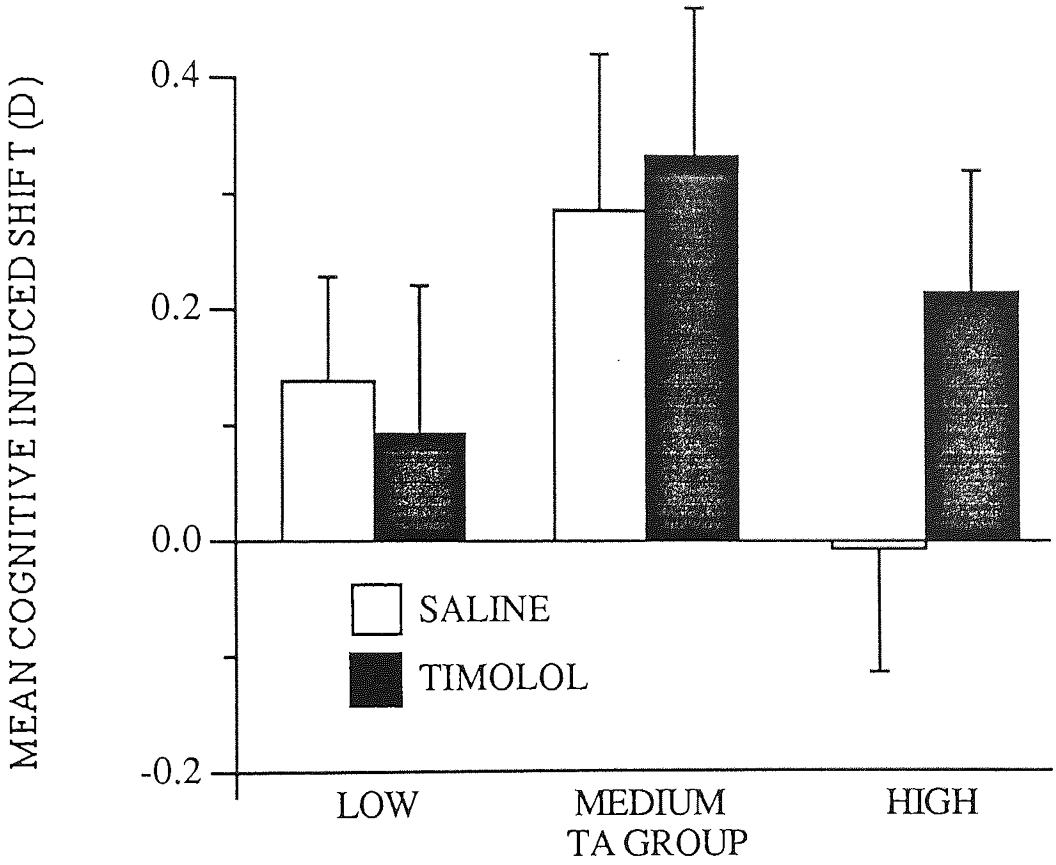


FIG. 4.5. - Mean cognitive induced shifts in TA for the saline trial (light bars) and timolol trial (dark bars) for three TA groups (low, medium and high).

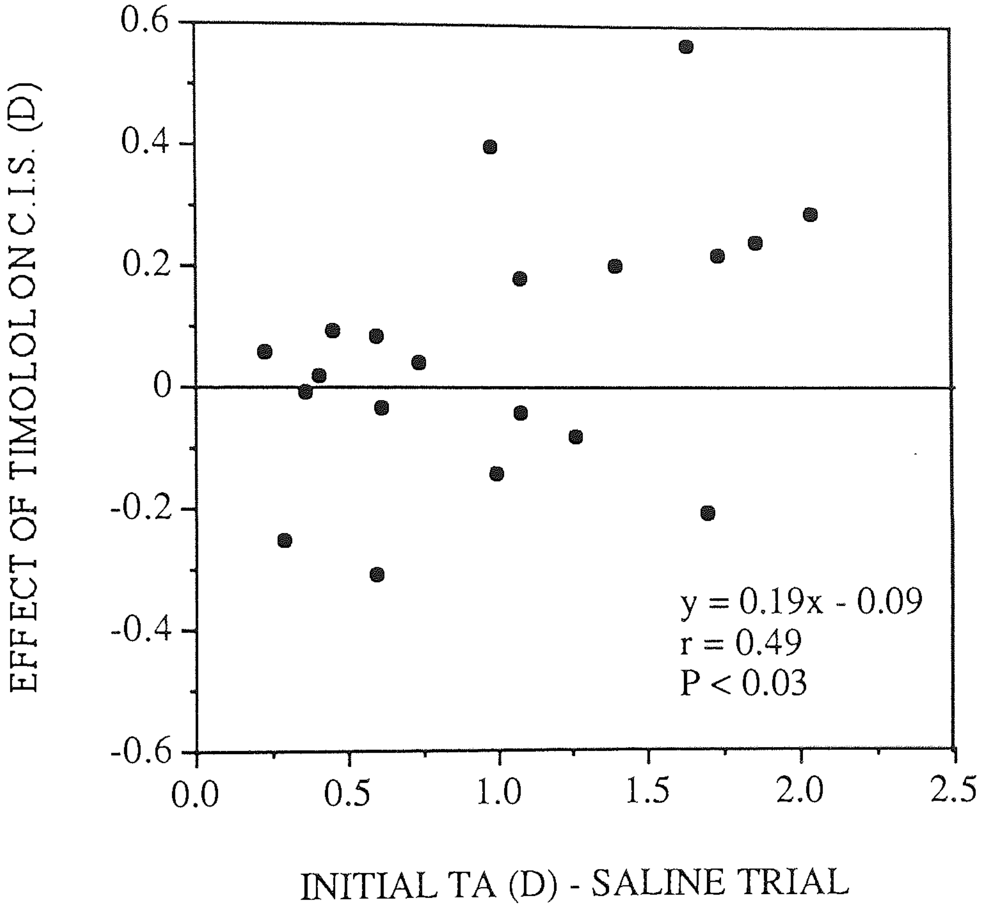


FIG. 4.6. - Effect of timolol on the cognitive induced shift in TA (timolol trial shift minus saline trial shift) as a function of initial TA (saline trial).

and cognitive induced shift although it is possible that certain individuals found the task more stressful than others. It is interesting to note that the largest cognitive induced shift was found in the most myopic subject in the experimental group. The following chapter compares the cognitive induced TA shifts for myopes with those for emmetropes; this is of interest because psychological differences between different refractive groups have been previously reported (Young *et al.*, 1976; Gawron, 1981). Recently attention has been directed towards short term changes in TA induced by sustained visual tasks at distance and near (see section 1.5D pps. 50-55). This study indicates that cognitive demand may be a component of task-induced changes in TA.

The results of this study have been published in *The American Journal of Optometry and Physiological Optics*, see Appendix X.7.

CHAPTER 5

MENTAL EFFORT AND TONIC ACCOMMODATION IN EMMETROPIA AND LATE-ONSET MYOPIA

5.1 - INTRODUCTION

The work reported in the previous chapter established that the imposition of mental effort can induce predominantly positive changes in tonic accommodation (TA) which are largely the result of an increase in parasympathetic innervation to the ciliary muscle. It was also suggested that cognitive induced shifts in TA may be a component of the adaptation of TA. A further observation made in the study was that the largest cognitive induced shift was found in the most myopic subject, although all the subjects participating in the study were essentially emmetropic. Furthermore, certain workers have suggested that significant differences exist in the mean TA values for various refractive groups (Maddock *et al.*, 1981; Charman, 1982; McBrien and Millodot, 1987). It was decided, therefore, to investigate the interaction of mental effort and TA in the myopic and emmetropic populations.

The evidence for environmental and genetic influences in the development of myopia has been reviewed earlier (see section 1.7 pps. 61-71). It was decided to investigate those subjects who had developed myopia after the age of 15 years, who may be referred to as 'late-onset myopes'. The reasons for restricting the selection of subjects to this portion of the population were fourfold:

1. The majority of workers have demonstrated that myopia which develops during childhood stabilises at around 15 years of age (Slataper, 1950; Hirsch, 1963; Goss and Winkler, 1983) although

Saunders (1986) has shown that myopia progression may continue to much greater ages in a small but significant minority of the population.

2. Certain authors have proposed that myopia which develops later in life is associated with environmental factors and may also be termed induced myopia (Goldschmidt, 1968; Stevenson, 1984).

3. Since the subjects for the present study (and indeed subsequent studies) were to be taken from the student population it was felt appropriate to choose subjects whose myopia had developed as recently as possible.

4. Patients who, in general optometric practice, demonstrate myopic changes in refraction in their late-teens and early twenties frequently associate their myopia with a large amount of near-work, e.g. VDU usage.

It would be inappropriate, however, to suggest that the aetiology of myopia which is late in onset precludes genetic factors. It is clear that a proportion of late-onset myopes may represent a sample of myopia which is essentially genetic in nature. Furthermore there may be a genetically determined predisposition to induced myopia.

Psychological differences appear to exist between emmetropes and myopes (Young *et al.*, 1976; Baldwin, 1981; Gawron, 1981). Young *et al.* (1976) proposed that personality characteristics may play a role in the development of myopia. Furthermore, Van Alphen (1961) suggested that stress, emotion or extreme autonomic endowment might interfere with the emmetropization mechanism and that the stress associated with studying for exams may be responsible for the development of 'school myopia' (see section 1.7D pps. 68-70).Van Alphen proposed that the psycho-visual consequences of sustained near vision that requires learning (e.g. studying for college examinations) were different from that of a more leisurely nature (e.g. crafts such as needlework). The former task appears to induce myopia whereas the latter does not. Van Alphen suggested that learning situations can involve substantial levels of stress and anxiety which may trigger myopic changes.

This study was undertaken, therefore, to compare TA for emmetropes and late-onset myopes. A further comparison was made of the effect of mental effort on these resting positions in order to elucidate further the mechanisms underlying the adaptation of accommodation and the development of induced myopia.

5.2 - METHOD

Subjects consisted of two age matched refractive groups, namely emmetropes and myopes, each comprised 15 male optometry students, aged between 19 and 26 (mean age = 21.3 years). The emmetropic group had refractive errors between plano and +0.50 dioptres best sphere (mean = +0.16 D) with no more than 0.50 dioptres of astigmatism. All myopes participating in the experiment had developed myopia at the age of 15 or above, the mean age of onset being 16.7 years (s.d. = 1.8 years). The myopic subjects had refractive errors between -0.50 and -3.50 dioptres best sphere (mean = -1.90 D) with not more than 0.50 dioptres of astigmatism. Subjects' refractive errors were determined prior to the experiment by distance subjective refraction and, when corrected, each subject could achieve 6/5 visual acuity. Refractive corrections were not worn during the experiment but all measures of accommodation were corrected for each subjects refractive error. Accommodation was measured using the Canon R-1 autorefractor. All readings in the present study were taken from the left eye.

Subjects were placed in darkness for the entire experiment and TA measured under two conditions: a passive condition (TA1) and an active condition (TA2). The experimental session commenced with 10 minutes *in situ* on the optometer in order to eliminate pre-experimental influences on TA. Following this period any necessary adjustments in alignment were made and the subject encouraged to relax as much as possible. Two minutes of successive readings were then taken, yielding some 100 values which were averaged (TA1). Following a two-minute break the subject was verbally presented with a three digit number and instructed to count backwards in sevens for an additional two minute period during which a further 100 accommodation measurements were taken (TA2). This active task has been employed previously to produce high levels of cognitive demand (Post *et al.*, 1985). Subjects had been briefed that during the experiment they were to count conscientiously to themselves and to keep their head and eyes still and open. Subjects were also asked to tell the experimenter the number they had reached at the end of the second measurement period in order to encourage consistent task performance and to assess variations in counting speed.

5.3 - RESULTS

Mean values of tonic accommodation (TA) were calculated for both the passive condition (TA1) and the active condition (TA2) for each subject. The mean values of TA1 and TA2 for each refractive group are given in Table 5.1. It can be seen that for the passive condition (TA1) there is a clear difference between the mean TA values for emmetropes (mean = 1.14 D, s.d. = 0.46 D) and myopes (mean = 0.81 D, s.d. = 0.46 D). This difference, however, has a relatively low level of statistical significance ($t = 2.00$, d.f. = 28, $p = 0.05$) and is significantly lower for the task condition (TA2).

The difference between the two values of TA was calculated for each subject, in order to examine the effect of the task on TA. This value (TA2 - TA1) is termed the cognitive induced accommodative shift. The mean values of these shifts for each refractive group are given in Table 1. The mean cognitive induced shift for myopes is significantly higher than that of the emmetropic group. (myopic mean = +0.35 D, s.d. = 0.31 D, emmetropic mean = +0.07 D, s.d. = 0.27 D, t = 2.57, d.f. = 28, p = 0.016). It is possible that the greater mean cognitive induced shift found for the myopic group is due to differences in the mean baseline TA values. An analysis of covariance was therefore carried out in order to equate the two groups for differences in mean baseline TA levels. The mean shift was still found to be significantly higher for myopes (F = 4.32, d.f. = 27, $p < 0.05$). Mean counting speeds were also calculated for each group. The emmetropes were found to count slightly faster than the myopes but not significantly so (emmetropic mean = 220 in two minutes, myopic mean = 186 in two minutes, t = 1.37, d.f. = 28, p =0.18).

TABLE 1. Mean tonic accommodation values for the passive condition (TA1) and the active condition (TA2) in the emmetropic group (N = 15) and the myopic group (N = 15). Mean cognitive induced shifts are also given for each group. All values given are in dioptres and figures in brackets represent standard deviations.

MEAN VALUES	**EMMETROPES**	**LATE-ONSET MYOPES**
PASSIVE CONDITION (TA1)	1.14 (0.46)	0.81 (0.46)
ACTIVE CONDITION (TA2)	1.21 (0.43)	1.16 (0.56)
COGNITIVE INDUCED SHIFT	0.07 (0.27)	0.35 (0.31)

5.4 - DISCUSSION

The results of this study show that under darkroom conditions involving minimal mental effort (TA1) there is a trend for late-onset myopes to have lower values of tonic accommodation (TA) than emmetropes. The imposition of a task requiring mental effort (reverse counting), however, induced a positive shift in TA for the myopic group which was significantly greater than that for the emmetropic group.

Previous studies have produced somewhat conflicting results with respect to the relationship between TA and refractive error. The most extensive study (N = 301) was that of Simonelli (1981) who found no clear relationship between TA and refractive error and similarly tenuous trends have been found in most other studies (Gawron, 1981; Heron *et al.*, 1981; Hogan and Gilmartin, 1983; Smith, 1983; Ramsdale, 1985). Maddock *et al.* (1981) are the only workers whose results suggest a clear relationship between TA and refraction, reporting similar trends to those of the present study. In addition they found that hyperopes have higher TA values than emmetropes. McBrien and Millodot (1987) also found that hyperopes (mean = 1.33 D) have higher values of TA than emmetropes (mean = 0.89 D). Their myopic subjects were divided into two groups depending on their age of onset; early-onset myopes whose myopia developed prior to 13 years of age and late-onset myopes who developed myopia after the age of 15. McBrien and Millodot found that early-onset myopes (mean = 0.92 D) had similar values of TA to emmetropes, whilst late-onset myopes (mean = 0.49 D) showed lower values of TA than both groups. McBrien and Millodot's finding that late-onset myopes have significantly lower values of TA than emmetropes supports the results of the present study.

The largely unconvincing results produced by previous workers may be partially explained by considering the measurement techniques used. Most of the previous studies have used subjective optometers, mainly the laser optometer devised by Hennessy and Leibowitz (1972). Post *et al.* (1985) have shown, however, that the observational demands of the laser optometer may influence estimates of TA. The present study utilised an objective infra-red optometer requiring minimal mental effort on the part of the subject. During the task condition (TA2), however, the subject is required to apply mental effort to the task and the difference between the two refractive groups virtually disappears. Hence it is feasible that the interactive nature of the laser optometer may influence the relationship between TA and refractive error. An alternative explanation may be that only late-onset myopes took part in the study whereas the majority of previous workers have not attempted to distinguish between myopia of genetic and environmental origin. McBrien and Millodot (1987) have demonstrated that late-onset myopes have significantly lower values of TA than early-onset myopes. It should also be noted that various authors apply different criteria for refractive groups, e.g. Maddock *et al.* (1981) described their emmetropic group as having refractive errors between -2.00 and +2.00 D whereas the emmetropes in the present study had refractive errors between plano and +0.50 D.

Van Alphen (1961) suggested that individuals with high levels of ciliary tone would be hyperopic, whereas low levels of cillary tone would be conducive to the development of myopia. The findings of the present study along, with other reports, would support this concept (Maddock *et al.*, 1981; McBrien and Millodot, 1987). Van Alphen also proposed that stress and anxiety may lead to a sympathetically mediated reduction in ciliary-choroidal tone which may result in the development of 'school myopia'. The results of the current study suggest, however, that the imposition of mental effort induces a significant increase in ciliary tone in the myopic group, a finding which is inconsistent with the above proposals of Van Alphen. It may be inappropriate to equate the mental effort or heightened attention, induced by the counting task employed in the present study, with the stress of studying for exams. It is apparent, however, that simple problem solving and mental arithmetic induce similar changes in physiological variables such as heart rate and pupil size as those produced by other stressful conditions (Hess and Polt, 1964; Libby *et al.*, 1973).

The present study has demonstrated that differences in TA exist between two refractive groups and this adds further evidence for the importance of ciliary muscle function in the development of induced myopia. The full importance of TA (and changes therein) in the development of induced myopia has yet to be established. Ebenholtz (1983) proposed that accommodative hysteresis, the changes in TA induced by a period of closework, may be a precursor to induced myopia. This would suggest that some late-onset myopes would be more susceptible to accommodative hysteresis. The fact that late-onset myopes have lower values of TA and are more susceptible to myopic shifts in TA induced by mental effort may render them more susceptible to accommodative hysteresis.

The cognitive induced shifts in TA found in this study were generally in a positive direction and similar to those reported in the previous chapter. Miller and Lebeau (1982) reported that the presence of stress caused an increase in TA and suggested that such an effect was cholinergically mediated. The study described in the previous chapter confirmed this hypothesis by demonstrating that shifts in TA induced by cognitive demand were largely the result of an increased parasympathetic input to the ciliary muscle. In the present study late-onset myopes showed a greater cognitive induced shift in TA than emmetropes and previous work would suggest that this increased shift in the late-onset myopes is the result of an enhanced parasympathetic response to the task. It is questionable, however, as to whether this enhanced response is due to differences in a myope's psychological response to the task or to physiological response variations. It may be that late-onset myopes have an enhanced facility of "near-imagery" which would produce an increased proximal response under the open-loop condititions. Previous workers have demonstrated the presence of psychological differences between refractive groups (Young *et al.*, 1976; Baldwin, 1981; Gawron, 1981). It is possible, therefore, that mental effort induces a different psychological reaction in myopes and emmetropes.

It has been suggested that the sympathetic input to the ciliary muscle serves to attenuate myopic shifts in TA (Gilmartin and Hogan, 1985a; Gilmartin, 1986) and it may be that myopes have an inadequate inhibitory facility. The work described in chapter 3 (pps. 107-125) suggests that an inhibitory sympathetic facility is derived from an endogenous source i.e. tonic accommodation, and that this facility increases with increasing levels of

TA. If, as found in the present study late-onset myopes have lower values of TA than emmetropes, it is possible that they do not have access to such an inhibitory facility. The study also demonstrated that an inhibitory sympathetic facility is augmented by relatively high levels of concurrent parasympathetic (i.e. accommodation) activity. It would, therefore, seem appropriate to examine the effects of mental effort on the accommodative response at various levels of stimulus vergence and this aspect is considered in chapter 6.

The results of this study have been published in *The American Journal of Optometry and Physiological Optics*, see Appendix X.11.

CHAPTER 6

THE INFLUENCE OF MENTAL EFFORT ON THE STEADY-STATE ACCOMMODATIVE RESPONSE

6.1 - THE ROLE OF THE SYMPATHETIC NERVOUS SYSTEM

6.1A - Introduction

The studies reported in chapters 4 and 5 have demonstrated that the imposition of mental effort can induce significant changes in a subject's tonic accommodation (TA). It has been demonstrated that these cognitive induced shifts are generally in a myopic direction. In addition the shifts are mediated predominantly by an increase in parasympathetic innervation of the ciliary muscle although the sympathetic input may serve to attenuate the shifts at higher levels of pre-task TA. Furthermore, it was shown that late-onset myopes are more susceptible to these shifts.

One problem associated with the assessment of cognitive induced changes in TA is that the pre-task TA levels are such that the level of baseline accommodative effort does not exceed 1.5 to 2.0 D. Previous studies would predict, however, that the sympathetic input to the ciliary muscle would have limited influence at such levels of accommodation (Törnqvist, 1966; 1967; Hurwitz *et al.*, 1972a). It would be appropriate, therefore, to examine the interaction of mental effort and the sympathetic input at higher levels of accommodative demand if the nature and role of this inhibitory input is to be understood further.

Several previous workers have examined the influence of mental effort on the accommodative response. Kruger (1980) showed that when 20 subjects changed from passive reading of two-digit numbers at 40 cm to adding the numbers there was a significant increase in mean accommodative response of 0.28 D. Malmstrom *et al.* (1980) demonstrated, however, that a written backward-counting task could produce a decrease in accommodative response of 0.25-0.75 D for a -3.00 D target. Malmstrom and his co-workers have suggested that cognitive induced shifts in accommodation are caused by changes in the autonomic balance of the subject. Furthermore Birnbaum (1984) postulates that, during a near visual task, mental activity may evoke an increase in sympathetic input to the ciliary muscle and hence produce a hyperopic shift in accommodation. Gawron *et al.* (1985) had difficulty in reproducing the results of Malmstrom *et al.* (1980) but reached similar conclusions.

The existing experimental evidence concerning mental effort and accommodation appears, therefore, to be contradictory. Certain authors have found that mental effort induces a decrease in accommodation (Malmstrom *et al.*, 1980; Gawron *et al.*, 1985) suggesting an increase in sympathetic innervation to the ciliary muscle (Birnbaum, 1984). Conversely, other studies have shown increases in accommodation associated with mental effort (Kruger, 1980) and probably due to an increase in parasympathetic innervation (see Chapter 4 pps. 126-140). It was decided, therefore, to investigate the influence of mental effort on the accommodative response to three stimulus vergences in emmetropes and, furthermore, examine the role of sympathetic innervation of the ciliary muscle with respect to each response by employing the non-selective beta receptor antagonist timolol maleate.

6.1B - Method

Twelve emmetropic male volunteers aged between 20 and 23 (mean age = 20.7 years) participated in two experimental sessions. Subjects had refractive errors between plano and +0.50 dioptres best sphere (with not more than 0.25 dioptres of astigmatism). All subjects could achieve visual acuities of 6/5 or better and had normal binocular vision. Refractive corrections were not worn during the experiment and values of accommodative response were not corrected for this factor. Measurements of accommodation were made using a modified Canon R-1 autorefractor. All readings in the present study were taken from the left eye only.

A double-blind protocol was employed between timolol maleate (0.5%) and normal saline. In order to monitor the well established ocular hypotensive effects of timolol intraocular pressures were measured at the beginning and end of each session using a Perkins hand-held applanation tonometer. Topical anaesthesia was achieved by the instillation of two drops per eye of 0.4% benoxinate. The instillation procedures for timolol and saline were the same. Each subject was given two instillations of the drug separated by a period of ten minutes. The instillations were made using a precision micro-pipette such that each instillation comprised 25μl of drug (i.e. total amount per eye = 50μl).

Measurements of accommodation commenced thirty minutes after initial drug instillation and were made for targets located at three stimulus vergences namely -1, -3 and -5 D. Targets consisted of a five by five matrix of black single-digit numbers on a white background (luminance = 25 cd/m^2). Targets were scaled for each stimulus distance such that the digits subtended 0.4 degrees at the eye and the total angular subtense of the matrix was 6.5 x 6.5 degrees.

Two problems are inherent in measuring changes in the accommodative response induced by mental effort. First, it could be expected that changes in accommodative state would be limited to the depth of focus of the eye, in order to avoid a blurred retinal image (Campbell, 1957) and hence any such changes would be less than ~0.20 D. Secondly, the accommodative response is not static but subject to short-term fluctuations (Campbell *et al.*, 1959; Denieul, 1982). The magnitude of these microfluctuations varies between subjects but are typically ~0.10 D in amplitude with a frequency bandwidth ranging from 0 to 5 Hz. Certain workers have suggested the power spectrum of these fluctuations is characterised by a predominance of frequencies between 1 and 2Hz. In addition the fluctuations increase with increasing accommodation and are larger in the presence of small pupils (Campbell *et al.*, 1959). It is important to differentiate between changes in accommodation induced by the experimental condition and those which are due to short-term fluctuations. In order that any small changes in accommodation may be assssed it was decided to sample accommodative state over a two minute period.

Accommodative responses were measured for two conditions each of which required a low or a high level of mental effort. For both conditions the subject viewed the numbers binocularly. The low-level task (i.e. the passive condition) required the subject to read the array of numbers to himself. Subjects were instructed to fixate each digit successively, working from left-to-right for each row and then from top-to-bottom for each column. Subjects were instructed to change their fixation to the next number every time the optometer took a reading, signified by an audible 'click', which occured at intervals of approximately one second. Hence fifty fixations generated fifty readings for each array of numbers. Measurements were made for two arrays of numbers yielding a total of one hundred estimates of the accommodative response from which the mean and standard deviations were calculated. Each measurement period, therefore, lasted approximately two minutes.

The higher level of mental effort (i.e. the active condition) involved the subjects adding the numbers in rows or columns of five. The same fixation pattern was adopted as for the passive condition and thus for each matrix the subject would make fifty fixations and ten calculations. Two arrays of numbers were presented consecutively yielding one hundred estimates of the accommodative response. It is important to note that the visual nature of the task, the targets and the changing of fixation, were identical for the two conditions. Consequently, it is assumed that differences in accommodative response between the two conditions are solely attributable to the amount of mental effort exerted.

Each experimental session consisted, therefore, of six sets of measurements, i.e. two mental conditions at each of the three stimulus vergences. A two minute rest period was allowed between each measurement period during which the subject was permitted to freely gaze around the laboratory. The order in which these measurements were taken was randomised in order to minimize the effects of tonic adaptation (Schor *et al.*, 1986) or accommodation fatigue (Malmstrom *et al.* 1981).

6.1C - Results

Each experiment session yielded six mean values of the accommodative response for each subject. The mean of each of these values for the group of twelve subjects are given for both the saline trial and the timolol trial in Table 6.1. The effect of the imposition of mental effort can be assessed by subtracting the passive accommodative response from the active response. This change in accommodation, termed the cognitive induced shift, was calculated for each subject and the mean values are given in Table 6.1. The IOP data in Table 6.1 demonstrates the efficacy of timolol as an ocular hypotensive agent. The reductions in IOP did not correlate with any of the changes in accommodative state induced by timolol.

The mean cognitive induced shifts for each experimental condition are plotted as histograms in Fig. 6.1. It can be seen that for the saline trial the imposition of mental effort induces a significant increase in mean accommodative response for the -1 D stimulus, a response approximately equivalent to the passive condition at -3 D and a reduction in response at -5 D. Mental effort induces similar responses for the -1 D and -3 D locations when sympathetic innervation to the ciliary muscle is blocked with timolol maleate. Responses for the -5 D location were, however, significantly increased for the timolol trial (see below for statistical analyses).

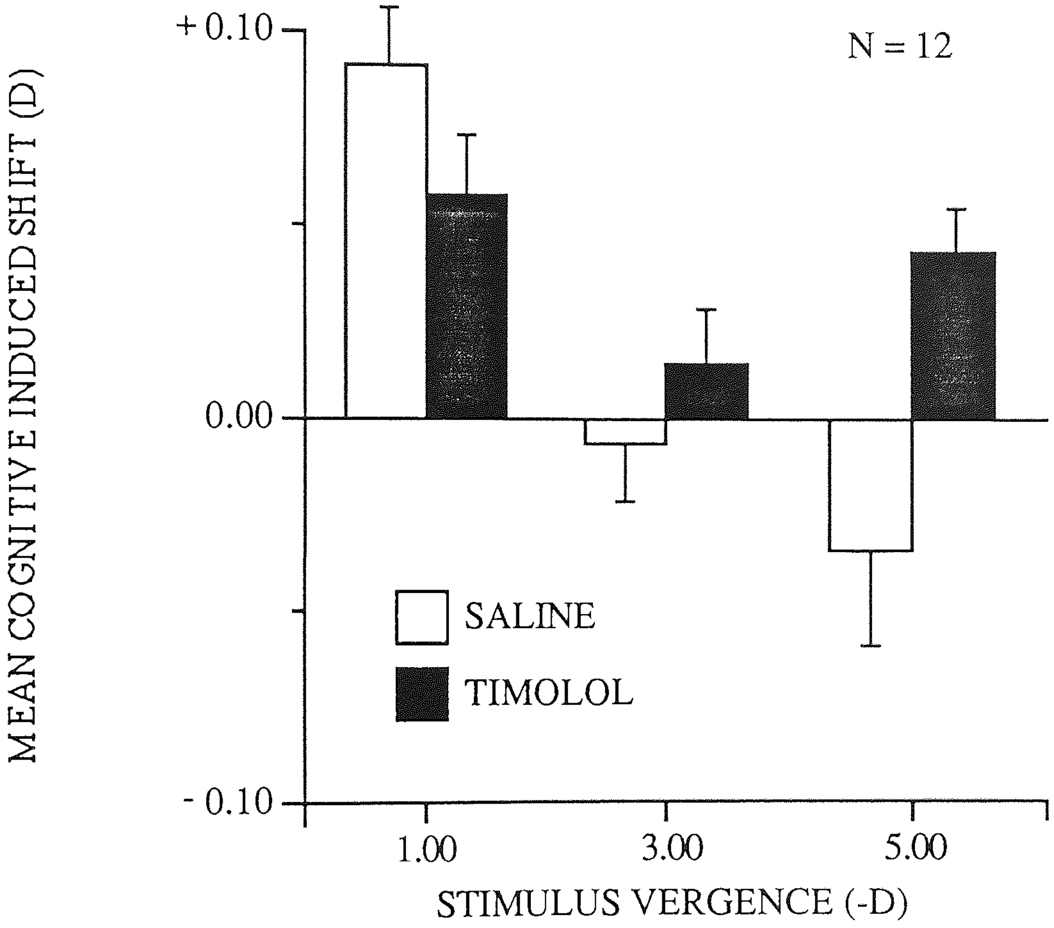


FIG. 6.1. - Mean cognitive induced shifts in accommodation for the saline trial (light bars) and timolol trial (dark bars) for each stimulus vergence. Error bars represent one standard error of the mean.

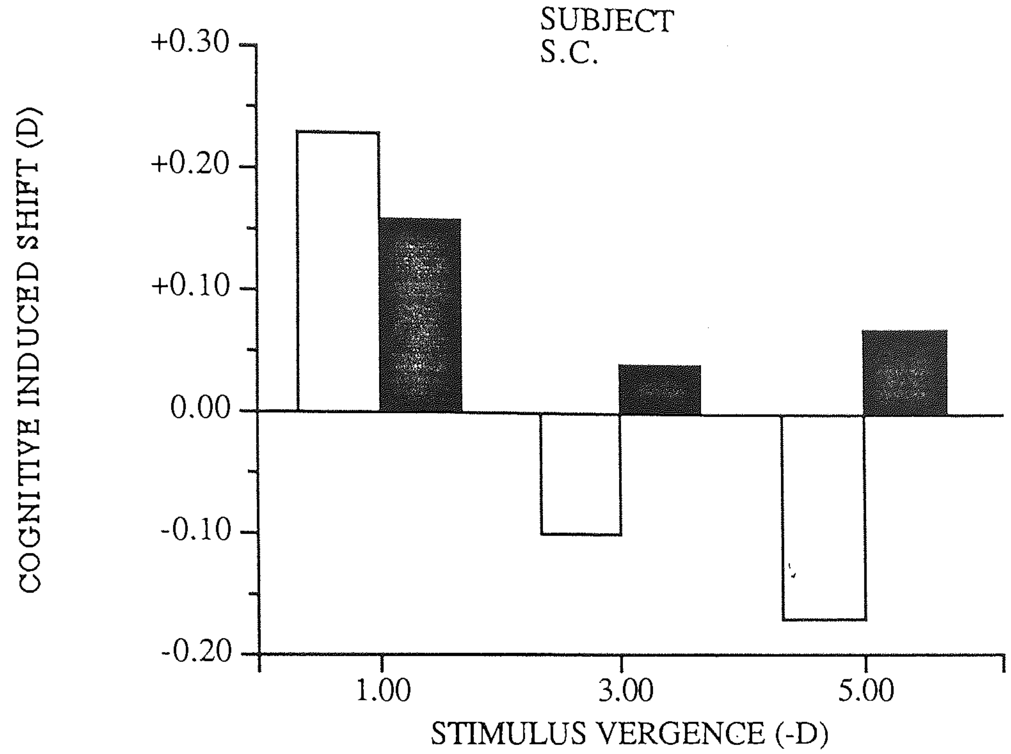
TABLE 6.1. - Mean accommodative response values for the group of twelve subjects for the saline trial and the timolol trial. The mean cognitive induced shifts for each experimental condition are also shown. Mean IOP and drug induced changes in IOP are given. Figures in brackets represent standard errors of the mean.

STIMULUS VERGENCE		SALINE		TIMOLOL	
-1.00 D	PASSIVE	1.07	(0.05)	1.07	(0.06)
	ACTIVE	1.16	(0.06)	1.13	(0.07)
	SHIFT	+0.09	(0.02)	+0.06	(0.02)
-3.00 D	PASSIVE	2.69	(0.05)	2.71	(0.04)
	ACTIVE	2.68	(0.06)	2.72	(0.05)
	SHIFT	-0.01	(0.02)	+0.01	(0.02)
-5.00 D	PASSIVE	4.39	(0.05)	4.38	(0.07)
	ACTIVE	4.36	(0.07)	4.42	(0.06)
	SHIFT	-0.04	(0.03)	+0.04	(0.01)
INITIAL IOP (mmHg)		12.10	(0.82)	12.44	(0.48)
Δ IOP (mmHg)		-0.10	(0.40)	-3.87	(0.38)

Inspection of individual data suggests that seven subjects demonstrated similar trends to those shown by subject SC illustrated in Fig. 6.2, namely evidence for sympathetic induced changes in accommodation at near. In contrast three subjects showed similar results to those of subject DJ (see Fig. 6.2), i.e. parasympathetic induced increases in accommodation at near. Mental effort induced minimal or no clear changes in the accommodative response in the two remaining subjects.

6.1D - Statistical analyses

Four factor analyses of variance [drug (saline *vs.* timolol), stimulus vergence, task (passive *vs.* active) and subject] were carried out for the values of accommodative response shown in Table 1. F-ratios for main treatment effects and second order interactions were computed using denominators that took account of the interactive



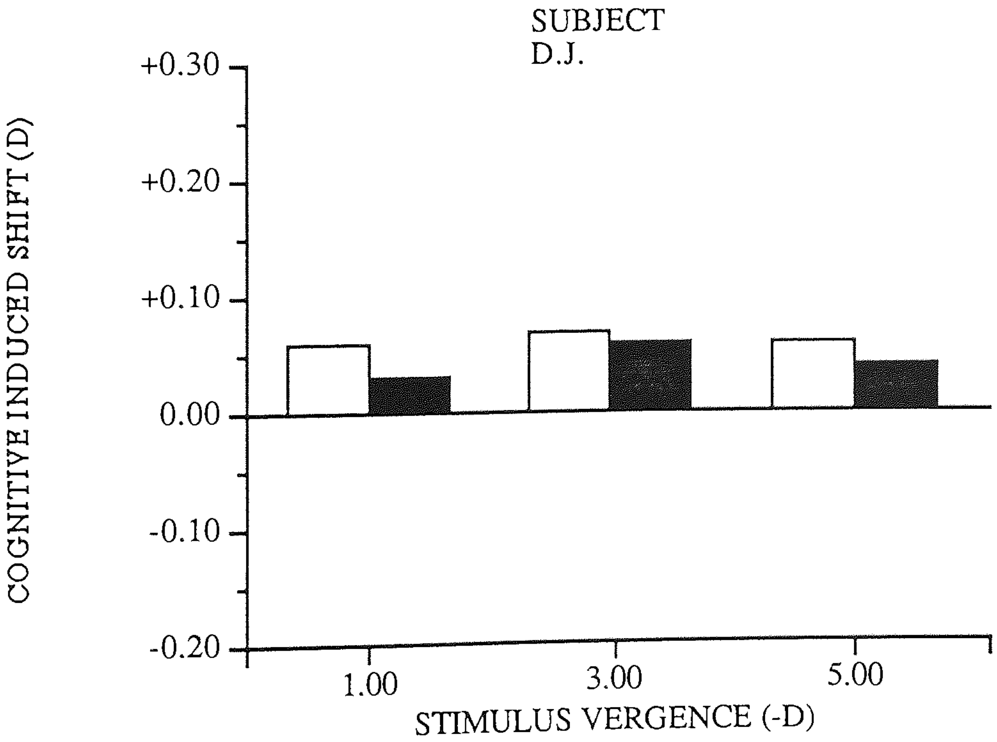


FIG. 6.2. - Cognitive induced shifts in accommodation for the saline trial (light bars) and timolol trial (dark bars) for each stimulus vergence for subjects SC and DJ.

effects with respect to subjects. For example, F-ratios for task effects were calculated by dividing the mean square for task by the mean square for the task/subject interaction (Willemsen, 1974). Analyses revealed that sympathetic blockade had no effect on the accommodative response but the effects of subject (F = 176.34; P < 0.001; d.f. = 11, 132), task (F = 8.02; P < 0.001; d.f. = 1, 132) and stimulus vergence (F = 2455.57; P < 0.001; d.f. = 2, 132) were all significant. Task/vergence interactions were also significant (F = 8.76; P < 0.001; d.f. = 2, 132) and although drug/task interactions were insignificant, there was a significant interaction between drug, task and stimulus vergence (F = 5.08; P < 0.025; d.f. = 2, 132). This interaction is pertinent to the central theme of this paper and demonstrates that sympathetic inhibition can modify the effect of mental effort on the accommodative response at near.

6.1E - Discussion

The results of the present study demonstrate that when viewing the -1 D stimulus, the imposition of mental effort induces a parasympathetically mediated increase in the accommodative response. For the -5 D stimulus, however, the majority of subjects demonstrate a sympathetically mediated decrease in accommodation for the active condition. In order to interpret these findings consideration should be given to two factors relating to the accommodative response. First, the general effects of stress on the autonomic nervous system and secondly the nature of ciliary muscle innervation.

Whilst it was originally thought that the physiological response to stress was an increase in sympathetic acitivity (Cannon, 1929) more recent studies have suggested that a bi- or tri-phasic response occurs (see section 1.3E pps. 36-39) i.e. an increase in sympathetic activity followed by an antagonistic rebound in parasympathetic activity (Wenger *et al.*, 1956; Sternbach, 1966; Anisman, 1975; Porges, 1976). Much of the previous work on the physiology of stress has involved transient stimuli, whereas the present study employed a task which lasted two minutes and hence the stress was more sustained. It is possible, therefore, that such a prolonged period of stress may produce a sustained enhancement of both sympathetic and parasympathetic activity, the response of the organ under examination being dependent on the relative dominance of these two systems. In addition the magnitude of the response will be dependent on how stressful the subject found the situation.

There is clear experimental evidence for dual innervation of the ciliary muscle (see section 1.3 pps. 30-41 and Gilmartin, 1986). It is important, however, to acknowledge the nature of the sympathetic input. It would appear from physiological studies that sympathetic innervation to the ciliary muscle has minimal effect for low levels of accommodation and that the effect of sympathetic inhibition increases with increases in concurrent levels of parasympathetic background tone (Törnqvist, 1967; Hurwitz *et al.*, 1972).

Previous studies of the effects of stress on the autonomic nervous system would suggest, therefore, that both sympathetic and parsympathetic excitation may occur. Furthermore, it is thought that the sympathetic input to the ciliary muscle has little or no influence at low levels of accommodative demand. Using these two pieces of evidence it is possible to account for the results obtained in the present study. For the majority of subjects (e.g. subject SC) viewing a target at -1 D the presence of mental effort would induce a parasympathetic mediated increase in accommodation, since a general increase in sympathetic activity would not be expected to have any influence on accommodation at this level. At higher levels of accommodation demand, however, the sympathetic input to the ciliary muscle can modify the effects of mental effort on the accommodative response, an increase in sympathetic innervation producing a decrease in response. It appears then that parasympathetic activity associated with the -5 D stimulus augments the sympathetic facility evident in certain individuals, a finding consistent with the results of Chapters 3 and 4. This facility subsequently attenuates the parasympathetically mediated shift in accommodation associated with mental effort.

It should be noted that some of the experimental group (e.g. subject DJ; see Fig. 2) show no evidence of sympathetic inhibition at higher levels of accommodative demand. It is unclear whether this is due to a different psychological reaction to the task or physiological differences between subjects. This will be discussed further in section 6.2E (pps. 166-168).

6.2. MENTAL EFFORT AND THE STEADY-STATE ACCOMMODATIVE RESPONSE IN EMMETROPIA AND LATE-ONSET MYOPIA

6.2A - Introduction

The study reported in the previous section demonstrated that at low levels of accommodative demand the imposition of mental effort induces a parasympathetically mediated increase in accommodation for emmetropic subjects. At higher levels of accommodative demand, however, the majority of experimental group demonstrated a sympathetically mediated decrease in accommodation in the presence of mental effort. It should be noted that the experiment was carried out on emmetropes. It was felt appropriate, therefore, to compare the influence of mental effort on the steady-state accommodative response in emmetropes and late-onset myopes since this would parallel the study reported in Chapter 5 (pps. 166-168).

A recent report (McBrien and Millodot, 1986a) has suggested that myopic subjects show greater accommodative lag than emmetropes. McBrien and Millodot postulate that this lower steady-state accommodative response is associated with myopes having lower values of tonic accommodation (Maddock et al., 1981; McBrien and Millodot, 1987; see chapter 5 pps. 141-149). The results reported in Chapter 5 demonstrate, however, that the imposition of mental effort influences the distribution of TA values in emmetropes and late-onset myopes such that there is no significant difference between the two groups. A logical extension of this work would be to examine the influence of mental effort on the steady-state accommodative response in the two refractive groups.

The aim of this study is to investigate the accommodative response for stimuli located at three different stimulus vergences in emmetropes and late-onset myopes. In addition the influence of mental effort on the accommodative response is examined for both refractive groups.

6.2B - Method

Fourteen male emmetropes and fourteen male myopes aged between 19 and 23 (mean age = 20.9 years) participated in the study. 10 of the emmetropic subjects had participated in the study described in section 6.1 (pps. 150-160). Subjects' refractive errors were determined prior to the experiment by distance subjective refraction. All subjects could achieve corrected visual acuities of 6/5 or better and had normal binocular vision. The emmetropic subjects had refractive errors between plano and +0.50 dioptres best sphere (with not more than 0.25 dioptres of astigmatism). The myopic subjects selected for this study had developed myopia at the age of 15 years or later and had refractive errors between -0.50 and -3.50 dioptres best sphere (mean = -1.74 D, s.d. = 0.91 D). Their refractive errors were corrected with ultra-thin soft contact lenses†. These were inserted at least twenty minutes before any measurements being taken in order to allow adequate adaption.

Measurements were made for stimuli at three vergences namely -1, -3 and -5 dioptres. Targets consisted of a five by five matrix of black single-digit numbers on a white background (luminance = 25 cd/m^2). Targets were scaled for each stimulus distance such that the digits subtended 0.4 degrees at the eye and the total angular subtense of the matrix was 6.5 x 6.5 degrees. All measurements of accommodation were made using a modified Canon R-1 autorefractor. All readings in the present study were taken from the

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† Hydron 06 Soft contact lenses: Hydron Europe Limited, Camberley Surrey, U.K.

left eye. In order to differentiate between changes in accommodation induced by the imposition of mental effort and those which are due to micro-fluctuations, accommodation was sampled over a two minute period for each experimental condition (see section 6.1B pps. 151-154).

Accommodative responses were measured for two conditions, as described in section 6.1B (pps. 151-154), each of which required a low or a high level of mental effort. The low-level task (i.e. the passive condition) required the subject to read the array of numbers to himself. The higher level of mental effort (i.e. the active condition) involved the subjects adding the numbers in rows or columns of five. Two arrays of numbers were presented consecutively and one hundred estimates of the accommodative response were made. It is important to note that the visual nature of the task, the targets and the changing of fixation, were all identical for the two conditions. Consequently it is assumed that any difference in accommodative response between the two conditions is solely attributable to the amount of mental effort exerted.

Each experimental session consisted, therefore, of six sets of measurements, i.e. two mental conditions at each of the three stimulus vergences. A two minute rest period was allowed between each measurement and the subject was permitted to gaze freely around the laboratory. The order in which these measurements were taken was randomised in order to minimize the influence of tonic adaptation (Schor *et al.*, 1986) or accommodation fatigue (Malmstrom *et al.*, 1981).

6.2C - Results

Each experimental session yielded six mean values of the accommodative response for each subject. The mean of each of these values for both the myopic group and the emmetropic group are given in Table 6.2. For the passive condition the myopic subjects exert less accommodation than the emmetropes. There is not, however, such a marked difference in the responses for the active condition.

The effect of the imposition of mental effort can be assessed by subtracting the accommodative response for the passive condition from that for the active condition. This change in accommodation, termed the cognitive induced shift, was calculated for each subject and the mean values are given, for each refractive group, in Table 6.2. The mean cognitive induced shifts for each refractive group are plotted as histograms in Fig. 6.3. It can be seen that for the emmetropic group the imposition of mental effort induces a significant increase in mean accommodative response for the -1 D stimulus, a response approximately equivalent to the passive condition at -3 D and a reduction in response at -5 D, as reported in section 6.1B (pps. 151-154). For the myopic group, however, mental effort induces an increase in accommodative responses for all stimulus locations. This response to the imposition of mental effort is comparable to that for emmetropes who show no evidence of sympathetic inhibition or where the sympathetic input had been blocked using timolol (see section 6.1 pps. 150-160).

TABLE 6.2. Mean accommodative response values for each refractive group and each experimental condition. The mean cognitive induced shifts are also given. Figures in brackets represent standard errors of the mean.

STIMULUS VERGENCE		EMMETROPES		LATE-ONSET MYOPES	
	PASSIVE	1.06	(0.04)	1.00	(0.05)
-1.00 D	ACTIVE	1.14	(0.05)	1.08	(0.05)
	SHIFT	+0.09	(0.02)	+0.08	(0.02)
	PASSIVE	2.70	(0.04)	2.62	(0.05)
-3.00 D	ACTIVE	2.69	(0.04)	2.69	(0.05)
	SHIFT	-0.01	(0.01)	+0.07	(0.02)
	PASSIVE	4.40	(0.05)	4.27	(0.06)
-5.00 D	ACTIVE	4.37	(0.06)	4.34	(0.07)
	SHIFT	-0.03	(0.02)	+0.07	(0.02)

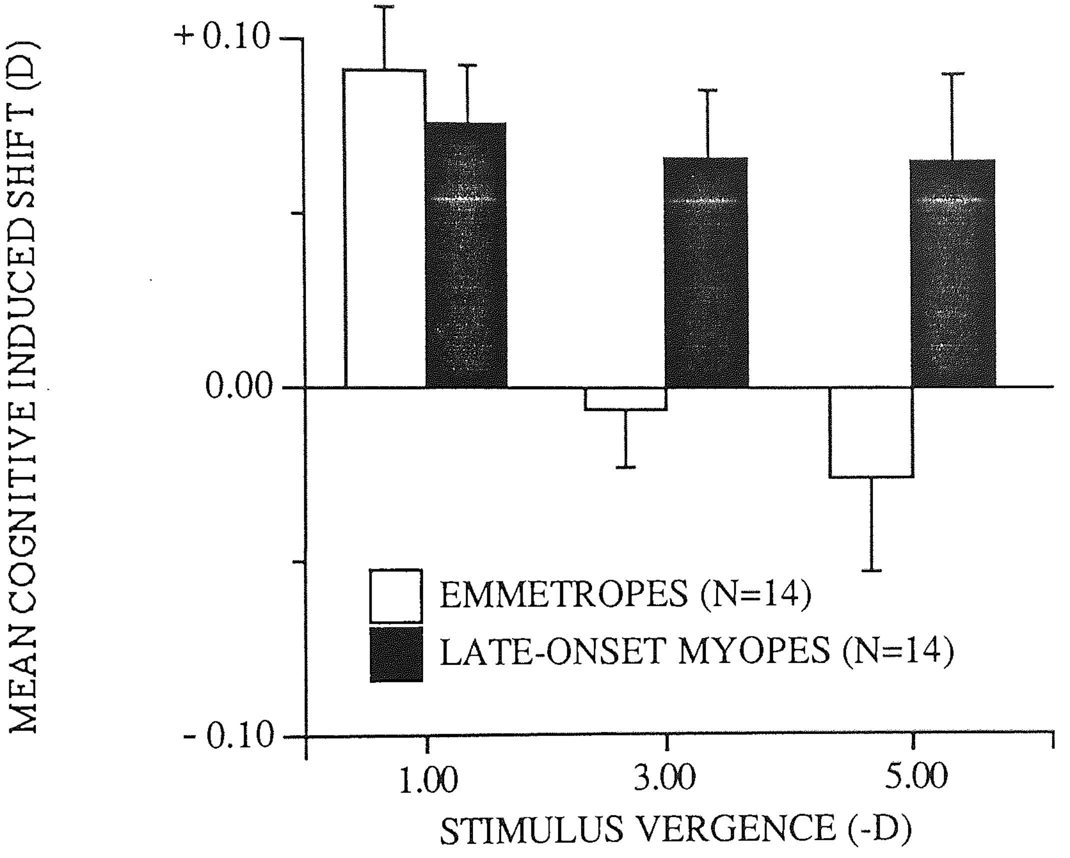

FIG. 6.3. - Mean cognitive induced shifts in accommodation for each refractive group and for each stimulus vergence. Error bars represent one standard error of the mean.

6.2C - Statistical analyses

Three-factor analyses of variance [refractive group (myopes *vs*. emmetropes), stimulus vergence and task (passive *vs*. active)] were carried out for the values of accommodative response shown in Table 1. Analyses revealed significant effects for vergence (F = 4566.33; P < 0.001; d.f. = 2, 156) and refractive group (F = 4.966; P < 0.05; d.f. = 1, 156). Such analyses take no account, however, of the within-subject design of this experiment. Three-factor analyses of variance (stimulus vergence, task and subject) were, therefore, carried out for the values of accommodative response for each refractive group. *F*-ratios for main treatment effects and second order interactions were computed using denominators that took account of the interactive effects with respect to subjects. For example, *F*-ratios for task effects were calculated by dividing the mean square for task by the mean square for the task/subject interaction (Willemsen, 1974). For the emmetropic group significant effects were indicated for subjects, (F = 45.41; P < 0.001; d.f. = 13, 78) vergence (F = 2744.01; P < 0.001; d.f. = 2, 78). The task/vergence interaction was also significant (F = 9.97; P < 0.001; d.f. = 2, 78) indicating that the changes in accommodative state induced by the imposition of mental effort are dependent on the stimulus vergence. Conversely, analyses for the myopic group revealed significant effects for subjects, (F = 101.24; P < 0.001; d.f. = 13, 78), stimulus vergence (F = 2792.23; P < 0.001; d.f. = 2, 78) and task (F = 27.69; P < 0.001; d.f. = 1, 78) but no significant task/vergence interaction. This demonstrates that, for the myopic group, mental effort induces a significant increase in accommodative responses which is independent of stimulus location.

Partial analyses of variance (two-factor: vergence and refractive group) were also carried out for the values of accommodative response for the passive condition and for the active condition. These revealed that there was a significant difference in accommodative response between the two refractive groups for the passive condition (F = 5.55; P < 0.05; d.f. = 1, 78) but not for the active condition.

6.2E - Discussion

It can be seen from Table 6.2 that myopes exert significantly less accommodation than emmetropes for the passive condition. This increase in accommodative lag in myopes has been reported previously by McBrien and Millodot (1986a) and may be due to a number of factors. It is feasible that the lower accommodative response found in myopes is due to optical factors, such as depth-of-focus. The myopic group may, for example, be more tolerant of blur due to their experience of poor distance vision. Conversely, emmetropes who are used to clear vision at all distances may accommodate more critically.

The accommodative response is dependent on a number of subject and target characteristics but, in general, as the stimulus is degraded the accommodative response approaches the subject's tonic accommodation (TA) (Heath, 1956a; Owens and Leibowitz, 1975; Johnson, 1976; Charman and Tucker, 1977; Charman, 1986). McBrien and Millodot (1986a) suggesed that the lower accommodative response in myopes is associated with myopes having lower values of TA (Maddock *et al.*, 1981; McBrien and Millodot, 1987). It should be noted that in the present study all measurements were made under binocular conditions. It has been suggested, however, that the accommodation exerted when viewing a near target is determined by the vergence requirements of the stimulus (Fincham and Walton, 1957). It is possible, therefore, that differences in the accommodative response may reflect variations in the AC/A ratio between emmetropes and myopes (Baldwin, 1965; Rosenfield and Gilmartin, 1987b). It may, therefore, prove interesting to compare monocular and binocular accommodative responses in emmetropes and late-onset myopes.

The present study demonstrates accommodative differences between emmetropes and late-onset myopes. It would appear that for the passive condition myopes exert significantly less accommodation than emmetropes. It is interesting to note, however, that for the active condition there is no significant difference in accommodative response between the two refractive groups. This is consistent with a previous study which measured TA in emmetropes and late-onset myopes under passive and active conditions (see chapter 5 pps. 141-149). It was found that, under passive conditions, the mean TA of the myopic group was 0.81 D (sd = 0.46 D) which was significantly lower than that of the emmetropic group (mean = 1.14 D, s.d. = 0.46 D). Under the active condition, however, there was no significant difference between the two groups.

The imposition of mental effort induces changes in the accommodative state of both refractive groups. The nature or pattern of these cognitive induced shifts in accommodation are, however, different for the two refractive groups. This may be due to the well established psychological differences that exist between emmetropes and myopes (Young *et al.*, 1975; Baldwin, 1981; Gawron, 1981; 1983). Indeed, certain authors have suggested that psychological factors may influence the development of refractive errors (Van Alphen, 1961; Young *et al.*, 1975). Van Alphen (1961) suggested that stress or emotion may interfere with the emmetropization mechanism and that the stress associated with studying for exams may contribute to the development of 'school myopia'. Hence the findings of the present study may be due to variations in the groups' psychological response to the task. One would anticipate, however, that differences would exist at all stimulus locations yet the cognitive induced shifts in accommodation are almost identical for the -1 D stimulus and significant differences only exist for the -3 and -5 D stimuli.

An alternative explanation is that the results reflect variations in physiological response to the psychogical stress of the task. In the previous section it was shown that at low levels of accommodative demand the imposition of mental effort induces a parasympathetically-mediated increase in accommodation for the majority of emmetropic subjects whilst at higher levels a sympathetically-mediated decrease in accommodation. In a small number of the experimental group, however, the imposition of mental effort induced increases in accommodation at all stimulus locations. In these subjects sympathetic blockade had no effect on the cognitive induced shifts in accommodation. For the myopic group in the present study the imposition of mental effort induces increases in accommodation at all stimulus vergences. The inference is, therefore, that these shifts are parasympathetically mediated and that myopes lack an inhibitory sympathetic input which, in most emmetropes, attenuates such shifts during near-vision.

Previous research has demonstrated that a period of sustained closework induces myopic shifts in TA (see section 1.5D pps. 50-55). Such tonic after-effects have been termed accommodative 'hysteresis' or 'adaptation of tonic accommodation' and Ebenholtz (1983) proposes that accommodative hysteresis may be a precursor to induced myopia. Furthermore Gilmartin and Hogan (1985a) suggested that the sympathetic input to the ciliary muscle serves to attenuate myopic shifts in TA and that induced myopia may develop due to an inadequate inhibitory sympathetic input. The present study has demonstrated that at near, emmetropes show evidence for sympathetic innervation to the ciliary muscle whilst myopes show no evidence for such an input. These findings would, therefore, support the hypothesis that myopes have a reduced inhibitory sympathetic facility.

6.3 - DISCUSSION ON MENTAL EFFORT AND THE STEADY-STATE ACCOMMODATIVE RESPONSE

As indicated earlier, the existing experimental evidence concerning mental effort and accommodation is somewhat contradictory. Kruger (1980) found that when 20 subjects changed from passive reading of a series of two-digit numbers at 40 cm to adding the numbers the level of accommodation increased by a mean of 0.28 D. Conversely Malmstrom *et al.* (1980) demonstrated that a written backward-counting task could induce hyperopic shifts of 0.25-0.75 D from a 3.00 D target stimulus.

Birnbaum (1985) postulated that the conflicting results of Malmstrom *et al.* (1980) and Kruger (1980) may be explained by optical factors. Kruger's concurrent mental task was centred on the visual stimulus for which accommodation was measured. The need for greater attention to the task may have, therefore, required more accurate accommodation. In the study of Malmstrom and his co-workers a written backwards counting task was employed to induce high levels of mental effort. This may have diverted the subject's attention away from the fixation target thus causing accommodation to relax towards some intermediate resting position.

Attempts were made in the present study to limit the influence of optical factors by keeping the visual nature of the task identical for both the passive and active conditions. In addition the angular subtense of the targets was constant for all stimulus vergences. Furthermore, instillation of the drugs employed in section 6.1, *viz.* saline and timolol should not influence pupil size (Gilmartin *et al.*, 1984). If optical factors do influence the shifts in accommodation induced by mental effort, one might expect similar trends for both the saline and timolol trials. Inspection of the results, however, shows that for the -5 D stimulus the imposition of mental effort induces a mean decrease in accommodation for the saline trial and a mean increase for the timolol trial. It would appear, therefore, that psycho-physiological and not optical factors are responsible for the cognitive induced changes in the accommodative response.

Finally it is possible that the significant difference in cognitive induced shifts at near for the two refractive groups may explain why the results of previous investigations have conflicted (Kruger, 1980; Malmstrom *et al.*, 1980). Inspection of the results of the present study shows that for the -5 D stimulus the imposition of mental effort induces a mean decrease in accommodation for the emmetropic group but a mean increase for the myopic group. It is feasible, therefore, that the conflicting results found in previous studies may be due partly to the refractive error of the subjects selected.

CHAPTER 7

THE ADAPTATION OF TONIC ACCOMMODATION IN EMMETROPIA AND LATE-ONSET MYOPIA

7.1 - INTRODUCTION

The evidence for environmental and genetic influences in the development of refractive errors has been reviewed in section 1.7 (pps. 61-71). The particular aspect of refractive error of interest to this thesis is the development of late-onset myopia. Goldschmidt (1968) and Stevenson (1984) suggested that myopia which is late in onset is related to particular visual functions such as excessive near-work and is influenced little by genetic factors. Various workers have suggested that accommodation plays an important role in the development of myopia (e.g. Bedrossian, 1966; Young, 1975). Furthermore, McBrien and Millodot (1986a) proposed that if accommodation is a factor in myopia development then one would expect fundamental differences in accommodative responses between various refractive groups. This proposal is supported by the findings that late-onset myopes have lower values of tonic accommodation (TA) than emmetropes (see Chapter 5 pps. 141-149) and also show a greater lag of accommodation for near visual stimuli (see Chapters 6).

It is well established that a period of sustained fixation can produce significant changes in a subject's TA (see section 1.5D pps. 50-55). Ebenholtz (1983) demonstrated that 8 minutes of monocular fixation at the far point (FP) produced a mean decrease in TA of -0.21 D whereas a similar period of near point (NP) fixation produced a mean increase in TA of 0.34 D. He noted, however, that the FP target was, on average, 5.12 D closer than the subject's resting position, whilst the FP target was 0.98 D beyond the subject's

TA and it might have been expected, therefore, that the effect of NP fixation on TA would be some five times that of the FP target. Ebenholtz proposed that this non-linearity was evidence for the existence of two sub-sytems for the control of accommodation, one controlling accommodation for near vision and one for distance vision, although he did not speculate on the nature of these systems. Ebenholtz's results led Gilmartin and Hogan (1985a) to suggest that the non-linearity of hysteresis effects was a result of an enhanced inhibitory sympathetic input associated with the high level of concurrent parasympathetic activity during near point fixation and that the inhibitory sympathetic input to the ciliary muscle may serve to attenuate task-induced increases in TA.

The study reported in chapter 3 (pps. 107-125) demonstrated that, in emmetropes, inhibitory sympathetic innervation of ciliary smooth muscle provides the facility to attenuate the magnitude and duration of the positive shifts in TA induced by a sustained near-vision task. The facility was, however, restricted to those individuals having relatively high levels of pre-task TA. Furthermore, it was found that concurrent parasympathetic activity was a pre-requisite for the operation of sympathetic inhibition. This work was supplemented by the findings that late-onset myopes have values of TA which are lower than those of emmetropes (see Chapter 5 pps. 141-149; McBrien and Millodot, 1987). A prediction from the studies described in Chapters 3 and 5 would be that the myopic group would be more susceptible than emmetropes to positive shifts in TA induced by a sustained near visual task since their relatively low levels of TA may restrict the operation of an inhibitory sympathetic input.

Whether or not short-term task-induced changes in TA accumulate to an extent whereby the manifest refractive state of the eye is modified remains speculative. If, however, excessive tonic adaptation is a precursor to myopia one might predict significant differences between the adaptational facility of late-onset myopes and emmetropes. Indeed, if late-onset myopia has developed as a result of excess tonic adaptation it might be predicted that such a group of myopes would be more susceptible to TA after-effects. It was decided, therefore, to conclude the programme of experimental work with a comparison of the adaptation of TA to near-vision tasks in emmetropes and late-onset myopes.

An important methodological consideration of the study was the method used to open the accommodative loop. In a recent study, Schor *et al.* (1986) demonstrated that the imposition of darkroom conditions immediately following a task effectively masks the adaptation of TA that has been induced by a sustained near-vision task. TA after-effects were investigated under three open-loop conditions; Maxwellian view (pin-hole pupil), empty-field (Ganzfeld) and darkness. Following 1 minute of sustained fixation at -2 D, TA regressed to baseline levels after a few seconds in darkness. For the empty-field and Maxwellian view conditions, however, several minutes was required for TA to reach pre-task levels. Furthermore, if allowed to regress in darkness, TA would return to its adapted state when Maxwellian view conditions were reinstated.

Wolfe and O'Connell (1987) compared the adaptation of TA under darkroom and bright empty-field conditions in 21 subjects using a vernier optometer. They found that the adaptation of TA was significantly greater for the empty-field condition than for the darkroom condition (difference = 0.43 D, $t = 2.24$, $p < 0.05$). These differences in adaptation were, however, due entirely to a subset of subjects ($N = 5$) who showed much larger TA after-effects (> 2.5 D) for the empty-field condition. Wolfe and O'Connell also found that pre-task TA values measured under empty-field conditions were significantly higher than those measured under darkroom conditions.

The study reported in Chapter 3 (pps. 107-125) adopted darkness as the method of opening the accommodative loop. It was decided, however, to investigate further the influence of the method of opening the accommodative loop on the time-course and duration of TA after-effects. This chapter consists, therefore, of two studies. The first investigates the adaptation of TA for two open-loop conditions in a group of 10 subjects. The second experiment is a more extensive investigation of the nature of tonic adaptation in late-onset myopes and emmetropes. The results of the first study would help to decide the method of opening the accommodative loop used in the second experiment. It was also felt appropriate to adopt a similar experimental design for both studies to that described in Chapter 3 (pps. 107-125).

7.2 - MEASUREMENT OF ADAPTATION OF TONIC ACCOMMODATION UNDER TWO OPEN-LOOP CONDITIONS

7.2A - Method

Ten male subjects participated in the study. All subjects were aged between 19 and 25 years (mean = 21.9) and 5 were classed as emmetropic and 5 were classed as myopic. The emmetropic subjects had refractive errors between plano and +0.25 best sphere (mean = +0.08 D) with no more than 0.25 dioptres of astigmatism. All myopes participating in the experiment had developed myopia after the age of 15, the mean age of onset being 18.2 years (s.d. = 3.2 years). The myopic subjects had refractive errors between -0.75 and -2.25 diopters best sphere (mean = -1.42 D) with no more than 0.50 dioptres of astigmatism and were corrected using ultra-thin soft lenses[†]. Twenty minutes were allowed between lens insertion and the commencement of the experiment to allow adequate adaption. Small errors of refraction were determined prior to accommodation measurements being taken by accurate distance subjective refraction. All subjects, when corrected, could achieve a distance visual acuity of 6/5. All measurements of accommodation were made using the Canon R-1 autorefractor and were made on the left eye only.

[†] Hydron 06 Soft contact lenses: Hydron Europe Limited, Camberley Surrey, U.K.

Subjects were randomly allocated to six experimental sessions each of which lasted approximately 30 minutes. Each session comprised a combination of 1 of 2 open-loop conditions (empty-field or darkness) and 1 of 3 task conditions (-1 D, -3 D or -5 D). The ganzfeld (empty-field condition) was produced by placing an opaque white screen against the semi-silvered mirror on the Canon R-1, which is around 12 cm from the subject's eye. The screen was back illuminated by four 40 watt bulbs mounted one metre from the subject while the room lights were extinguished. The luminance of the field was measured as 60 cd/m^2. The ganzfeld so produced subtended 35 degrees horizontally by 20 degrees vertically. Any contours visible to the subject beyond this eccentricity should have little or no influence on accommodation (see Section 2.3 pps. 93-101). The right eye was occluded to avoid possible vergence interactions and subjects were instructed to relax, to look straight ahead and not to make any effort to focus on the white screen.

An experimental session commenced with an initial 10 minute period in one of two open-loop conditions to limit the effect of pre-task influences on initial TA values. After this "wash-out" period 10 TA measurements were taken every minute for 5 minutes and later averaged to give a pre-task estimate of TA. This was followed by a 10 minute task at either -1, -3 or -5 D. While viewing through the semi-silvered mirror of the infra-red optometer subjects were required to add together a series of black numbers on a white background (90% contrast). The targets were scaled for each task location such that the digits subtended 0.4 degrees at the eye. The task was employed so that active accommodation was required for the duration of the task and furthermore provided a specific level of mental effort. Following the task, open-loop conditions were reinstated and TA was immediately measured at approximately 1 second intervals over a 90 second period. Five seconds was allowed following the imposition of open-loop conditions for slight re-alignment of the instrument.

7.2B - Results

The mean values of pre-task tonic accommodation (TA) for each experimental condition are given in Table 7.1. All individual TA values have been adjusted for each subject's small residual refractive error. The mean values of TA are similar for the darkroom and empty-field conditions, indeed statistical analysis revealed that the method of opening the accommodative loop has no significant influence on the the value of TA recorded (t = 1.58, d.f. = 9, p = 0.15). Furthermore, by plotting the values obtained for the empty-field condition against those recorded for the darkroom condition (see Fig. 7.1), it can be seen that the two sets of values are well correlated (r = 0.89, p = 0.001).

TABLE 7.1 - Mean pre-task tonic accommodation (TA) for each experimental condition (N = 10). Figures in brackets represent standard deviations.

	LIGHT		**DARK**	
-1.00	1.02	(0.38)	0.95	(0.43)
-3.00	1.07	(0.42)	0.93	(0.47)
-5.00	0.89	(0.32)	0.82	(0.40)
MEAN	0.99	(0.30)	0.90	(0.38)

The post-task TA data was summarised for each subject using the procedure described in chapter 3 (pps. 107-125): the means and standard deviations were calculated for the nine sets of 10 data points that were symmetrically placed about the 10, 20, 30..........90 second points; the respective pre-task level of TA was subtracted from each of these mean values and graphs of mean post-task shift in TA were plotted against time for each experimental condition (see Figs. 7.2, 7.3 and 7.4).

The -1 D task produced no significant change in post-task TA for either open-loop condition. The -3 and -5 D tasks produced, however, an increase in mean post-task TA of around +0.50 which dissipated after around 60 seconds consistent with the findings

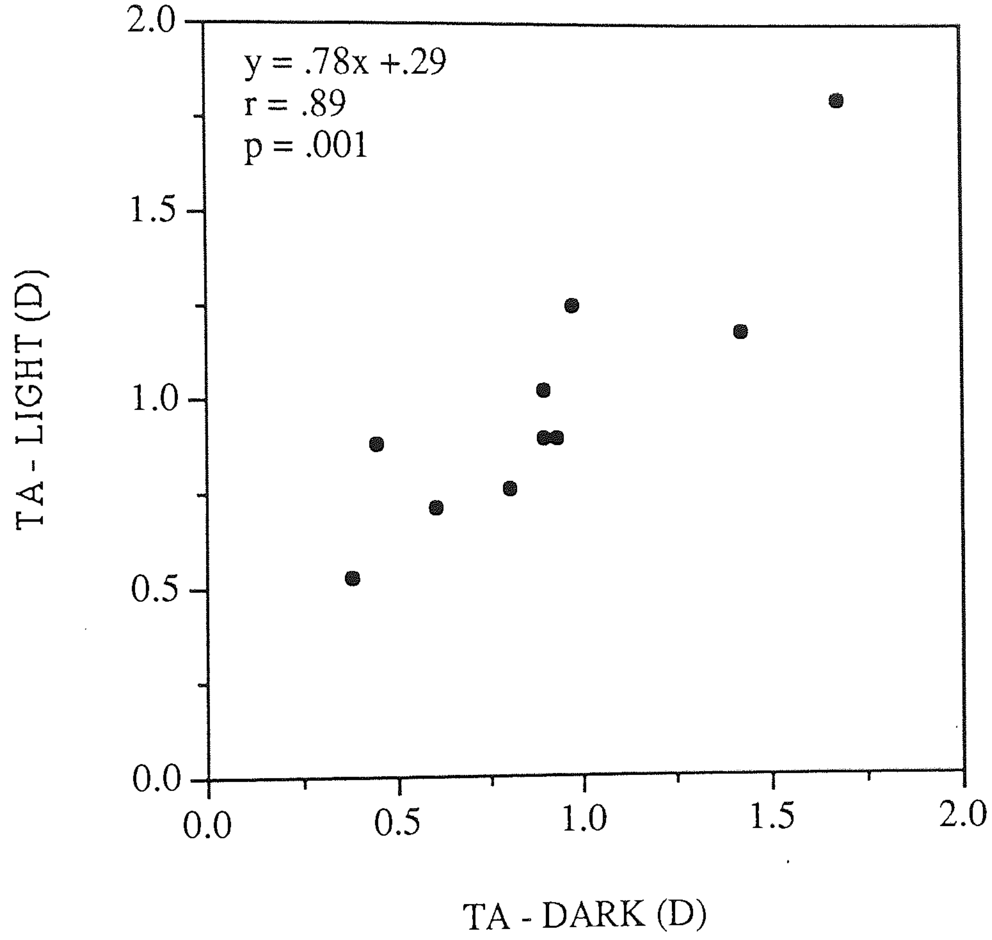

FIG. 7.1. - Relationship between pre-task TA values for ten subjects measured under empty-field (light) and darkroom conditions.

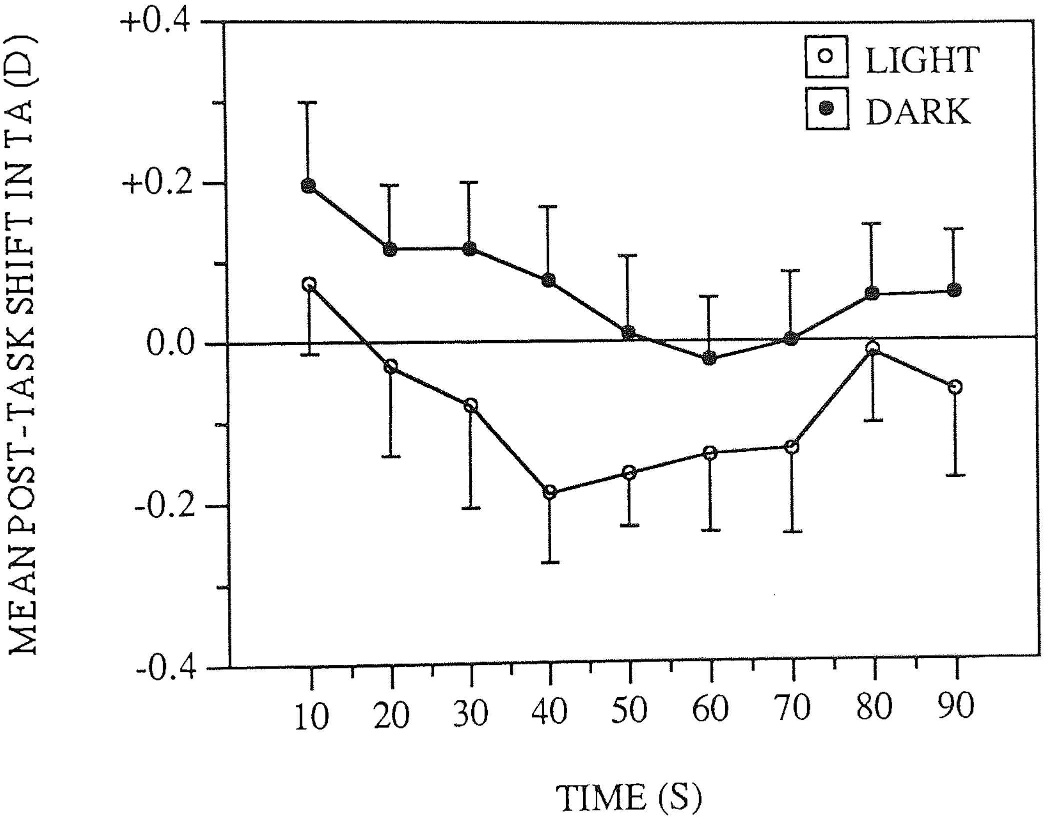

FIG. 7.2. - Mean post-task shift in TA for ten subjects following a ten minute task at -1 D. Error bars represent one standard error of the mean.

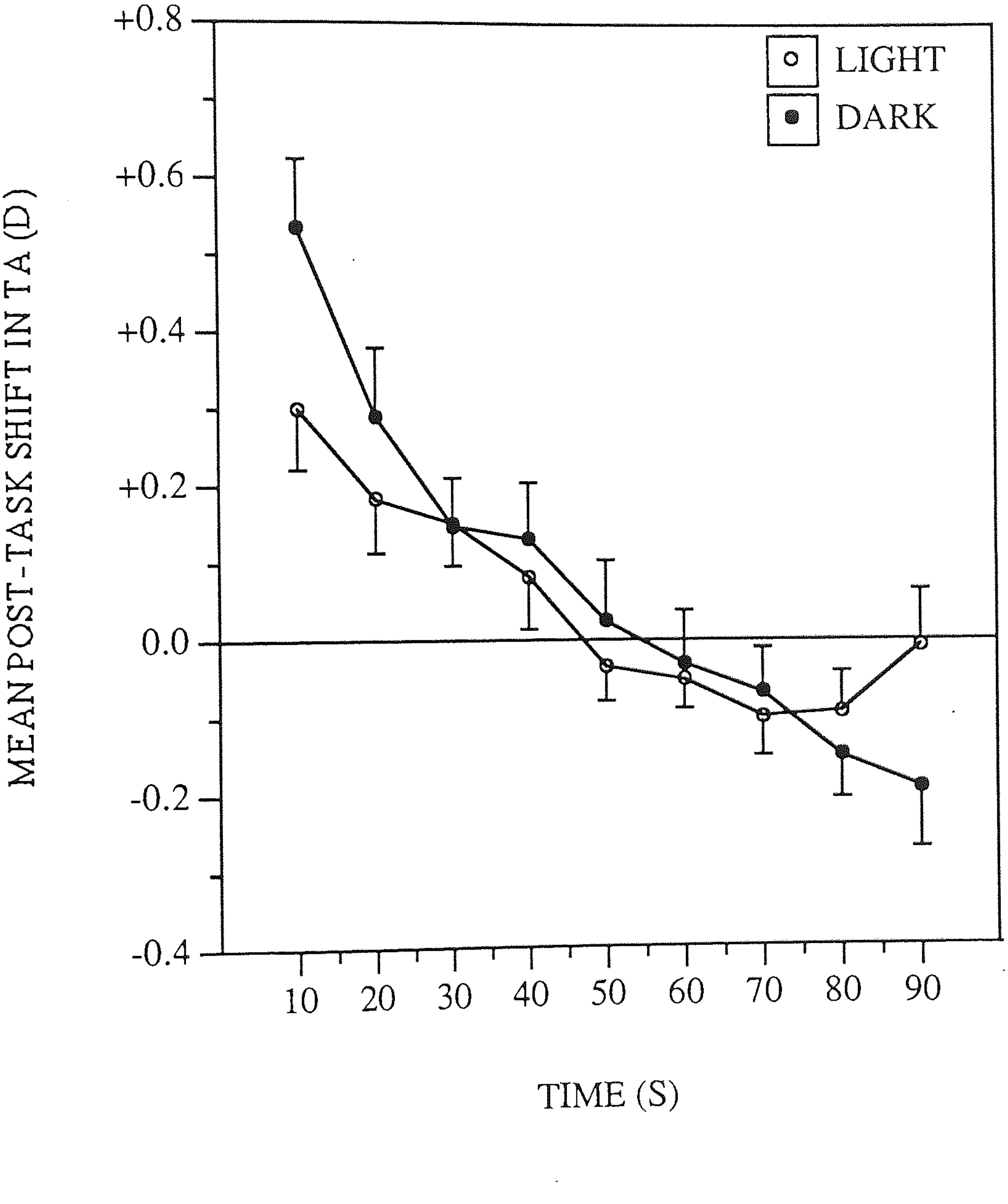

FIG. 7.3. - Mean post-task shift in TA for ten subjects following a ten minute task at -3 D. Error bars represent one standard error of the mean.

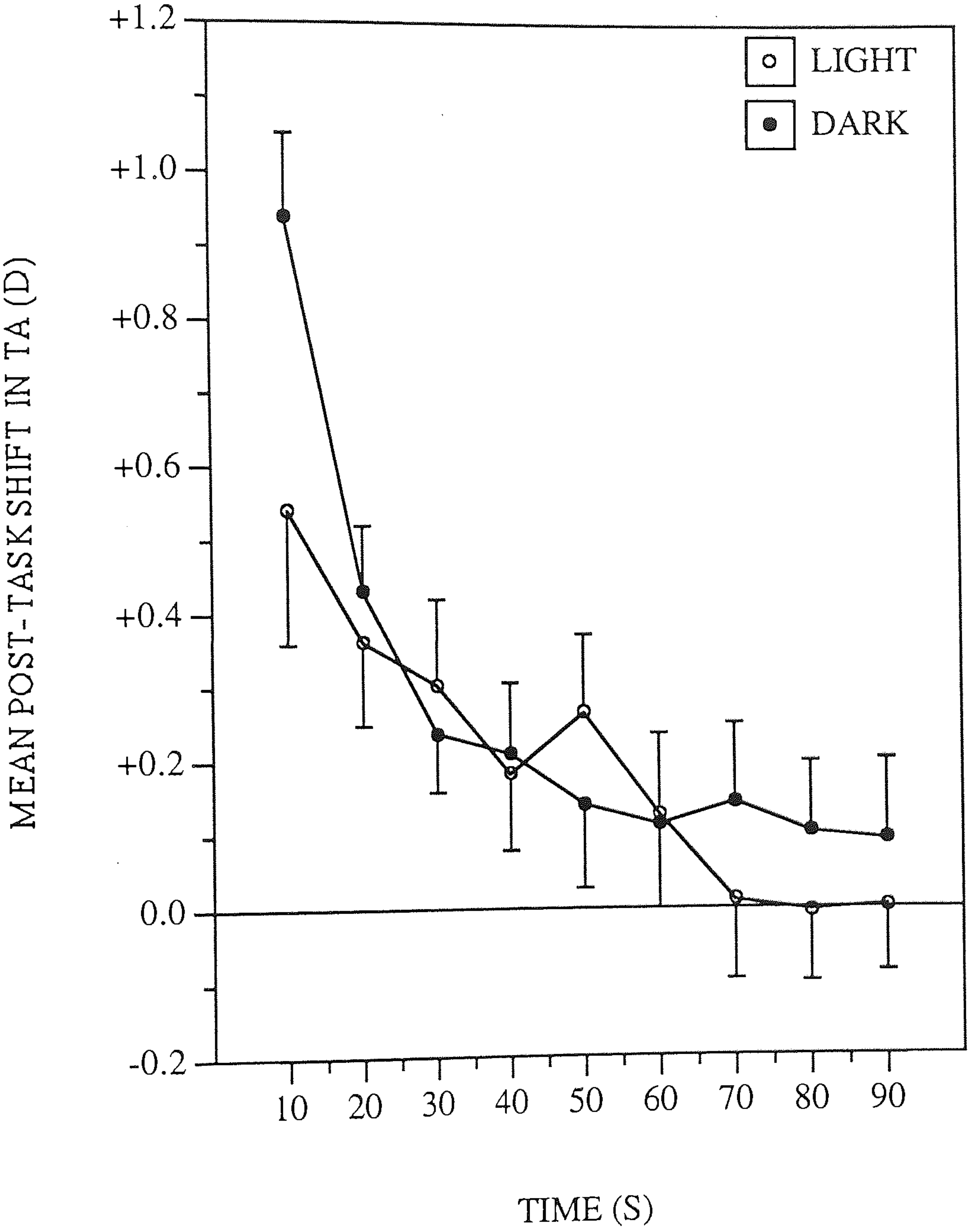

FIG. 7.4. - Mean post-task shift in TA for ten subjects following a ten minute task at -5 D. Error bars represent one standard error of the mean.

of Chapter 3 (see Figs. 7.3 and 7.4). Inspection of Figs. 7.3 and 7.4 indicates that the the regression of TA towards pre-task values is similar for darkroom and empty-field conditions. A comparison of the regression patterns for the two refractive groups was not made in the present study (see section 7.3 pps. 184-194). Inspection of the results revealed, however, no interaction between refractive group and the method of opening the accommodative loop.

Four- factor analyses of variance [i.e. condition (empty-field *vs.* darkroom), vergence (1, 3 or 5 D), time and subject] were carried out on the post-task shifts in TA illustrated in Figs. 7.2, 7.3 and 7.4). F-ratios for main treatment effects and second-order interactions were computed using denominators that took account of the interactive effects with respect to subjects. For example, F-ratios for vergence effects would be calculated by dividing the mean square for vergence by the mean square for the vergence/subject interaction (Willemsen, 1974). Analyses indicated significant effects for subjects ($F = 21.03$; $p < 0.001$; df = 9, 486), time ($F = 17.30$; $p < 0.001$; df = 8, 486) and vergence ($F = 7.63$; $p < 0.001$; df = 2, 486). Condition was found to be insignificant indicating that the magnitude of the post-task shifts in TA are independent of the open-loop condition adopted. Vergence/time interactions and condition/time interactions were also significant ($F = 4.17$; $p < 0.001$; df = 16, 486) and ($F = 3.37$; $p < 0.05$; df = 8, 486) respectively. This indicates that the open-loop condition adopted have a minor influence on the time-course of the post-task shifts in TA.

7.2C - Discussion

The significant correlation found in the present study between pre-task tonic accommodation (TA) values obtained under darkroom and bright empty-field conditions supports previous studies (Westheimer, 1957; Heath, 1962; Phillips, 1974; Leibowitz and Owens, 1975a). Leibowitz and Owens (1975a) compared TA in darkroom and empty-field conditions using a laser optometer. They found the two accommodative states to be well correlated ($r = 0.68$, $p < 0.001$). Wolfe and O'Connell (1987) found, however, that estimates of TA under empty-field conditions were significantly higher than those measured under darkroom conditions (difference = 0.50 D, t = 4.40, d.f. = 20, $p < 0.001$). They do not offer any convincing explanation for these differences but propose the existence of two resting states; the accommodative system being at rest in the dark but maintaining a more vigilant state when any light is present. It is important to note that in the present study 7 out of 10 of the subjects showed more myopic resting positions under empty-field conditions. A further study comparing estimates of TA under the two open-loop conditions in a larger number of subjects would contribute further to the existing experimental data.

The results of the present study demonstrate similar patterns of regression of TA towards pre-task levels following a sustained near-visual task for both darkroom and empty-field conditions. This fails to support the findings of Schor *et al.* (1986) who proposed that the duration of tonic after-effects is dependent on the method of opening the accommodative loop. Schor *et al.* (1986) found that following 1 minute fixation of a target at -2 D, the duration of TA after-effects for the Maxwellian view (pin-hole pupil) and empty-field conditions was several minutes and contrasted with the several seconds required for the darkroom condition. Furthermore, if allowed to regress in darkness, TA would return to its adapted state when Maxwellian view conditions were reinstated. Schor *et al.* (1986) concluded, therefore, that rather than decaying more rapidly in darkness, tonic adaptation was masked by darkness. No attempt was made in the present study to reinstate empty-field conditions following regression of TA in darkness but it would not be unreasonable to assume that the masking effects described by Schor *et al.* (1986) would not be observed.

Ciuffreda and Kenyon (1983) cite the data of Phillips (1974) who, like Schor *et al.* (1986), compared the regression of accommodation towards its resting position for darkness, empty-field and Maxwellian view conditions and found time constants of 4, 6 and 10 seconds respectively. He found that, under darkroom conditions, accommodation took around 15 seconds to reach the resting position whereas under Maxwellian view conditions 40 seconds was required. No data is provided, however, concerning the duration of accommodation prior to open-loop conditions being introduced. These results show similar trends to those of Schor *et al.* (1986) yet the decay time for Maxwellian view conditions is twice that for darkroom conditions compared with Schor and his co-workers who found that tonic after-effects took some ten times longer to dissipate for Maxwellian view and empty-field conditions than for darkroom conditions.

Wolfe and O'Connell (1987) report findings that concur with those of Schor *et al.* (1987). They used a vernier optometer to compare the adaptation of TA under darkroom and bright empty-field conditions in 21 subjects. They found that the adaptation of TA was significantly greater for the empty-field condition than for the darkroom condition (difference = 0.43, t = 2.24, p < 0.05). This differences in adaptation were, however, due entirely to a subset of five subjects who showed much larger TA after-effects (> 2.5 D) for the empty-field condition. Wolfe and O'Connell term these subjects 'superadaptors'. It possible, therefore, that the subjects used by Schor and his co-workers were all superadaptors while the subjects who participated in the present study were from the remaining population. It is appropriate, however, to consider other possible reasons for the discrepancies between the present study and those of other studies (Phillips,1974; Schor *et al.*, 1986; Wolfe and O'Donnell, 1987). Little is known about the experimental protocol of Phillips (1974) so the remaining dicussion will be confined a comparison of the results of Schor *et al.* (1986) and the present study.

There are certain methodological differences between the studies which should be considered. First, Schor and his co-workers employed monocular fixation to produce adaptation of TA whereas in the present study changes in TA were produced by a binocular task. It is possible, therefore, that the interaction of accommodation and vergence may account for the conflicting results of the two studies. This explanation seems unlikely, however, since Schor *et al.* (1986) and Wolfe and O'Connell (1987) have shown that both vergence accommodation and accommodative vergence produce adaptation of TA. A second possible explanation for the differences in results is that Schor *et al.* (1986) employed a 1 minute fixation period at -2 D compared with the ten minute task at -5 D adopted in the present study. Wolfe and O'Connell (1987) suggested that TA after-effects are found only if strong adapting stimuli are used. It may prove fruitful, therefore, to compare the adaptation of TA under the two open-loop conditions for various task durations.

An additional factor which may influence the time taken for post-task TA to regress to pre-task levels is the age of the subjects participating in the study. Patients in their late thirties frequently complain of a reduction in the speed of their accommodation (Allen, 1956). It is possible, therefore, that this increased accommodation response time is reflected in TA after-effects taking longer to dissipate in older subjects. Subjects participating in the present study were aged between 19 and 25 years and although Schor *et al.* (1986) do not disclose the age of their volunteers, it is understood that at least two were over thirty years of age (Kotulak, personal communication).

Finally, it is should be noted that Schor *et al.* (1986) employed a badal optical system to produce the Maxwellian view and empty-field conditions. Such apparatus may induce proximal accommodation for these conditions since a large amount of experimental apparatus is visible to the subject but not for the darkroom condition (Schober *et al.*, 1970). Hence, more sustained TA after-effects might be found for the Maxwellian view and empty-field conditions. It would be interesting, therefore, to compare the adaptation of TA using different techniques to produce bright empty-field conditions.

Whatever the reasons for the discrepancies between the present study and that of Schor *et al.* (1986) the present study found little or no difference between the regression of TA towards pre-task levels for darkroom and empty-field conditions. The following section compares the adaptation of TA in emmetropes and late-onset myopes and it was decided to adopt darkroom conditions for the measurement of TA since this technique has been employed in Chapters 2 to 5.

7.3 - THE ADAPTATION OF TONIC ACCOMMODATION IN EMMETROPIA AND LATE-ONSET MYOPIA

7.3A - Method

Thirty subjects (26 male and 4 female) participated in the study. All subjects were aged between 19 and 25 years (mean = 21.5) and 15 were classed as emmetropic and 15 were classed as myopic. The emmetropic subjects had refractive errors between plano and +0.50 best sphere (mean = +0.15 D) with no more than 0.50 dioptres of astigmatism. All myopes participating in the experiment had developed myopia after their 15th birthday, the mean age of onset being 17.5 years (s.d. = 2.3 years). The myopic subjects had refractive errors between -0.50 and -2.25 diopters best sphere (mean = -1.42 D) with no more than 0.50 dioptres of astigmatism and were corrected using ultra-thin soft lenses[†]. Twenty minutes were allowed between lens insertion and the commencement of the experiment to allow adequate adaption. Small errors of refraction were determined prior to accommodation measurements being taken by accurate distance subjective refraction. All subjects, when corrected, could achieve a distance visual acuity of 6/5. All measurements of accommodation were made using the Canon R-1 autorefractor and were made on the left eye only.

Subjects were randomly allocated to three experimental sessions each of which lasted approximately 30 minutes. Each session commenced with an initial 10 minute period in darkness to limit the effect of pre-experiment influences on initial TA values. Following this "wash-out" period 10 TA readings were taken every minute for 5 minutes

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[†] Hydron 06 Soft contact lenses: Hydron Europe Limited, Camberley Surrey, U.K.

and later averaged to give a pre-task estimate of TA. This was followed by a 10 minute task at either -1, -3 or -5 D. While viewing through the semi-silvered mirror of the infra-red optometer subjects were required to add together a series of black numbers on a white background (90% contrast). The targets were scaled for each task location such that the digits subtended 0.4 degrees at the eye. The task was employed so that active accommodation was required for the duration of the task and furthermore provided a specific level of mental effort. The accommodative response was measured at one minute intervals during the task. Following the task, the room lights were extinquished and TA was immediately measured at approximately 1 second intervals over a 90 second period. Five seconds was allowed following extinction of the room lights for slight re-alignment of the instrument.

7.3B - Results

The mean pre-task values of TA for each task condition are given in Table 7.1. All individual TA values have been adjusted for each subject's small residual refractive error. The mean TA value for the myopic group is significantly lower than that of the emmetropic group (myopic mean = 0.75 D, s.d. = 0.19; emmetropic mean = 1.10 D, s.d. = 0.36; t = 3.25, d.f. = 28, P = 0.003).

The mean accommodative response during the task is also given for each task location and for each refractive group. Two-factor analyses of variance [task location and refractive group (emmetropes vs. myopes)] were carried out for the values of accommodative response recorded during the task, given in Table 7.1. The effect of task location and refractive group were both found to be significant (F = 1078.14; $p < 0.001$; df = 1, 84 and F = 5.336; $p < 0.05$; df = 2, 84 respectively). This is consistent with previous studies which have demonstrated that, at near, myopes show increased accommodative lag (McBrien and Millodot, 1986a; see section 6.2 pps. 160-168).

TABLE 7.2 - Mean pre-task tonic accommodation (TA) for each group of 15 subjects and for each experimental condition. The mean accommodative response during the task is also shown for each group and for each experimental condition. Figures in brackets represent standard deviations. EMM = Emmetropes.

	PRE-TASK TA (D)		ACCOMMODATIVE RESPONSE (D)	
	EMM	**MYOPES**	**EMM**	**MYOPES**
-1.00	1.16 (0.41)	0.73 (0.24)	1.04 (0.28)	0.96 (0.21)
-3.00	1.04 (0.40)	0.83 (0.25)	2.69 (0.16)	2.55 (0.29)
-5.00	1.05 (0.36)	0.66 (0.23)	4.40 (0.20)	4.33 (0.40)
MEAN	1.08 (0.36)	0.75 (0.19)		

The post-task TA data was summarised for each subject using the procedure described in chapter 3: the means and standard deviations were calculated for the nine sets of 10 data points that were symmetrically placed about the 10, 20, 30..........90 second points; the respective pre-task level of TA was subtracted from each of these mean values and graphs of mean post-task shift in TA were plotted against time for each experimental condition and for both refractive groups (see Figs. 7.5, 7.6 and 7.7).

For the -1 D task location the myopic group show a small mean increase in post-task TA whereas the emmetropic group show a mean decrease (see Fig. 7.5). It is possible that this is due to the task location being proximal to the mean pre-task TA of the myopic group (0.75 D) whilst it is slightly distal to that of the emmetropic group. For the -3 and -5 D tasks the emmetropes show a regression of accommodation towards pre-task TA levels, with control levels being reached in around 40 s (see Figs. 7.6 and 7.7). This is consistent with the results of an earlier study reported in Chapter 3. The myopic group, however, show a much flatter regression pattern than the emmetropic group, particularly for the -5 D task (see below for statistical analysis).

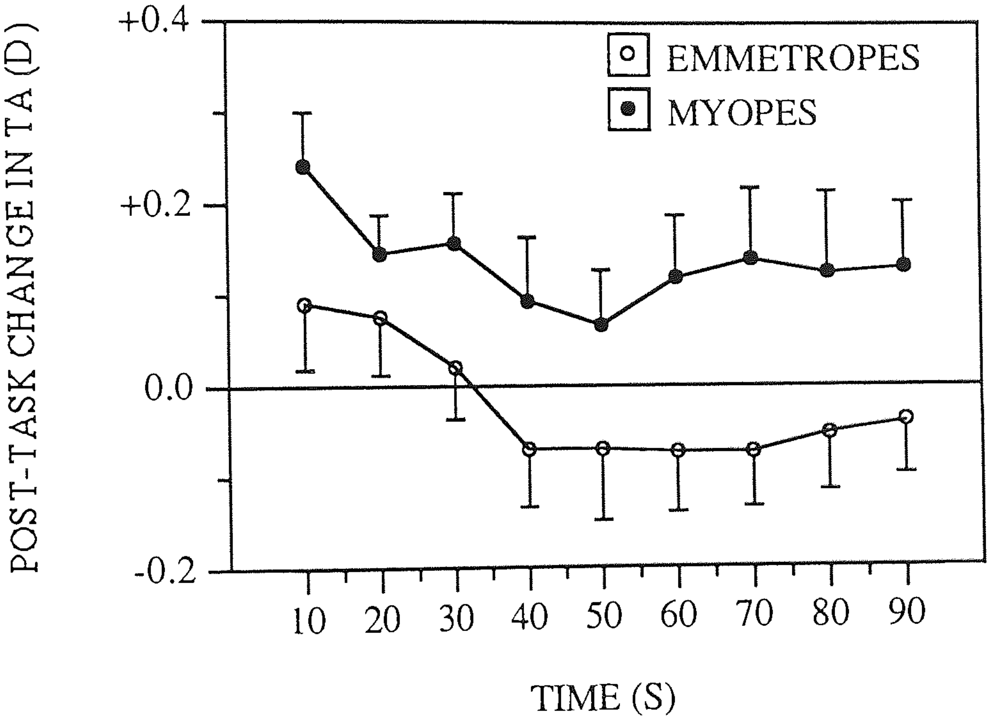

FIG. 7.5. - Mean post-task change in TA following a ten minute task at -1 D for both refractive groups. Error bars represent one standard error of the mean.

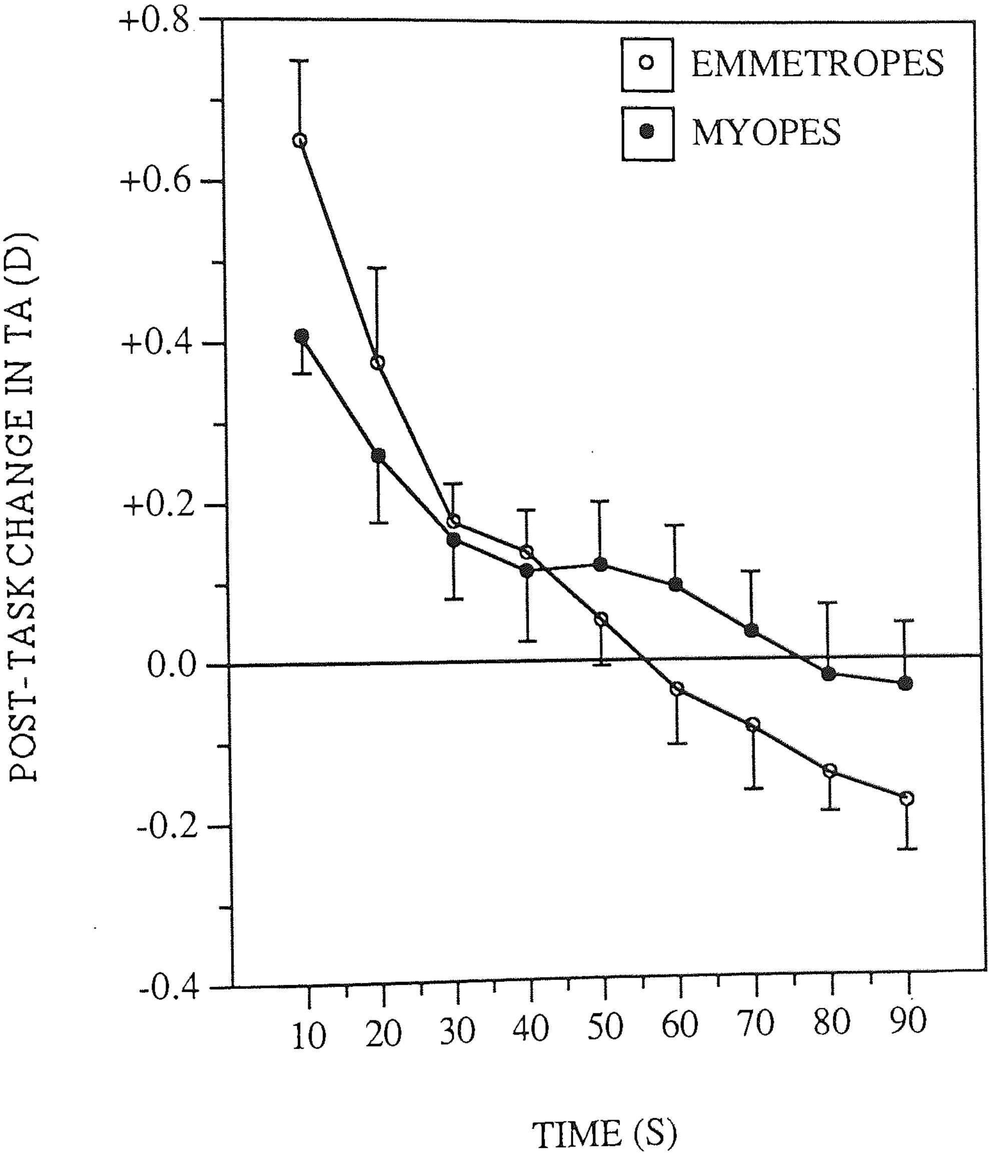

FIG. 7.6. - Mean post-task change in TA following a ten minute task at -3 D for both refractive groups. Error bars represent one standard error of the mean.

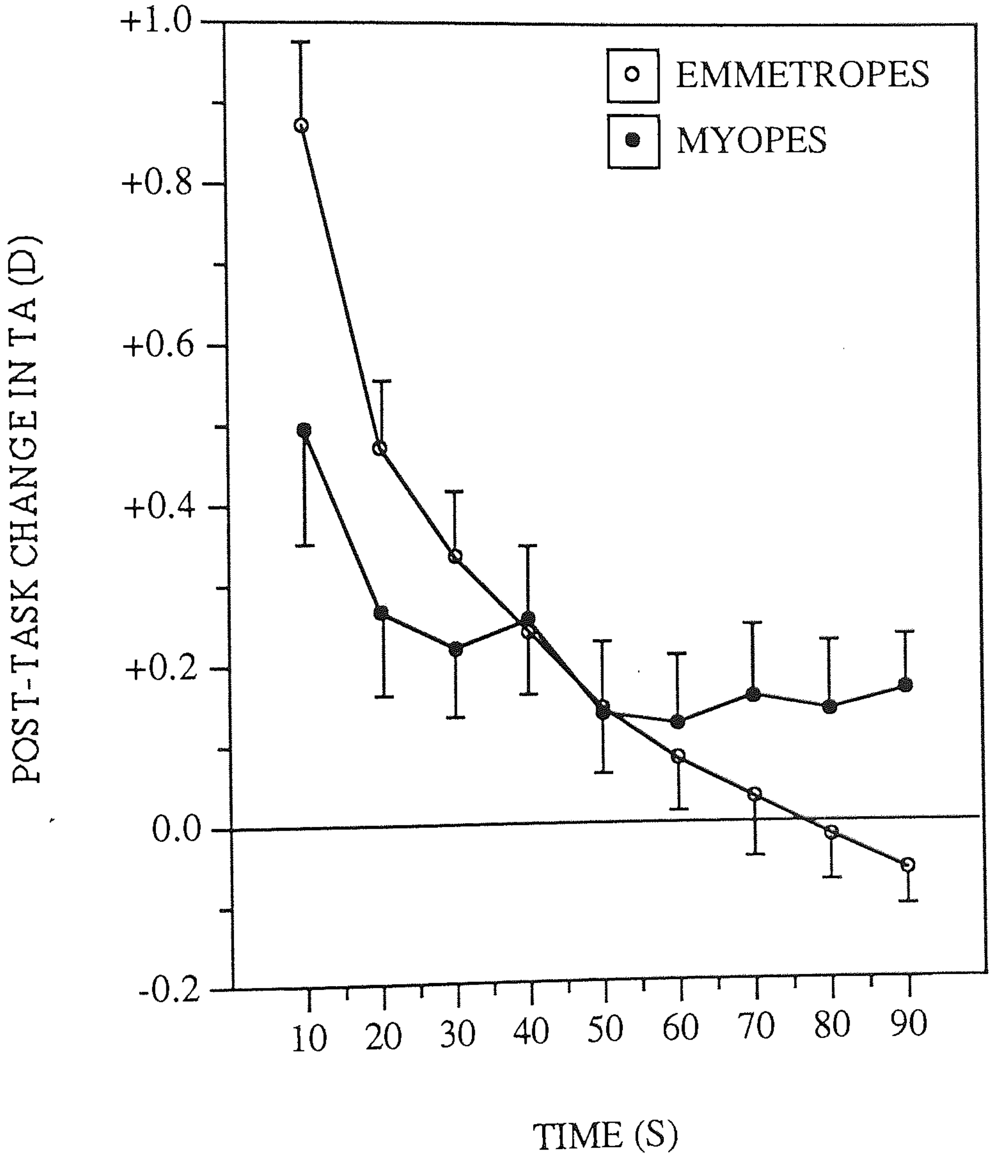

FIG. 7.7. - Mean post-task change in TA following a ten minute task at -5 D for both refractive groups. Error bars represent one standard error of the mean.

Three-factor analyses of variance (i.e. refractive group, task location, and time) were carried out on the post-task shifts in TA. Analyses revealed significant effects for refractive group (F = 5.967; $p < 0.025$; df = 1, 756), task location (F = 22.209; $p < 0.001$; df = 2, 756) and time (F = 22.164; $p < 0.001$; df = 8, 756). Furthermore, interactions between refractive group and task location (F = 6.308; $p < 0.005$; df = 2, 756), refractive group and time (F = 3.562; $p < 0.005$; df = 8, 756) and task location and time (F = 2.873; $p < 0.001$; df = 16, 756) were all significant. This demonstrates significant differences between the adaptation facility of late-onset myopes and emmetropes to sustained near-vision.

It can be seen from Figs. 7.6 and 7.7 that the gradient of the post-task regression patterns are markedly different for the two refractive groups and this may be examined by further statistical analysis. Inspection of the data suggests that the regression of accommodation towards pre-task TA values is quasi-linear. Linear regression analysis was, therefore, carried out for each individual subject's regression patterns and for each task location. The mean values of the slopes for each refractive group are shown in Table 7.3. Student t-tests were carried out on the mean values the slopes and it can be seen that the myopic group have significantly flatter regression patterns than the emmetropes for both the -3 and -5 D task locations (see Table 7.3).

TABLE 7.3. - Mean slopes of post-task regression patterns for each task location and for each refractive group. Figures in brackets represent standard deviations. Computed values of t and p are also given for each task location.

TASK LOCATION	SLOPE (x 10^{-3} D.SEC^{-1})		T-TEST	
	EMMETROPES	MYOPES	t	p
-1.00	-1.85 (4.94)	-0.89 (4.19)	0.58	0.568
-3.00	-9.31 (5.03)	-4.39 (4.67)	2.78	0.010
-5.00	-9.97 (5.97)	-3.21 (5.93)	3.11	0.004

7.3C - Discussion

Several previous workers have investigated the relationship between tonic accommodation (TA) and refractive error, most of whom have produced inconclusive results (see section 1.7C pps. 63-68). The study reported in chapter 5 (pps. 141-149) demonstrated, however, that late-onset myopes have lower values of TA than emmetropes (myopic mean = 0.81 D, s.d. = 0.46; emmetropic mean = 1.14 D, s.d. = 0.46; t = 2.00, d.f. = 28, p = 0.05) and the results of the present study support these findings (myopic mean = 0.75 D, s.d. = 0.19; emmetropic mean = 1.10 D, s.d. = 0.36; t = 3.25, d.f. = 28, p = 0.003). It is interesting to note that the difference in TA between the two refractive groups is similar for both studies, yet the results of the present study achieve greater significance due to the narrower distribution of the two groups.

It is clear from the post-task regression patterns shown in Figs. 7.6 and 7.7 that, for the -3 and -5 D tasks, the myopic group show significantly flatter regression slopes than the emmetropes. It is not unreasonable to assume, therefore, that the post-task shifts in TA takes longer to dissipate in the myopic group. It is proposed that differences in the adaptational facility of the two refractive groups imply that there is a relationship between excessive near-work and myopia. It is fundamental to such a proposal, however, that the differences between the two groups are greatest for task locations requiring the greatest levels of accommodation. It is important, therefore, to note that the difference between the regression characteristics of the two groups is greatest for the task requiring the highest level of accommodation, *viz.* the -5 D task (see Table 7.3).

In a recent report McBrien (1987) compared pre- and post-task values of TA for 11 hyperopes, 16 emmetropes, 10 early-onset myopes and 10 late-onset myopes using the Canon R-1 autorefractor, post-task TA being monitored for a 15 minute period. Subjects participated in four experimental sessions, performing a visual counting task at four locations *viz.* 6m, their pre-task TA position, 37cm and 20cm. McBrien found that late-onset myopes showed significant positive post-task shifts in TA for both near task locations which did not decay during the 15 minute post-task period. Conversely, hyperopes showed transient decreases in TA for both near tasks while emmetropes and early-onset myopes showed little change in TA. McBrien's results, therefore, show similar trends to those of the present study, post-task shifts taking longer to decay in late-onset myopes. McBrien suggests that changes in TA may play a role in refractive development.

In a similar experiment, Fisher *et al.* (1987b) examined the effect of a 10 minute period of monocular fixation at the near point on TA. Subjects consisted of 12 hyperopes, 12 emmetropes, 12 low myopes and 12 high myopes and measures of TA, far point and near point were made using a subjective Hartinger optometer. The task produced significant increases in both TA and near point, the largest changes being recorded for the high myope group. It is generally considered that myopia which is early in onset reaches higher levels than late-onset myopia (Goldschmidt, 1968). It would appear, therefore, that the results of McBrien (1987) and Fisher *et al.* (1987b) are contradictory: McBrien claiming that late-onset (presumably low) myopes show larger sustained post-task shifts in TA whilst Fisher and her co-workers report that high (probably early-onset) myopes are more susceptible to adaptation of TA. It would be prudent, however, to avoid further comparison of these two studies until the results are published in full.

Inspection of the post-task data of the present study, reveals that the myopic group show a increase in mean TA of around +0.15 D following the -1 D task which shows little regression towards pre-task values. This may be explained by the findings of Baker *et al.* (1983) who investigated the time-course of TA following 5 seconds fixation at 0, -1, -2 and -3 D using an infra-red optometer. They proposed the existence of a zone of 'inactive accommodation' within which accommodation was relatively stable in darkness, rather than a single resting position. Following fixation at stimulus levels within the rest zone there would be little change in accommodation when the lights were extinguished. It is possible, therefore, that the -1 D stimulus lies within the rest zone for the myopic group and that consequently accommodation shows little regression towards pre-task levels when the lights are extinguished.

The proposals of Baker *et al.* (1983) may be applied to the data for the -5 D location. Their results demonstrated that following fixation proximal to the rest zone TA drifted towards the near edge of the zone. In the present study the -5 D task induces a mean increase in TA for both refractive groups but the increase is more sustained for the myopic group. It is possible, therefore, that this is due to the myopic group having a larger zone of inactive accommodation than the emmetropic group. This proposal could be examined by measuring changes in post-task TA for a larger number of task locations close to the zone of inactive accommodation.

It is interesting to note that during the first 30 seconds following the -3 and -5 D tasks the emmetropic group show a greater increase in TA than do the myopic group. Although the initial shifts in TA are smaller for the myopic group, they take longer to dissipate. A possible explanation for this difference in regression patterns is that the initial increase in TA for the emmetropic group initiates counter-adaptive mechanisms, i.e. processes which result in a more rapid decay of post-task shifts in TA. The mean TA value for the emmetropic group 10 seconds immediately post-task approaches 2.00 D, whereas the mean TA value for the myopic group is around 1.25 D. It is possible that the higher level of TA triggers mechanisms that result in the adaptation of TA dissipating more swiftly in the emmetropic group. The study in chapter 3 (pps. 107-125) demonstrated that, in emmetropes, inhibitory sympathetic innervation of ciliary smooth muscle provides the facility to attenuate the magnitude and duration of the positive shifts in TA induced by a near-vision task. The facility was, however, restricted to those individuals having relatively high levels of pre-task TA. It is feasible, therefore, that since the myopic group have lower levels of pre-task TA and, indeed, lower levels TA immediately following the task, the lack of inhibitory facility results in more sustained adaptation effects.

The cognitive demand of the visual task may play a role in the differences in post-task regression patterns of the two refractive groups. The results described in chapter 5 (pps. 141-149) demonstrate that the imposition of mental effort induces a significant increase in TA (mean = +0.35 D) for late-onset myopes compared with emmetropes (mean = +0.07 D). No attempt was made in the present study to influence or monitor mental activity during the post-task measurement period but the mental effort exerted during the task may have a prolonged effect on a subject's TA although this remains speculative.

This study has demonstrated significant differences in the adaptational facility of late-onset myopes and emmetropes and that increases in TA induced by a sustained near-vision task take longer to decay in late-onset myopes than emmetropes. It remains speculation, however, as to whether an accumulation of short-term task induced changes in TA can result in a myopic shift in the refractive state of the eye. Further aspects of adaptation of TA and the development of late-onset myopia are discussed in the final chapter.

CHAPTER 8

GENERAL DISCUSSION AND CONCLUSIONS

8.1 - REVIEW OF EXPERIMENTAL RESULTS

Infra-red optometry has been employed to investigate various aspects of the accommodative response. The majority of the experiments conducted have been published or are in press. A brief review of the contributions made by the current programme of research is given below.

1. Laser optometry and infra-red optometry provide estimates of tonic accommodation (TA) which are well correlated (see section 2.2 pps. 80-93 and Bullimore *et al.*, 1986).

2. Near retinoscopy results can be mathematically adjusted to yield reasonable estimates of TA (see section 2.2 pps. 80-93 and Bullimore *et al.*, 1986).

3. The accuracy of the accommodative response decreases with increasing retinal target eccentricity. This decrease in accuracy can be attributed to the increase in minimum angle of resolution associated with increasing retinal eccentricity (see section 2.3 pps. 93-102 and Bullimore and Gilmartin, 1987b and 1987d).

4. Following a ten minute visual task at -5 D emmetropes show a +0.40 D increase in TA which dissipates in around 50 seconds (see Chapter 3 pps. 107-125 and Gilmartin and Bullimore, 1987).

5. In emmetropes inhibitory sympathetic innervation of ciliary smooth muscle provides the facility to attenuate the magnitude and duration of positive shifts in TA induced by sustained near-vision tasks. This facility is, however, restricted to those individuals with relatively high levels of pre-task TA. In addition, concurrent parasympathetic activity is a pre-requisite for the operation of sympathetic inhibition (see Chapter 3 pps. 107-125 and Gilmartin and Bullimore, 1987).

6. The imposition of mental effort can induce concurrent changes in TA which are

largely positive in magnitude and predominantly due to an increase in parasympathetic innervation to the ciliary muscle (see Chapter 4 pps. 126-140 and Bullimore and Gilmartin, 1987a).

7. Late-onset myopes have significantly lower values of TA than emmetropes (see Chapter 5 pps. 141-149, section 7.3 pps. 184-194 and Bullimore and Gilmartin, 1986a and 1987e).

8. The imposition of mental effort induces a concurrent increase in TA in late-onset myopes which is significantly greater than that in emmetropes (see Chapter 5 pps. 141-149 and Bullimore and Gilmartin, 1986a and 1987e).

9. In emmetropes the imposition of mental effort induces a concurrent increase in accommodative response for a -1 D stimulus, no change in response at -3 D and a reduction in response at -5 D. In myopes the imposition of mental effort induces an increase in accommodative response at all stimulus locations (see section 6.2 pps. 160-168).

10. In emmetropes sympathetic inhibition can modify the effect of mental effort on the near accommodative response (see section 6.1 pps. 150-159 and Bullimore and Gilmartin, 1986b).

11. Late-onset myopes have significantly lower values of steady-state accommodative response than emmetropes (see sections 6.2 pps. 160-168 and 7.2 pps. 184-194).

12. Estimates of TA obtained under bright empty-field conditions are well correlated with those obtained under darkroom conditions. There is little or no difference in the regression of TA towards pre-task values between darkroom and empty-field post-task conditions (see section 7.2 pps. 173).

13. Significant differences in the post-task shifts in TA induced by sustained near-vision tasks exist between late-onset myopes and emmetropes. The post-task shifts in TA take longer to dissipate in the myopic group (see section 7.3 pps. 184-194).

8.2 - DISCUSSION OF EXPERIMENTAL RESULTS

The present thesis has considered the factors affecting the accommodative response during sustained visual tasks, in particular the adaptation of tonic accommodation (TA). These studies have considered five main areas:

1. The evaluation of objective techniques of TA measurement.
2. An investigation of the time course of the adaptation of TA to sustained visual tasks.
3. An evaluation of the role of the sympathetic innervation of the ciliary muscle in the adaptation of TA.
4. An investigation of the contribution of cognitive demand of the task to the adaptation properties of TA.
5. A comparison of the the adaptation of TA in emmetropia and late-onset myopia.

8.2A - The evaluation of objective techniques of TA measurement

The methodological studies described in Chapter 2 (pps. 80-93) compared the measurement of TA by three techniques; infra-red optometry, He-Ne laser optometry and near retinoscopy. Measurements of TA made by infra-red optometry, using the Canon R-1 autorefractor, correlated well with those obtained by the more established technique of laser optometry. This is at variance with the study of Post *et al.* (1984) who found a poor agreement between infra-red and laser techniques. This discrepancy may be partially explained by the laser speckle exposure times adopted by the two studies, which is thought to be a contaminant of laser estimates of TA (Hogan and Gilmartin, 1984b; Kothe *et al.*, 1987). Furthermore, it was found that reasonable estimates of TA could be determined by mathematical adjustment of near retinoscopy results. Hence optometrists in practice can use near retinoscopy to gain access to the refractive data which may aid the clinical management of the anomalous myopias and ocular problems associated with VDU work.

The question of correction factors for laser and infra-red optometry was also addressed in Chapter 2 (pps. 88-93 and 102-106). An attempt was made to determine the correction factor necessary to obtain an 'absolute' value of accommodation for the Canon R-1. This was estimated to be +0.20 D. All measures of accommodation in subsequent chapters were adjusted to account for this factor. Finally the relationship between retinal target eccentricity and the accommodative response was examined. It was found that the accuracy of the accommodative response diminishes with increasing target eccentricity and that targets more than 10 degrees from the fovea have little influence on accommodation. It is likely that this decrease in accommodative accuracy is due to the decrease in visual acuity with increasing retinal eccentricity. It is proposed that in future studies of the accommodative response experimenters should avoid using apertures with radii less than ten degrees.

8.2B - The time-course of the adaptation of TA

Previous studies of the adaptation of TA and accommodative hysteresis have produced somewhat conflicting results concerning the duration of TA after-effects. Ebenholtz (1983), using laser optometry, estimated that the increases in TA produced by an 8 minute period of near point fixation should take 10.26 hours to decay. Tan and O'Leary employed similar experimental apparatus and found that the increases in TA produced by a one hour reading task at -3 D were still present at the end of a 6 hour post-task measurement period. Conversely, Wolf *et al.* found that TA, measured with a haploscope optometer, returned to baseline levels within 3 minutes of the cessation of a 45 minute binocular reading task at -5 D.

The work described in Chapter 3 (pps. 107-125) investigated the time-course of the adaptation of TA. It was found that a ten minute visual task at -5 D induced a post-task increase in TA of around +0.50 D. Accommodation returned to pre-task levels, however, within around 50 seconds. These findings agree with those of Schor *et al.* (1986) who employed infra-red optometry to demonstrate that under darkroom conditions TA regressed to baseline values in around 5 to 10 seconds following one minute fixation at -2 D. It should be noted that studies which have employed laser optometry (e.g. Ebenholtz, 1983; Hogan, 1985; Tan and O'Leary, 1986) have found more sustained TA after-effects than those using infra-red optometry (Schor *et al.*, 1986; see Chapter 3 pps. 107-125). It is proposed, therefore, that the interactive nature of the laser optometer enhances the duration of post-task increases in TA. Furthermore it could be argued that the cognitive demand associated with laser optometry contributes to the increased decay-times found by Ebenholtz (1983) and Tan and O'Leary (1986). The influence of cognitive demand on accommodation is discussed further in section 8.2D.

8.2C - The role of the sympathetic innervation of the ciliary muscle in the adaptation of TA

The influence of the non-selective beta receptor antagonist timolol maleate on the post-task shifts in TA produced by sustained visual tasks was investigated in Chapter 3 (pps. 107-125). The regression of TA towards pre-task values was examined over a 90 second measurement period following a ten minute visual counting task at far (-0.3 D) and at near (-5.0 D) subsequent to the instillation of timolol or saline. Beta-antagonism induced significant differences between far and near regression patterns during the 50 second period immediately following the task. This demonstrates that inhibitory sympathetic innervation of the ciliary muscle provides the facility to attenuate the magnitude and duration of the positive shifts in TA induced by sustained near-vision. The facility was restricted, however, to those individuals having relatively high levels of pre-task TA. It is proposed, therefore, that subjects with relatively high values of TA have a sympathetic facility that is augmented by substantial levels of concurrent parasympathetic activity.

The above findings support the original proposal of Gilmartin and Hogan (1985a) that the sympathetic input to the ciliary muscle serves to attenuate task-induced increases in TA. This proposal was based on the studies of Ebenholtz (1983) and Hogan (1985).

Hogan (1985) investigated the effect of a 15 minute interactive task at 2.75, 1.00 and 0.33m on TA and tonic vergence (TV) in 27 subjects. For the far and intermediate tasks, post-task changes in TA and TV were biased towards the task position and proportional to the dioptric distance between the task and the subject's pre-task resting position. For the near task, however, the positive shifts in TA and TV were reduced significantly when the difference between the task location and initial TA and TV positions was greater than 1.5 D and 3.5 degrees respectively, i.e. for relatively low values of TA and TV. This led Gilmartin and Hogan (1985a) to propose that this attenuation of post-task increases in TA may be mediated by the inhibitory sympathetic input to the ciliary muscle. The findings of Chapter 3 demonstrate, however, that subjects having relatively low levels of pre-task TA do not have access to an inhibitory sympathetic facility. It would appear that although the original postulate of Gilmartin and Hogan has been shown to be correct, it is subjects with relatively high levels of TA that have access to an inhibitory sympathetic facility. It should be acknowledged, however, that study of Hogan (1985) was conducted using a subjective laser optometer which may affect the categorization of pre-task levels of TA.

8.2D - The contribution of cognitive demand of the task to the adaptation of TA

The study described in Chapter 4 (pps. 126-140) demonstrated that a task involving relatively high levels of mental load can produce significant shifts in TA. These shifts are mainly positive and appear to be predominantly parasympathetically mediated, although there is evidence than the inhibitory sympathetic innervation to the ciliary muscle may attenuate these changes at higher levels of TA.

A comparison of the influence of the imposition of a mental effort on TA was made for emmetropes and late-onset myopes and reported in Chapter 5 (pps. 141-149). Under the passive condition late-onset myopes (mean TA = 0.81 D, s.d. = 0.46 D) were found to have lower values of TA than emmetropes (mean TA = 1.14 D, s.d. = 0.46 D). The imposition of mental effort, however, induced a positive shift in TA for the myopic group (mean = +0.35 D, s.d. = 0.31 D) which was significantly higher than that for the emmetropic group (mean = +0.07 D, s.d. = 0.27 D). It is possible, therefore, that the cognitive demand associated with the subjective laser optometer may mask the difference in TA between the two groups. This would partially explain why the majority of previous workers have found no convincing relationship between refractive error and TA.

The influence of mental effort on the steady-state accommodative response was investigated in Chapter 6 (pps. 150-169). For a group of emmetropic subjects the imposition of mental effort induced a significant increase in mean respose for a -1 D stimulus, a response equivalent to the passive condition at - 3 D stimulus and a reduction in response at -5 D. Mental effort induced similar responses for the -1 and -3 D locations when sympathetic innervation to the ciliary muscle was blocked with timolol. Responses for the -5 D location were, however, significantly increased and it is proposed that sympathetic inhibition can modify the effect of mental effort on the near accommodative response.

The effect of mental effort on the steady-state accommodative response was compared in emmetropes and late-onset myopes. For the passive condition the myopic subjects showed a significantly lower accommodative response than the emmetropic group. For the emmetropic subjects the imposition of mental effort induced a significant increase in mean respose for the -1 D stimulus, a response equivalent to the passive condition for the - 3 D stimulus and a reduction in response at -5 D. For the late-onset myopes the imposition of mental effort induced an increase in accommodative response for all stimulus locations. The results for the myopic subjects were consistent with those for emmetropic subjects who showed parasympathetically-mediated cognitive induced shifts in accommodative response and no evidence for an inhibitory sympathetic input. This finding supports the proposal that late-onset myopes do not have access to an inhibitory sympathetic facility.

The above studies have demonstrated conclusively that the imposition of mental effort can influence a subject's TA and steady-state accommodative response. This finding has ramifications for any study of accommodation which employs a subjective optometer since the value of accommodation recorded by the instrument may have been artificially elevated or depressed due to the cognitive demand inherent in the method of measurement. Although it was found in section 2.2 (pps. 80-93) that estimates of TA in emmetropes recorded by infra-red optometry correlated with those determined by laser optometry, the findings of chapter 5 (pps. 141-149) would suggest that a poorer relationship would be found if the experiment was repeated with late-onset myopes, since they have been shown to be more susceptible to cognitive induced shifts in TA.

8.2E - The adaptation of TA in emmetropia and late-onset myopia

One of the most challenging proposals addressed in this thesis is that of Ebenholtz (1983) who postulated that accommodative hysteresis or the adaptation of TA is a precursor to induced myopia. It is well established that a sustained near-vision task can result in increases in TA (see section 1.5D pps. 50-55). It is unclear, however, if, and how, these short-term task-induced changes in TA accumulate to an extent whereby the manifest refractive state of the eye is altered.

It was proposed in Chapter 7 (pps. 170-194) that, if late-onset myopia is the result of excessive tonic adaptation, individuals with myopia which is late in onset would be more susceptible to increases in TA induced by a sustained near-vision task. This proposal was investigated by comparing the regression of TA towards pre-task values following a ten minute visual counting task at -1, -3 and -5 D in fifteen late-onset myopes and fifteen emmetropes. Significant differences in the post-task shifts in TA were found between the two refractive groups. Although the initial increase in post-task TA is greatest for the emmetropic group, the myopic group show more sustained shifts in TA as evinced by significantly flatter post-task regression patterns. It may be assumed, therefore, that the post-task shifts in TA take longer to dissipate in the myopic group. It is also important to emphasise that the difference between the regression characteristics of the two groups was shown to be greatest for the task requiring the highest level of accommodation. These results provide further evidence for the role of accommodation in the development of refractive errors, principally late-onset myopia.

8.3 - CONCLUSIONS AND POSSIBLE AREAS FOR FUTURE RESEARCH

The thesis has considered various factors associated with the adaptation of tonic accommodation (TA). Certain fundamental aspects of the adaptation process need to be considered further, particularly with respect to the development of late-onset myopia. The present study has shown that post-task shifts in TA take longer dissipate in the myopic group than in the emmetropic group. If short-term task induced changes in TA are culmulative one might expect late-onset myopes to have higher values of TA than emmetropes. The findings of Chapter 3 and 7 demonstrate, however, that late-onset myopes have lower TA values than emmetropes. A possible explanation is that late-onset myopes show more sustained adaptation of TA for distance vision as well as for near-vision. A period of sustained distance fixation, *e.g.* sitting in a lecture, would thus induce a more sustained reduction in TA in myopes. It would prove interesting, therefore to compare the adaption of TA for distance vision in the two groups.

If we assume that all of the subjects participating in this programme of research undertook a similar amount of near-work it might be expected that the individuals who are more susceptible to TA after-effects would show an increase in TA over a given time. It is interesting to note than Owens and Harris (1986) have recently reported that subjects' TA values increase during the first year of college and propose that this is associated with the amount of near-work. It would be very interesting to conduct a longitudinal study comparing changes in TA and refractive error in emmetropes and late-onset myopes. The results of such a study would hopefully contribute to the understanding of adaptation of TA.

The possible mechanisms by which accommodation results in myopia have been reviewed in section 1.7C (pps. 63-68). If excessive tonic adaptation is a precursor to late-onset myopia, then it is clearly important that the processes by which the cumulative increases in TA become manifest myopic shifts in refraction are understood. Recent work has suggested that the changes in refractive error in late-onset myopia are due to an increase in axial length (Adams *et al.*, 1986; Adams, 1987) and preliminary studies within this department would support this hypothesis. How then do changes in ciliary tonus induce increases in axial length? It is possible that changes in vitreous pressure play an important role in the mechanism (Young, 1975). Young (1975) demonstrated that, in monkeys, near-point accommodation induces an increase in vitreous pressure of around 6-7mmHg. It is possible, therefore that an increase in TA may produce a small but significant elevation increase in vitreous pressure. It is interesting to note that Westheimer and Blair (1973b) found that during sleep accommodation assumes its tonic resting position. It is feasible, therefore, that increases in TA following a day of sustained near-vision contribute to the elevation of vitreous pressure during sleep. Further physiological research into accommodation and intraocular pressure during sleep may provide interesting results concerning the mechanisms of axial elongation.

It is important to acknowledge that the premise that task-induced increases in TA lead to myopia (Ebenholtz, 1983) is inconsistent with the theory of emmetropization as proposed by Van Alphen (1961). Ebenholtz postulated that increases in ciliary tone might accumulate to an extent whereby the manifest refractive state of the eye is altered. Conversely, under Van Alphen's model myopia is brought about by low ciliary-choroidal tone. It seems difficult, therefore, to find any common ground between these two theories of refractive error development. The findings of this thesis would support Van Alphen's prediction that myopes have lower ciliary tone than emmetropes. Van Alphen postulated, however, that this was the result of a strong sympathetic input to the ciliary muscle yet the findings of Chapter 3 (pps. 107-125) would suggest that individuals having low values of TA do not have access to an inhibitory sympathetic input.

The present research programme has demonstrated that a sustained near visual task can induce transient increases in TA, supporting the original findings of Ebenholtz (1983).

The changes in TA found in the present studies were, however, less sustained than those reported by Ebenholtz. He predicted that the increase in TA produced by 8 minutes near-point fixation would take over 10 hours to decay whereas the results of Chapters 3 and 7 (pps. 107-125 and 170-194 respectively) demonstrate that, in emmetropes, the TA after-effects produced by a 10 minute task dissipate within 60 seconds. Ebenholtz also postulated that the adaptation of TA was a precursor to induced myopia. It is encouraging, therefore, to note that TA after-effects are more sustained in late-onset myopes.

A final problem that should be addressed is whether those individuals who have developed late-onset myopia show the same accommodative characteristics as when they were emmetropic or indeed hyperopic. Did they, for example, always have low values of TA or is this a product of the myopic shift in refraction. It is possible that the different accommodative characteristics found in late-onset myopia are a form of oculomotor adaptation to the change in refractive error. Alternatively, the increase in axial length may have weakened the choroid and sclera which has subsequently lowered the ciliary tone. This would seem unlikely since ciliary muscle tone is almost certainly neurogenic in origin (Van Alphen, 1961; Lograno and Reibaldi, 1986). An appropriate approach to this problem would be to conduct a longitudinal study of refraction and TA in teenagers. Indeed, it would be interesting to discover whether emmetropes with low values of TA are more predisposed to developing late-onset myopia than those with high TA values. The findings of this study would suggest that those subjects with low TA values would be more likely to become myopic, possibly due to a lack of inhibitory sympathetic facility.

APPENDIX I

THE MEASUREMENT OF TA BY LASER OPTOMETRY, INFRA-RED OPTOMETRY AND NEAR RETINOSCOPY

Table I.1 - Values of tonic accommodation (in dioptres) as measured by laser optometry, infra-red optometry and near retinoscopy for 25 subjects. Laser measures do not incorporate a correction factor for chromatic aberration.

SUBJECT	LASER OPTOMETRY	INFRA-RED OPTOMETRY	NEAR RETINOSCOPY
JW	2.26	2.69	1.62
NC	0.73	1.02	0.62
JW	1.34	1.67	1.50
IT	0.60	0.28	0.75
BC	1.10	1.16	1.00
GE	0.76	0.74	0.75
TT	3.43	4.03	2.00
CP	1.52	1.38	1.25
JR	1.04	1.06	1.12
SR	0.62	1.27	0.87
MB	1.55	1.21	1.25
CT	0.78	1.33	0.93
RD	0.30	0.74	0.75
RD	2.04	1.36	1.25
PC	-0.06	-0.13	0.50
AD	1.29	0.61	1.12
ND	0.79	1.38	1.50
MP	1.54	1.38	1.62
JS	1.60	1.36	2.00
CM	0.79	0.92	0.75
TM	1.03	0.56	0.75
AH	0.27	0.34	0.62
PD	0.85	1.00	0.75
WG	0.25	0.38	0.38
KD	0.98	1.10	0.87

Table I.2 - Values of tonic accommodation/cycloplegic refraction (in dioptres) as measured by laser optometry and infra-red optometry following the instillation of 0.5% tropicamide for 10 subjects. Laser measures do not incorporate a correction factor for chromatic aberration.

SUBJECT	LASER OPTOMETRY	INFRA-RED OPTOMETRY
IT	-0.21	-0.10
BC	0.32	0.03
MP	0.30	0.39
JW	0.66	0.28
JW	-0.05	0.32
NC	0.07	0.31
EM	0.24	0.52
MB	0.16	0.55
TM	0.06	0.11
CT	0.12	0.11

Table I.3 - Consecutive values of tonic accommodation (in dioptres) as measured by infra-red optometry for ten subjects for a five minute period. Each value of TA represents mean of readings taken per ten second period.

TIME (secs)	SUBJECT									
	MB	SR	CT	JW	JR	NC	TM	BC	MP	JW
10	0.28	0.77	0.32	0.61	0.13	0.34	0.36	0.09	0.15	0.32
20	0.29	0.62	0.15	0.62	0.14	0.32	0.40	0.16	0.27	0.23
30	0.28	0.67	0.22	0.58	0.10	0.26	0.40	0.14	0.22	0.33
40	0.33	0.74	0.10	0.46	0.10	0.26	0.38	0.19	0.26	0.40
50	0.26	0.77	0.01	0.35	0.07	0.28	0.45	0.19	0.20	0.56
60	0.29	0.79	0.05	0.45	0.17	0.35	0.55	0.20	0.23	0.41
70	0.36	0.74	0.09	0.45	0.11	0.30	0.55	0.16	0.23	0.48
80	0.39	0.66	0.00	0.46	0.17	0.30	0.58	0.18	0.26	0.49
90	0.34	0.72	0.25	0.47	0.09	0.27	0.53	0.21	0.29	0.48
100	0.36	0.73	0.09	0.49	0.09	0.32	0.55	0.20	0.27	0.38
110	0.31	0.58	0.04	0.41	0.12	0.34	0.67	0.15	0.31	0.37
120	0.28	0.54	0.04	0.41	0.06	0.37	0.60	0.08	0.31	0.47
130	0.29	0.59	-0.05	0.40	0.12	0.16	0.50	0.12	0.22	0.44
140	0.34	0.60	-0.10	0.37	0.04	0.23	0.40	0.16	0.20	0.44
150	0.32	0.60	-0.03	0.53	0.02	0.25	0.37	0.10	0.31	0.34
160	0.34	0.37	0.07	0.33	0.03	0.21	0.39	0.08	0.16	0.25
170	0.38	0.44	0.31	0.43	0.02	0.27	0.19	0.09	0.15	0.25
180	0.28	0.51	0.17	0.53	0.02	0.28	0.35	0.14	0.29	0.23
190	0.37	0.35	0.03	0.42	0.09	0.25	0.40	0.19	0.18	0.25
200	0.50	0.42	0.18	0.53	0.02	0.36	0.12	0.15	0.26	0.29
210	0.33	0.39	0.16	0.41	0.05	0.33	0.02	0.09	0.22	0.22
220	0.30	0.50	0.02	0.38	0.04	0.11	0.00	0.21	0.24	0.30
230	0.30	0.51	0.00	0.41	0.08	0.17	0.29	0.16	0.19	0.31
240	0.28	0.43	0.10	0.64	0.02	0.18	0.35	0.16	0.18	0.27
250	0.30	0.50	0.22	0.56	0.02	0.12	0.49	0.16	0.19	0.41
260	0.31	0.55	0.27	0.63	0.07	0.04	0.30	0.23	0.13	0.34
270	0.36	0.56	0.20	0.65	0.09	0.16	0.11	0.15	0.21	0.26
280	0.40	0.51	0.16	0.48	0.17	0.25	0.28	0.15	0.17	0.31
290	0.28	0.51	0.13	0.57	0.10	0.25	0.25	0.16	0.16	0.27
300	0.28	0.38	-0.02	0.47	-0.03	0.11	0.54	0.19	0.22	0.20
MEAN	0.32	0.57	0.11	0.48	0.08	0.25	0.37	0.15	0.22	0.35
S.D.	0.05	0.13	0.11	0.09	0.05	0.08	0.18	0.04	0.05	0.10

APPENDIX II

THE INFLUENCE OF RETINAL TARGET ECCENTRICITY ON THE ACCOMMODATIVE RESPONSE

Table II.1 - Values of accommodative response (in dioptres) for seven subjects viewing targets of six retinal eccentrity at five stimulus vergences. RTE = retinal target eccentricity (in degrees), SV = stimulus vergence (in dioptres).

RTE	SV	SUBJECT								
		RL	BF	RD	HS	JH	JL	TB	MEAN	S.D
0.5	0	-0.16	0.78	0.72	0.70	0.94	0.85	0.66	0.64	0.34
	-1	0.36	1.02	1.45	1.26	1.20	1.25	1.10	1.09	0.32
	-2	1.29	1.98	2.29	2.04	1.91	2.02	1.96	1.93	0.28
	-3	1.87	2.66	3.15	2.97	2.76	2.90	2.85	2.74	0.38
	-4	2.60	3.60	3.93	4.07	3.59	4.14	3.81	3.68	0.48
1.0	0	0.15	0.32	0.77	0.82	0.91	0.91	0.42	0.61	0.29
	-1	0.55	0.82	1.24	1.26	0.91	1.33	1.11	1.03	0.26
	-2	1.27	1.39	2.09	2.26	1.22	1.90	1.95	1.73	0.39
	-3	2.06	2.16	3.11	2.94	2.29	2.91	3.01	2.64	0.42
	-4	2.70	3.42	4.09	4.00	3.52	4.09	3.84	3.67	0.47
2.0	0	-0.18	0.57	0.71	0.87	0.88	0.73	0.57	0.59	0.34
	-1	0.29	0.56	1.26	1.40	0.96	1.23	1.01	0.96	0.37
	-2	1.32	1.76	2.21	2.07	1.13	2.04	1.65	1.74	0.37
	-3	1.84	2.61	2.78	2.96	2.31	2.87	2.63	2.57	0.36
	-4	2.92	2.91	3.81	4.27	1.43	4.16	3.62	3.30	0.91
3.0	0	-0.11	0.39	0.71	0.66	0.85	1.04	0.43	0.57	0.35
	-1	0.26	0.43	0.98	1.07	1.09	1.39	0.62	0.83	0.38
	-2	0.41	0.18	1.64	1.61	1.29	1.98	1.55	1.24	0.63
	-3	1.64	0.23	2.81	2.48	2.10	2.81	2.48	2.08	0.85
	-4	1.52	0.93	3.64	3.21	2.91	3.32	3.49	2.72	0.98
5.0	0	0.01	0.41	0.47	0.82	0.92	1.08	0.41	0.59	0.34
	-1	0.16	0.36	0.60	1.20	1.06	1.26	0.64	0.75	0.40
	-2	0.63	0.63	1.16	1.73	1.19	1.92	1.29	1.22	0.46
	-3	1.24	0.66	2.18	2.67	1.04	2.83	2.30	1.85	0.79
	-4	1.42	0.76	3.24	3.04	1.33	3.34	3.12	2.32	1.02
10.0	0	-0.13	0.28	0.52	1.26	0.89	1.66	0.76	0.75	0.55
	-1	0.03	0.55	0.77	1.40	0.87	1.30	0.56	0.78	0.44
	-2	0.14	0.43	0.91	1.55	0.82	1.73	0.57	0.88	0.54
	-3	0.20	0.03	1.61	1.54	0.74	1.45	0.96	0.93	0.60
	-4	0.18	0.01	2.43	1.68	0.85	1.51	1.86	1.22	0.83

APPENDIX III

THE ROLE OF SYMPATHETIC INNERVATION IN THE ADAPTATION OF TA

Table III.1 - The effect on the TA (in dioptres) of fifteen subjects of a ten minute sustained visual task at -0.30 D following the instillation of saline. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

FAR SALINE

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
JH	1.01	-0.11	-0.03	+0.01	+0.05	-0.03	-0.09	-0.20	-0.35	-0.28
DJ	1.7	+0.10	+0.89	+0.34	+0.33	+0.11	+0.09	-0.08	+0.04	-0.13
JM	1.87	+0.66	+0.13	+0.05	+0.02	-0.19	-0.06	-0.02	+0.06	+0.06
RDF	1.01	-0.26	-0.27	-0.20	-0.14	+0.03	-0.04	-0.19	-0.12	-0.04
TB	0.38	+0.03	+0.12	+0.05	-0.04	-0.09	+0.04	-0.08	-0.03	-0.09
PC	0.13	+0.38	+0.36	+0.34	+0.28	+0.27	+0.24	+0.34	+0.41	+0.35
BF	0.70	+0.13	+0.09	+0.24	+0.08	-0.18	-0.29	-0.35	-0.23	-0.26
SB	0.14	+0.50	+0.22	+0.13	+0.05	+0.07	+0.07	+0.07	+0.01	+0.06
RD	0.91	-0.09	-0.04	-0.08	+0.10	+0.07	+0.05	0.00	-0.07	+0.07
JE	0.89	-0.02	-0.04	0.00	0.00	+0.02	+0.08	+0.03	-0.35	-0.35
ND	1.79	-0.45	-0.45	-0.49	-0.63	-0.55	-0.39	-0.37	-0.46	-0.26
AD	0.81	-0.23	-0.05	-0.19	-0.37	-0.28	-0.20	+0.06	+0.04	-0.08
IT	0.33	+1.34	+0.74	+0.58	+0.36	+0.24	+0.23	+0.12	-0.07	+0.10
SS	1.04	+0.41	+0.36	0.00	+0.25	+0.03	-0.14	-0.20	+0.03	+0.14
TM	0.68	+0.30	+0.37	+0.36	+0.41	+0.32	+0.37	+0.44	+0.41	+0.41
MEAN	0.85	+0.18	+0.16	+0.08	+0.05	-0.01	-0.03	-0.03	-0.05	-0.02
S.D.	0.49	0.42	0.34	0.26	0.27	0.22	0.20	0.22	0.24	0.22

Table III.2 - The effect on the TA (in dioptres) of fifteen subjects of a ten minute sustained visual task at -0.30 D following the instillation of timolol. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

FAR TIMOLOL

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
JH	1.01	+0.04	+0.04	-0.03	-0.15	-0.12	-0.17	-0.18	-0.24	-0.24
DJ	1.17	+0.50	+0.76	+0.50	+0.25	+0.19	+0.21	-0.10	-0.13	-0.22
JM	1.55	+0.09	-0.23	-0.27	-0.36	-0.28	-0.32	-0.18	-0.31	-0.09
RDF	1.13	-0.10	-0.04	+0.06	+0.03	+0.05	+0.04	+0.14	+0.24	+0.27
TB	0.40	+0.17	+0.03	+0.15	+0.14	+0.06	+0.08	+0.20	+0.19	+0.09
PC	0.24	+0.44	+0.21	+0.24	+0.20	+0.11	+0.15	+0.08	+0.24	+0.40
BF	0.52	+1.23	+0.90	+0.17	+0.35	+0.24	+0.35	+0.36	+0.19	+0.07
SB	0.11	+0.21	+0.32	+0.29	+0.16	+0.20	0.00	+0.03	+0.18	+0.08
RD	1.07	+0.04	+0.07	+0.01	+0.13	+0.12	+0.04	-0.13	-0.14	-0.13
JE	0.74	+0.08	-0.17	-0.12	-0.14	+0.05	-0.09	-0.05	+0.01	+0.06
ND	1.44	-0.43	-0.35	-0.42	-0.34	-0.44	-0.51	-0.53	-0.46	-0.43
AD	0.81	+0.05	-0.11	-0.60	-0.38	-0.09	+0.10	+0.25	+0.09	+0.04
IT	0.41	+1.01	+0.89	+0.51	+0.44	+0.37	+0.37	+0.13	+0.19	+0.15
SS	0.81	+0.30	+0.06	-0.03	+0.25	+0.03	+0.12	+0.23	+0.20	+0.20
TM	0.56	+0.01	+0.01	-0.15	-0.16	0.00	0.00	+0.09	+0.17	+0.01
MEAN	0.80	+0.24	+0.16	+0.02	+0.03	+0.03	+0.02	+0.02	+0.03	+0.02
S.D.	0.41	0.41	0.38	0.30	0.26	0.22	0.22	0.22	0.22	0.21

Table III.3 - The effect on the TA (in dioptres) of fifteen subjects of a ten minute sustained visual task at -5.00 D following the instillation of saline. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

NEAR SALINE

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
JH	1.19	+0.08	+0.09	-0.12	-0.14	-0.31	-0.35	-0.22	-0.10	+0.03
DJ	1.03	0.00	-0.03	-0.09	-0.15	-0.18	-0.21	-0.14	-0.06	+0.01
JM	1.87	+0.95	+0.34	+0.08	-0.03	-0.39	-0.60	-0.53	-0.47	-0.40
RDF	1.14	-0.05	-0.02	+0.05	+0.21	+0.16	+0.26	+0.03	-0.21	-0.44
TB	0.42	+0.57	+0.26	+0.36	+0.13	+0.18	-0.03	+0.17	+0.16	+0.08
PC	-0.08	+0.21	+0.40	+0.65	+0.34	+0.27	+0.28	+0.27	+0.16	+0.19
BF	0.62	+0.03	+0.03	+0.13	-0.16	-0.11	-0.19	-0.05	-0.02	-0.08
SB	0.30	+0.27	+0.14	+0.04	-0.05	-0.05	-0.05	+0.01	-0.03	-0.05
RD	0.74	+0.15	+0.11	+0.13	+0.01	-0.10	+0.02	-0.17	-0.04	-0.07
JE	0.80	+0.60	+0.09	-0.05	-0.14	-0.24	-0.13	-0.16	+0.18	+0.07
ND	1.59	+0.66	+0.30	+0.05	+0.10	+0.17	+0.05	+0.08	+0.13	+0.22
AD	0.70	+0.49	+0.18	+0.03	+0.37	+0.25	+0.09	-0.22	-0.18	-0.16
IT	0.13	+0.89	+0.33	+0.18	+0.24	+0.22	+0.17	+0.19	+0.04	+O.17
SS	1.14	+0.87	+0.65	+0.07	-0.25	-0.43	-0.10	+0.04	-0.23	-0.15
TM	0.71	-0.07	+0.12	+0.11	+0.39	+0.12	+0.23	+0.49	+0.24	+0.40
MEAN	0.82	+0.38	+0.21	+0.12	+0.07	-0.02	-0.03	0.00	0.00	-0.02
S.D.	0.51	0.35	0.18	0.20	0.24	0.24	0.23	0.18	0.22	0.18

Table III.4 - The effect on the TA (in dioptres) of fifteen subjects of a ten minute sustained visual task at -5.00 D following the instillation of timolol. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

NEAR TIMOLOL

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
JH	1.08	+0.15	+0.21	+0.13	+0.07	+0.05	+0.11	+0.12	+0.12	+0.11
DJ	0.99	+0.30	+0.86	+1.26	+0.82	+0.20	+0.10	+0.15	+0.30	+0.07
JM	1.87	+1.02	+0.90	+0.33	+0.12	-0.17	-0.31	+0.09	-0.54	-0.45
RDF	1.35	-0.28	-0.01	+0.10	-0.08	-0.03	+0.02	+0.28	+0.18	+0.19
TB	0.44	+0.88	+0.42	+0.28	+0.10	+0.06	+0.17	+0.04	+0.06	+0.09
PC	0.31	+0.22	+0.30	+0.41	+0.27	+0.23	+0.26	+0.23	+0.27	+0.27
BF	0.52	+0.81	+1.17	-0.01	+0.19	+0.03	+0.20	-0.17	-0.29	-0.41
SB	0.30	+0.22	+0.13	+0.11	+0.09	+0.05	+0.11	+0.09	+0.06	+0.03
RD	1.05	+1.06	+0.62	+0.57	+0.46	+0.17	+0.20	+0.12	-0.13	-0.08
JE	0.76	+0.21	+0.14	-0.05	-0.07	+0.04	+0.03	-0.13	-0.17	-0.03
ND	1.49	+1.19	+0.77	+0.44	+0.30	+0.01	+0.04	+0.25	+0.19	+0.26
AD	0.78	+0.43	+0.35	+0.34	+0.23	+0.62	-0.28	-0.22	-0.11	+0.01
IT	0.19	+0.77	+0.41	+0.33	+0.31	+0.18	+0.18	+0.16	+0.15	+O.13
SS	1.25	+1.04	+0.58	+1.30	+1.28	+0.36	+0.34	+0.30	+0.27	+0.23
TM	0.85	+0.04	-0.06	-0.15	+0.07	+0.11	+0.06	-0.02	+0.11	-0.03
MEAN	0.88	+0.54	+0.45	+0.36	+0.27	+0.09	+0.08	+0.07	+0.03	+0.02
S.D.	0.47	0.44	0.34	0.41	0.34	0.12	0.17	0.15	0.23	0.20

Table III.5 - The effect on the TA (in dioptres) of fifteen subjects of a ten minute period in darkness following the instillation of saline. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

CONTROL SALINE

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
JH	1.28	+0.16	-0.14	-0.10	-0.20	-0.02	-0.10	-0.17	-0.05	+0.01
DJ	1.46	+0.03	+0.11	+0.03	+0.01	-0.19	-0.37	-0.27	-0.04	-0.32
JM	1.47	+0.05	+0.20	+0.06	+0.18	+0.11	+0.09	-0.10	-0.13	-0.02
RDF	0.91	+0.47	+0.09	+0.36	+0.44	+0.20	+0.39	+0.17	+0.25	+0.26
TB	0.46	+0.07	+0.06	+0.09	+0.07	+0.06	+0.07	+0.12	+0.06	+0.06
PC	0.14	+0.13	+0.10	+0.26	+0.17	+0.17	-0.04	+0.04	-0.07	-0.03
BF	0.79	+0.18	-0.01	0.00	-0.08	-0.17	-0.11	+0.05	-0.01	-0.22
SB	0.46	-0.01	+0.03	+0.19	+0.07	+0.09	+0.15	+0.21	+0.10	+0.16
RD	0.91	-0.17	-0.10	-0.08	+0.08	+0.08	+0.01	-0.11	-0.03	-0.08
JE	0.72	0.00	+0.32	+0.05	+0.23	+0.06	+0.06	+0.10	+0.12	+0.16
ND	1.60	+0.10	+0.05	+0.09	-0.10	-0.01	+0.20	+0.08	+0.10	-0.03
AD	1.05	-0.05	+0.16	+0.08	+0.24	+0.19	+0.09	+0.06	+0.14	+0.04
IT	0.42	+0.06	-0.10	-0.19	-0.20	-0.06	-0.24	+0.07	+0.12	-0.24
SS	0.99	+0.15	+0.09	+0.20	-0.01	-0.10	-0.10	-0.09	-0.07	-0.03
TM	0.46	+0.14	+0.07	+0.05	0.00	+0.17	+0.15	+0.17	+0.18	+0.28
MEAN	0.87	+0.09	+0.06	+0.07	+0.06	+0.04	+0.02	+0.02	+0.04	0.00
S.D.	0.43	0.14	0.12	0.14	0.17	0.12	0.18	0.13	0.11	0.17

Table III.6 - The effect on the TA (in dioptres) of fifteen subjects of a ten minute period in darkness following the instillation of timolol. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

CONTROL TIMOLOL

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
JH	1.21	+0.24	+0.04	-0.04	-0.02	+0.19	-0.02	+0.03	+0.01	+0.03
DJ	1.10	+0.19	+0.38	+0.02	-0.13	-0.37	-0.23	-0.14	-0.13	-0.28
JM	1.46	+0.28	+0.37	+0.24	+0.49	+0.58	+0.52	+0.32	+0.03	-0.07
RDF	1.16	-0.68	-0.36	-0.52	-0.63	-0.45	-0.52	-0.48	-0.36	+0.02
TB	0.70	+0.02	+0.09	+0.10	+0.15	+0.16	+0.11	+0.02	+0.28	+0.07
PC	0.13	-0.16	+0.02	-0.09	0.00	0.00	0.00	-0.28	-0.14	-0.16
BF	0.70	-0.01	+0.03	-0.02	+0.04	+0.15	+0.19	+0.06	-0.11	-0.10
SB	0.57	+0.04	-0.06	-0.04	-0.17	-0.04	-0.03	-0.08	+0.05	+0.03
RD	0.84	-0.12	-0.14	-0.01	+0.01	-0.09	-0.06	-0.03	+0.21	+0.03
JE	0.68	-0.15	-0.18	-0.13	-0.16	-0.11	-0.04	+0.02	0.00	+0.08
ND	1.46	+0.05	-0.09	-0.12	+0.07	+0.12	+0.03	+0.23	+0.12	0.00
AD	0.80	-0.16	+0.42	+0.17	+0.16	+0.34	-0.04	+0.20	+0.09	+0.04
IT	0.39	+0.07	-0.16	-0.18	-0.38	-0.12	+0.24	+0.24	+0.23	+0.10
SS	1.11	-0.12	-0.09	+0.01	+0.06	+0.03	+0.10	+0.12	+0.06	+0.09
TM	0.79	-0.26	-0.27	-0.29	-0.11	-0.09	+0.04	-0.04	+0.06	+0.16
MEAN	0.87	-0.05	-0.03	-0.09	-0.04	+0.02	+0.02	+0.01	+0.03	0.00
S.D.	0.36	0.23	0.20	0.18	0.24	0.25	0.22	0.20	0.16	0.11

APPENDIX IV

MENTAL EFFORT, TONIC ACCOMMODATION AND CILIARY MUSCLE INNERVATION

Table IV.1 - Values of tonic accommodation (in dioptres) for each experimental condition for 20 subjects for both saline and timolol trials. TA1 = pre-drug TA, TA2 = post-drug TA, TA3 = post-drug TA during counting task, CS = Counting speed per two mins.

	SALINE				TIMOLOL			
SUBJECT	TA1	TA2	TA3	CS	TA1	TA2	TA3	CS
TM	0.36	0.50	0.36	150	0.72	0.75	0.60	160
BF	0.59	0.51	0.75	140	0.57	0.47	0.79	290
PC	0.29	0.40	0.36	180	0.33	0.52	0.23	200
RD	1.26	1.28	1.78	240	1.32	1.31	1.73	260
SS	0.97	0.85	0.72	220	1.25	1.02	1.29	250
JH	0.73	0.76	1.80	150	1.23	0.97	2.05	130
JE	0.99	0.78	1.18	250	0.89	0.85	1.11	260
ND	1.70	1.51	1.74	260	1.98	1.67	1.69	260
SB	0.22	0.49	0.72	190	0.35	0.40	0.69	215
SC	1.39	1.55	1.27	210	1.78	1.86	1.78	200
AD	1.07	1.13	1.06	100	1.11	0.97	0.86	130
AN	0.61	0.64	0.67	200	0.53	0.60	0.60	190
JR	0.40	0.35	1.02	280	0.30	0.09	0.78	270
HS	1.07	1.02	1.27	185	0.98	0.87	1.30	280
TB	0.45	0.29	0.35	350	0.65	0.75	0.90	225
TT	2.04	1.89	1.51	310	1.61	1.68	1.59	300
BC	0.59	0.74	0.69	180	0.77	0.96	0.60	225
AM	1.63	1.77	1.68	110	1.59	1.33	1.81	110
DJ	1.86	1.88	2.31	300	1.18	1.25	1.92	200
RB	1.73	1.60	1.68	200	1.18	1.36	1.66	270

APPENDIX V

MENTAL EFFORT AND TONIC ACCOMMODATION IN EMMETROPIA AND LATE-ONSET MYOPIA

Table V.1 - Values of tonic accommodation (in dioptres) for each experimental condition for 15 late-onset myopes. TA1 = Passive TA, TA2 = Active TA, CS = Counting speed per 2 mins.

LATE-ONSET MYOPES					EMMETROPES				
SUBJECT	RX	TA1	TA2	CS	SUBJECT	RX	TA1	TA2	CS
PS	-1.00	1.08	1.61	100	AN	0.00	1.02	0.96	250
CD	-1.50	0.88	0.88	130	AM	0.00	1.65	1.90	130
KP	-1.62	0.55	0.79	220	SB	0.00	0.24	0.57	160
AC	-2.62	0.57	0.97	165	PC	+0.62	0.56	0.29	280
MW	-3.50	1.72	2.22	310	DJ	0.00	1.10	1.63	280
CB	-3.00	1.45	2.29	260	SS	+0.25	0.97	1.35	290
AL	-2.25	0.13	0.79	180	RD	0.00	1.59	1.23	190
RL	-2.25	0.07	0.36	85	SC	0.00	1.88	1.68	240
AW	-2.75	0.74	0.86	340	RD	+0.50	1.78	1.48	200
MH	-1.87	0.79	0.85	100	BC	+0.37	0.90	1.26	220
RC	-0.75	0.58	0.60	-	BF	+0.37	0.59	0.71	260
MM	-2.25	0.74	0.79	-	NH	0.00	1.19	1.14	220
JH	-0.50	0.76	1.80	150	JE	0.00	1.04	1.09	400
GD	-1.37	0.87	1.29	150	RB	+0.25	1.60	1.66	200
RY	-1.25	1.18	1.28	235	HS	0.00	1.02	1.27	185

APPENDIX VI

THE INFLUENCE OF MENTAL EFFORT ON THE STEADY-STATE ACCOMMODATIVE RESPONSE

Table VI.1 - Values of accommodation (in dioptres) for each experimental condition for 12 emmetropic subjects for the saline trial.

SALINE

SUBJECT	1.00 D READ	1.00 D ADD	3.00 D READ	3.00 D ADD	5.00 D READ	5.00 D ADD
NH	1.11	1.23	2.47	2.53	4.37	4.35
JE	0.95	1.09	2.71	2.60	4.40	4.37
SC	1.19	1.42	2.71	2.61	4.49	4.32
HS	0.79	0.83	2.35	2.31	4.09	3.84
RD	0.87	0.98	2.67	2.66	4.60	4.68
BC	0.92	0.94	2.50	2.52	4.47	4.46
AN	0.69	0.72	2.55	2.53	4.42	4.35
TT	0.81	0.88	2.67	2.74	4.51	4.57
DJ	0.82	0.88	2.67	2.74	4.51	4.57
SS	0.57	0.63	2.28	2.30	4.21	4.15
CS	0.89	1.02	2.57	2.58	4.43	4.41
TB	0.88	0.97	2.86	2.87	4.71	4.77

Table VI.2 - Values of accommodation (in dioptres) for each experimental condition for 12 emmetropic subjects for the timolol trial.

TIMOLOL

SUBJECT	1.00 D READ	1.00 D ADD	3.00 D READ	3.00 D ADD	5.00 D READ	5.00 D ADD
NH	0.94	1.09	2.54	2.55	4.23	4.35
JE	1.10	1.11	2.65	2.67	4.44	4.47
SC	1.44	1.60	2.94	2.98	4.67	4.74
HS	0.79	0.86	2.41	2.31	3.99	3.99
RD	0.76	0.84	2.50	2.57	4.51	4.60
BC	0.59	0.65	2.46	2.48	4.22	4.29
AN	0.80	0.81	2.57	2.57	4.55	4.59
TT	0.94	0.97	2.52	2.51	4.19	4.24
DJ	0.87	0.90	2.57	2.63	4.54	4.58
SS	0.59	0.55	2.43	2.37	4.13	4.21
CS	0.84	0.96	2.70	2.70	4.59	4.51
TB	0.91	0.92	2.78	2.90	4.70	4.71

Table VI.3 - Values of accommodation (in dioptres) for each experimental condition for 14 emmetropes.

EMMETROPES

SUBJECT	1.00 D READ	1.00 D ADD	3.00 D READ	3.00 D ADD	5.00 D READ	5.00 D ADD
NH	1.11	1.23	2.47	2.53	4.37	4.35
JE	0.95	1.09	2.71	2.60	4.40	4.37
SC	1.19	1.42	2.71	2.61	4.49	4.32
HS	0.79	0.83	2.35	2.31	4.09	3.84
RD	0.87	0.98	2.67	2.66	4.60	4.68
BC	0.92	0.94	2.50	2.52	4.47	4.46
AN	0.69	0.72	2.55	2.53	4.42	4.35
TT	0.81	0.88	2.67	2.74	4.51	4.57
DJ	0.82	0.88	2.67	2.74	4.51	4.57
SS	0.57	0.63	2.28	2.30	4.21	4.15
CS	0.89	1.02	2.57	2.58	4.43	4.41
TB	0.88	0.97	2.86	2.87	4.71	4.77
PC	0.82	1.01	2.74	2.66	4.67	4.66
RB	0.79	0.76	2.56	2.55	4.29	4.34

Table VI.4 - Values of accommodation (in dioptres) for each experimental condition for 14 late-onset myopes.

LATE-ONSET MYOPES

SUBJECT	1.00 D READ	1.00 D ADD	3.00 D READ	3.00 D ADD	5.00 D READ	5.00 D ADD
CB	0.57	0.69	2.44	2.49	4.17	4.18
KP	0.78	0.95	2.31	2.44	4.29	4.43
JH	0.77	0.87	2.57	2.74	4.43	4.54
MM	0.88	1.01	2.51	2.64	4.39	4.37
RC	1.07	1.12	2.37	2.47	4.13	4.11
GD	1.04	1.13	2.46	2.51	4.19	4.30
CD	0.59	0.59	2.43	2.40	4.12	4.28
PS	1.10	1.09	2.95	2.95	4.76	4.83
RE	0.61	0.68	2.46	2.58	4.07	4.31
MH	0.65	0.71	2.46	2.48	4.14	4.10
HP	0.87	0.90	2.39	2.50	4.07	4.07
AB	0.96	1.14	2.77	2.83	4.75	4.86
LP	0.57	0.57	2.38	2.34	4.18	4.17

APPENDIX VII

MEASUREMENT OF THE ADAPTATION OF TA UNDER TWO OPEN-LOOP CONDITIONS

Table VII.1 - The effect on the TA (in dioptres) of ten subjects of a ten minute visual task at -1.00 D measured under empty-field conditions. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-1.00 D LIGHT

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
AN	1.32	-0.17	-0.26	-0.36	-0.32	-0.30	-0.59	-0.61	-0.34	-0.26
ND	1.84	-0.43	-0.23	-0.17	-0.30	+0.06	+0.04	+0.25	+0.22	+0.26
SB	0.62	+0.03	-0.07	-0.12	-0.14	-0.11	0.00	+0.02	-0.12	-0.04
DJ	1.39	-0.13	-0.31	-0.57	-0.68	-0.57	-0.57	-0.79	-0.23	-0.77
BF	0.84	+0.63	+0.80	+0.68	+0.08	-0.02	+0.47	+0.09	+0.57	+0.47
LP	0.87	-0.06	-0.04	-0.14	-0.11	-0.12	-0.07	-0.07	0.00	-0.28
JH	0.73	+0.17	-0.12	-0.20	-0.12	-0.11	-0.14	-0.06	+0.08	+0.27
RC	0.67	+0.82	+0.19	-0.50	-0.59	-0.49	-0.38	-0.38	-0.47	-0.35
KH	0.81	+0.35	+0.21	+0.50	+0.23	+0.04	-0.07	+0.20	+0.20	+0.16
MEAN	1.02	+0.07	-0.03	-0.08	-0.19	-0.16	-0.14	-0.14	-0.01	-0.06
S.D	0.36	0.28	0.35	0.40	0.27	0.21	0.30	0.33	0.29	0.35

Table VII.2 - The effect on the TA (in dioptres) of ten subjects of a ten minute visual task at -3.00 D measured under empty-field conditions. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-3.00 D LIGHT

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
AN	1.54	+0.04	-0.14	+0.23	+0.39	+0.21	+0.16	-0.04	-0.35	+0.03
ND	1.90	+0.44	+0.22	+0.26	+0.19	+0.15	-0.03	-0.21	-0.25	-0.31
SB	0.54	+0.18	-0.02	-0.04	-0.01	-0.11	-0.17	-0.06	-0.10	-0.04
DJ	1.28	+0.29	+0.16	0.00	-0.20	-0.10	+0.12	-0.39	+0.12	+0.03
BF	0.80	+0.72	+0.53	+0.22	-0.23	-0.20	-0.23	-0.13	-0.18	-0.25
LP	1.17	+0.68	+0.55	+0.51	+0.37	-0.02	-0.16	-0.02	0.00	+0.23
JH	0.91	+0.18	+0.20	+0.08	+0.03	-0.21	-0.08	-0.14	-0.19	-0.09
RC	1.10	-0.05	+0.16	+0.14	+0.25	0.00	+0.03	+0.26	+0.23	+0.48
HP	0.91	+0.21	0.00	-0.04	-0.05	-0.04	-0.10	-0.16	-0.13	-0.13
KH	0.58	+0.64	+0.56	+0.25	+0.18	+0.28	-0.03	-0.10	-0.12	-0.13
MEAN	1.05	+0.34	+0.24	+0.16	+0.10	0.00	-0.05	-0.10	-0.08	-0.01
S.D	0.43	0.27	0.27	0.16	0.21	0.16	0.12	0.16	0.17	0.22

Table VII.3 - The effect on the TA (in dioptres) of ten subjects of a ten minute visual task at -5.00 D measured under empty-field conditions. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-5.00 D LIGHT

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
AN	0.88	+0.69	+0.37	+0.28	+0.19	+0.56	+0.33	+0.29	+0.32	+0.35
ND	1.66	+0.36	+0.33	+0.34	+0.19	+0.32	+0.12	+0.09	-0.01	+0.05
SB	0.43	+0.23	+0.07	+0.01	-0.05	-0.03	-0.12	-0.17	-0.18	-0.13
DJ	0.88	+0.42	+0.63	+0.42	-0.09	+0.01	-0.09	-0.09	-0.41	-0.32
BF	0.63	+2.05	+1.16	+1.29	+1.05	+1.01	+0.46	+0.32	+0.03	+0.07
LP	1.01	+0.71	+0.45	+0.18	+0.15	+0.13	-0.43	-0.63	-0.38	-0.39
JH	0.85	+0.44	+0.33	+0.13	+0.03	+0.09	+0.15	+0.27	+0.22	+0.33
RC	0.87	-0.05	+0.10	+0.28	+0.34	+0.28	+0.62	+0.06	+0.24	+0.09
HP	0.91	-0.12	-0.27	-0.16	-0.28	-0.24	-0.34	-0.49	-0.35	-0.39
KH	0.73	+0.67	+0.45	+0.27	+0.30	+0.52	+0.58	+0.44	+0.48	+0.37
MEAN	0.88	+0.54	+0.36	+0.30	+0.18	+0.26	+0.13	+0.01	0.00	0.00
S.D	0.30	0.57	0.36	0.37	0.34	0.34	0.35	0.34	0.30	0.28

Table VII.4 - The effect on the TA (in dioptres) of ten subjects of a ten minute visual task at -1.00 D measured under darkroom conditions. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-1.00 D DARK

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
AN	0.98	+0.11	+0.06	-0.10	-0.15	-0.09	+0.06	+0.01	+0.24	+0.15
ND	1.85	-0.49	-0.44	-0.39	-0.30	-0.30	-0.20	-0.35	-0.22	-0.19
SB	0.35			+0.36	+0.52	+0.71	+0.15	+0.05	+0.07	+0.08
DJ	1.31	+0.28	+0.23	-0.09	-0.06	-0.17	-0.11	+0.01	-0.11	-0.30
BF	0.94	+0.38	+0.34	+0.10	-0.38	-0.46	-0.65	-0.53	-0.15	-0.15
LP	0.64	+0.07	-0.16	-0.08	+0.09	-0.04	-0.04	-0.08	-0.36	-0.15
JH	1.13	+0.21	+0.16	+0.24	+0.14	+0.10	+0.16	+0.25	+0.27	+0.29
RC	0.45	+0.12	+0.33	+0.46	+0.56	+0.32	+0.30	+0.50	+0.70	+0.62
HP	0.94	+0.85	+0.18	+0.19	+0.07	+0.10	+0.10	+0.08	+0.10	+0.16
KH	0.88	+0.24	+0.35	0.47	+0.26	-0.08	-0.08	+0.06	+0.01	+0.06
MEAN	0.95	+0.20	+0.12	+0.12	+0.07	+0.01	-0.02	0.00	+0.05	+0.06
S.D	0.41	0.33	0.25	0.27	0.30	0.31	0.25	0.27	0.29	0.26

Table VII.5 - The effect on the TA (in dioptres) of ten subjects of a ten minute visual task at -3.00 D measured under darkroom conditions. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-3.00 D DARK

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
AN	0.77	+0.31	+0.01	+0.06	0.00	-0.17	+0.05	+0.05	+0.01	-0.09
ND	1.90	+0.44	+0.22	+0.26	+0.19	+0.15	-0.03	-0.21	-0.25	-0.31
SB	0.43	+0.39	+0.16	+0.16	+0.12	+0.13	-0.03	-0.13	-0.02	+0.01
DJ	1.50	+1.18	+0.88	-0.05	+0.35	-0.43	-0.30	-0.05	-0.52	-0.63
BF	0.72	+0.56	+0.17	+0.31	-0.38	-0.17	-0.43	-0.31	-0.14	-0.42
LP	1.17	+0.40	+0.16	-0.16	0.16	-0.07	-0.08	-0.27	-0.42	-0.49
JH	0.93	+0.79	+0.39	+0.53	+0.54	+0.52	+0.43	+0.38	+0.05	+0.23
RC	0.68	+0.15	-0.01	+0.08	+0.11	+0.02	-0.03	+0.01	-0.14	-0.01
HP	0.80	+0.38	+0.13	+0.07	-0.01	-0.04	+0.17	-0.02	-0.08	-0.14
KH	0.38	+0.75	+0.77	+0.24	+0.23	+0.30	-0.07	-0.14	0.00	-0.07
MEAN	0.93	+0.53	+0.29	+0.15	+0.13	+0.02	-0.03	-0.07	-0.15	-0.19
S.D	0.45	0.28	0.29	0.19	0.23	0.25	0.22	0.19	0.18	0.25

Table VII.6 - The effect on the TA (in dioptres) of ten subjects of a ten minute visual task at -5.00 D measured under darkroom conditions. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-5.00 D DARK

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
AN	1.17	+1.03	+0.33	+0.21	+0.71	+0.69	-0.02	-0.04	-0.19	-0.23
ND	1.28	+0.73	+0.50	+0.38	+0.29	+0.30	+0.38	+0.44	+0.36	+0.33
SB	0.37	+0.61	+0.35	+0.28	+0.27	+0.18	+0.18	+0.23	+0.08	+0.14
DJ	1.45	+0.93	+0.40	+0.03	-0.24	-0.42	-0.43	-0.43	-0.09	-0.17
BF	0.73	+1.19	-0.07	-0.12	-0.16	-0.11	-0.05	-0.05	+0.09	-0.30
LP	0.85	+0.83	+0.31	-0.03	-0.09	-0.39	-0.33	-0.20	-0.52	-0.35
JH	0.74	+1.81	+0.92	+0.65	+0.38	+0.26	+0.13	+0.35	+0.37	+0.37
RC	0.18	+1.12	+0.94	+0.49	+0.45	+0.44	+0.54	+0.39	+0.33	+0.36
HP	0.92	+0.48	+0.14	-0.02	+0.01	-0.09	-0.04	0.00	+0.07	+0.02
KH	0.53	+0.65	+0.50	+0.51	+0.50	+0.57	+0.77	+0.77	+0.55	+0.77
MEAN	0.62	+0.94	+0.43	+0.24	+0.21	+0.14	+0.11	+0.15	+0.10	+0.09
S.D	0.38	0.36	0.30	0.25	0.30	0.36	0.35	0.34	0.30	0.35

APPENDIX VIII

THE ADAPTATION OF TA IN EMMETROPIA AND LATE ONSET MYOPIA

Table VIII.1 - The effect on the TA (in dioptres) of fifteen emmetropic subjects of a ten minute visual task at -1.00 D. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-1.00 D EMMETROPES

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
AN	0.98	+0.11	+0.06	-0.10	-0.15	-0.09	+0.06	+0.01	+0.24	+0.15
AD	0.71	+0.21	+0.29	+0.32	-0.45	-0.48	-0.41	-0.46	-0.66	-0.43
SC	1.89	-0.16	+0.04	+0.15	+0.07	0.00	+0.01	+0.11	+0.02	-0.05
ND	1.85	-0.49	-0.44	-0.39	-0.30	-0.30	-0.20	-0.35	-0.22	-0.19
SS	1.25	-0.12	+0.18	+0.15	+0.07	-0.01	-0.22	-0.04	+0.19	+0.41
SB	0.35	+0.57	+0.46	+0.36	+0.52	+0.71	+0.15	+0.05	+0.07	+0.08
DJ	1.31	+0.28	+0.23	-0.09	-0.06	-0.17	-0.11	+0.01	-0.11	-0.30
BF	0.94	+0.38	+0.34	+0.10	-0.38	-0.46	-0.65	-0.53	-0.15	-0.15
KW	1.18	+0.36	-0.23	-0.27	-0.27	-0.43	-0.01	-0.10	-0.17	-0.20
PP	1.49	-0.36	-0.34	-0.25	-0.05	-0.20	-0.04	+0.12	+0.2	+0 0.19
BC	0.64	+0.31	+0.23	+0.14	+0.08	+0.19	+0.38	+0.05	+0.12	+0.13
DC	1.35	+0.11	+0.26	+0.31	+0.23	+0.20	-0.10	+0.05	+0.04	+0.10
JE	1.21	-0.03	-0.13	-0.11	+0.03	+0.01	-0.06	-0.23	-0.32	-0.30
LS	1.08	+0.10	+0.20	+0.23	0.00	+0.16	+0.32	+0.35	+0.23	+0.13
RB	1.19	+0.09	-0.01	-0.21	-0.37	-0.16	-0.22	-0.15	-0.26	-0.18
MEAN	1.16	+0.09	+0.08	+0.02	-0.07	-0.07	-0.07	-0.07	-0.05	-0.04
S.D.	0.40	0.28	0.25	0.23	0.25	0.30	0.25	0.23	0.24	0.22

Table VIII.2 - The effect on the TA (in dioptres) of fifteen emmetropic subjects of a ten minute visual task at -3.00 D. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-3.00 D EMMETROPES

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
AN	0.77	+0.31	+0.01	+0.06	0.00	-0.17	+0.05	+0.05	+0.01	-0.09
AD	0.82	+0.60	+0.24	-0.09	+0.17	+0.36	-0.05	-0.54	0.00	-0.57
SC	1.86	+0.77	+0.36	+0.31	+0.42	+0.29	-0.03	-0.26	-0.07	-0.13
ND	1.46	+0.30	+0.13	+0.13	-0.07	-0.10	-0.46	-0.37	-0.32	-0.23
SS	0.91	+1.32	1.32	+0.49	+0.47	+0.23	+0.31	+0.28	+0.25	+0.23
SB	0.43	+0.39	+0.16	+0.16	+0.12	+0.13	-0.03	-0.13	-0.02	+0.01
DJ	1.50	+1.18	+0.88	-0.05	+0.35	-0.43	-0.30	-0.05	-0.52	-0.63
BF	0.72	+0.56	+0.17	+0.31	-0.38	-0.17	-0.43	-0.31	-0.14	-0.42
KW	0.56	+1.03	+0.58	+0.25	+0.47	+0.47	+0.13	-0.18	-0.38	-0.23
PP	0.99	+0.39	+0.74	+0.59	+0.08	+0.14	+0.24	+0.12	+0.16	+0.04
BC	0.87	+0.21	-0.03	+0.07	+0.07	-0.07	-0.22	-0.20	-0.20	-0.18
DC	0.77	+1.18	+0.39	+0.16	+0.18	+0.13	+0.18	+0.36	-0.19	-0.02
JE	1.30	+0.47	+0.30	-0.01	-0.14	-0.18	-0.20	-0.19	-0.26	0.00
LS	1.37	+0.71	+0.24	+0.20	+0.17	+0.14	+0.13	-0.04	-0.51	-0.61
RB	1.27	+0.38	+0.13	+0.07	+0.16	+0.01	+0.10	+0.16	+0.03	+0.16
MEAN	1.04	+0.65	+0.37	+0.18	+0.14	+0.05	-0.04	-0.09	-0.14	-0.18
S.D.	0.39	0.35	0.35	0.18	0.26	0.23	0.23	0.24	0.22	0.26

Table VIII.3 - The effect on the TA (in dioptres) of fifteen emmetropic subjects of a ten minute visual task at -5.00 D. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-5.00 D EMMETROPES

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
AN	1.17	+1.03	+0.33	+0.21	+0.71	+0.69	-0.02	-0.04	-0.19	-0.23
AD	0.53	+0.73	+0.13	-0.01	-0.10	-0.40	-0.05	+0.01	-0.27	-0.17
SC	1.62	+0.89	+0.26	+0.07	+0.16	-0.21	+0.07	+0.25	+0.01	+0.13
ND	1.28	+0.73	+0.50	+0.38	+0.29	+0.30	+0.38	+0.44	+0.36	+0.33
SS	1.15	+0.69	+0.65	+0.64	+0.64	+0.63	+0.76	+0.35	-0.14	-0.24
SB	0.37	+0.61	+0.35	+0.28	+0.27	+0.18	+0.18	+0.23	+0.08	+0.14
DJ	1.45	+0.93	+0.40	+0.03	-0.24	-0.42	-0.43	-0.43	-0.09	-0.17
BF	0.73	+1.19	-0.07	-0.12	-0.16	-0.11	-0.05	-0.05	+0.09	-0.30
KW	0.68	+1.90	0.89	0.32	0.02	0.15	-0.27	-0.42	-0.51	-0.18
PP	0.90	+1.08	+0.98	+0.84	+0.38	+0.47	+0.31	+0.44	+0.44	+0.22
BC	0.95	+0.21	+0.26	+0.24	+0.14	+0.06	+0.01	-0.02	+0.05	-0.05
DC	0.98	+0.90	+0.62	+0.52	+0.24	+0.27	+0.16	+0.13	+0.11	-0.04
JE	1.39	+0.62	+0.74	+0.91	+0.92	+0.43	+0.08	0.00	-0.16	-0.23
LS	1.36	+1.28	+0.95	+0.73	+0.24	-0.04	+0.06	-0.45	-0.08	-0.12
RB	1.17	+0.29	+0.11	-0.03	+0.12	+0.18	+0.02	+0.01	+0.06	0.00
MEAN	1.05	+0.87	+0.47	+0.33	+0.24	+0.15	+0.08	+0.03	-0.02	-0.06
S.D.	0.35	0.40	0.31	0.32	0.31	0.33	0.27	0.28	0.23	0.18

Table VIII.4 - The effect on the TA (in dioptres) of fifteen myopic subjects of a ten minute visual task at -1.00 D. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-1.00 D LATE-ONSET MYOPES

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
LP	0.64	+0.07	-0.16	-0.08	+0.09	-0.04	-0.04	-0.08	-0.36	-0.15
JH	1.13	+0.21	+0.16	+0.24	+0.14	+0.10	+0.16	+0.25	+0.27	+0.29
HP	0.60	+0.17	+0.33	+0.49	+0.55	+0.17	+0.33	+0.49	+0.31	+0.15
SL	0.43	+0.21	+0.35	+0.49	+0.50	+0.60	+0.70	+0.60	+0.72	+0.47
CD	1.00	+0.48	+0.04	+0.17	+0.07	+0.10	+0.17	-0.06	-0.07	-0.02
AL	0.85	+0.27	+0.09	-0.14	-0.43	-0.31	-0.34	-0.38	-0.23	-0.27
JN	0.86	+0.31	+0.02	-0.07	-0.07	-0.13	-0.11	-0.05	-0.19	-0.13
RC	0.45	+0.12	+0.33	+0.46	+0.56	+0.32	+0.30	+0.50	+0.70	+0.62
NH	0.67	-0.01	-0.02	-0.06	-0.18	+0.12	+0.01	-0.03	-0.23	-0.22
SD	1.04	+0.04	+0.05	+0.04	+0.03	+0.30	+0.34	+0.31	+0.31	-0.03
AB	0.39	+0.02	+0.37	+0.10	-0.09	-0.23	-0.21	-0.28	-0.25	-0.04
HP	0.94	+0.85	+0.18	+0.19	+0.07	+0.10	+0.01	+0.08	+0.10	+0.16
KH	0.88	+0.24	+0.35	+0.47	+0.26	-0.08	+0.08	+0.06	+0.01	+0.06
MM	0.43	+0.48	+0.11	-0.04	-0.10	+0.17	+0.52	+0.64	+0.68	+0.56
PA	0.67	+0.19	-0.03	+0.09	+0.03	-0.18	-0.14	+0.05	+0.08	+0.49
MEAN	0.73	+0.24	+0.14	+0.16	+0.10	+0.07	+0.12	+0.14	+0.12	+0.13
S.D.	0.24	0.22	0.16	0.22	0.27	0.23	0.27	0.30	0.35	0.28

Table VIII.5 - The effect on the TA (in dioptres) of fifteen myopic subjects of a ten minute visual task at -3.00 D. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-3.00 D LATE-ONSET MYOPES

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
LP	1.17	+0.40	+0.16	-0.16	-0.16	-0.07	-0.08	-0.27	-0.42	-0.49
JH	0.93	+0.79	+0.39	+0.53	+0.54	+0.52	+0.43	+0.38	+0.05	+0.23
HP	1.04	+0.67	+0.16	+0.19	-0.05	-0.14	+0.06	+0.07	+0.16	-0.07
SL	0.71	+0.72	+0.82	+0.66	+0.70	+0.65	+0.73	+0.51	+0.59	+0.45
CD	0.91	+0.45	-0.05	+0.26	+0.11	+0.05	+0.02	-0.14	-0.23	-0.12
AL	0.82	+0.14	+0.05	-0.03	-0.06	+0.03	-0.06	+0.01	-0.07	-0.14
JN	0.94	+0.66	+0.78	+0.25	-0.13	-0.34	-0.50	-0.28	-0.30	-0.43
RC	0.68	+0.15	-0.01	+0.08	+0.11	+0.02	-0.03	+0.01	-0.14	-0.01
NH	0.49	+0.45	+0.29	+0.16	+0.26	+0.46	+0.33	+0.17	+0.21	+0.20
SD	1.34	-0.36	-0.16	-0.08	+0.23	+0.14	+0.12	-0.22	-0.32	-0.27
AB	0.85	-0.19	-0.18	-0.19	-0.18	-0.23	-0.20	-0.07	-0.04	-0.05
HP	0.80	+0.38	+0.13	+0.07	-0.01	-0.04	+0.17	-0.02	-0.08	-0.14
KH	0.38	+0.75	0.77	+0.24	+0.23	+0.30	-0.07	-0.14	0.00	-0.07
MM	0.77	+0.67	+0.45	+0.17	+0.29	+0.34	+0.57	+0.41	+0.22	+0.44
PA	0.61	0.00	0.00	0.00	-0.19	+0.14	-0.09	+0.10	+0.07	-0.03
MEAN	0.83	+0.41	+0.26	+0.15	+0.11	+0.12	+0.09	+0.03	-0.02	-0.03
S.D.	0.24	0.34	0.33	0.23	0.26	0.27	0.30	0.24	0.25	0.26

Table VIII.6 - The effect on the TA (in dioptres) of fifteen myopic subjects of a ten minute visual task at -5.00 D. Each value of post-task change in TA represents the mean of ten seconds of readings symmetrically placed about each ten second point.

-5.00 D LATE-ONSET MYOPES

SUBJECT	INITIAL TA	POST-TASK CHANGE IN TA								
		10	20	30	40	50	60	70	80	90
LP	0.85	+0.83	+0.31	-0.03	-0.09	-0.39	-0.33	-0.20	-0.52	-0.35
JH	0.74	+1.81	+0.92	+0.65	+0.38	+0.26	+0.13	+0.35	+0.37	+0.37
HP	0.71	+0.71	+0.24	+0.56	+0.92	+0.34	+0.44	+0.24	+0.20	+0.21
SL	0.35	+0.97	+0.86	+0.87	+1.00	+0.72	+0.39	+0.26	+0.43	+0.34
CD	0.95	+0.42	+0.25	+0.33	+0.02	+0.12	+0.16	+0.05	+0.31	+0.30
AL	0.67	+0.07	-0.03	-0.02	+0.01	-0.03	-0.04	-0.05	-0.05	-0.04
JN	1.01	+0.08	-0.03	-0.09	+0.00	-0.09	-0.27	-0.30	-0.32	-0.21
RC	0.18	+1.12	+0.94	+0.49	+0.45	+0.44	+0.54	+0.39	+0.33	+0.36
NH	0.57	+0.05	+0.08	-0.02	+0.09	+0.01	0.00	+0.14	-0.02	+0.06
SD	0.73	+0.67	+0.45	+0.27	+0.30	+0.52	+0.58	+0.44	+0.48	+0.37
AB	0.58	-0.31	-0.36	-0.44	-0.28	-0.52	-0.53	-0.54	-0.41	0.00
HP	0.92	+0.48	+0.14	-0.02	+0.01	-0.09	-0.04	0.00	+0.07	+0.02
KH	0.53	+0.65	+0.50	+0.51	+0.50	+0.57	+0.77	+0.77	+0.55	+0.77
MM	0.43	+0.09	0.00	+0.17	+0.03	+0.17	0.00	+0.04	+0.24	+0.21
PA	0.73	-0.24	-0.29	+0.10	+0.49	+0.06	+0.05	+0.77	+0.48	+0.09
MEAN	0.66	+0.49	+0.27	+0.22	+0.26	+0.14	+0.13	+0.16	+0.14	+0.17
S.D.	0.22	0.55	0.39	0.33	0.36	0.34	0.35	0.35	0.33	0.27

Table VIII.7 - Values of accommodative response during the visual counting task (in dioptres) for each experimental condition and for each refractive group.

EMMETROPES				LATE-ONSET MYOPES			
SUBJECT	1.00 D	3.00 D	5.00 D	SUBJECT	1.00 D	5.00 D	5.00 D
AN	0.92	2.54	4.34	LP	0.72	2.76	4.53
AD	1.12	2.87	4.63	JH	1.29	3.26	5.20
SC	1.42	2.71	4.21	HP	1.30	2.73	4.62
ND	1.70	2.73	4.46	SL	0.70	2.32	4.07
SS	0.57	2.51	4.15	CD	0.96	2.51	4.05
SB	0.87	2.70	4.38	AL	1.27	2.74	4.55
DJ	1.22	2.71	4.42	JN	0.73		
BF	0.92	2.62	4.18	RC	1.02	2.01	3.86
KW	1.20	2.91	4.66	NH	0.75	2.56	3.80
PP	0.69	2.61	4.08	SD	1.08	2.58	4.57
BC	0.82	2.41	4.49	AB	0.77	2.39	4.23
DC	0.84	2.65	4.62	HP	0.74	2.30	4.05
JE	1.17	2.61	4.59	KH	0.94	2.24	3.83
LS	1.14	3.10	4.51	MM	1.17	2.79	4.62
RB	1.01	2.66	4.20	PA	1.01	2.53	4.71

APPENDIX IX

CRITERIA FOR ACCEPTANCE AND REJECTION OF DATA FROM THE CANON AUTOREF R-1

The 'raw' data obtained from the Canon R-1 was subjected to a following rigorous selection procedure:

1. All error readings were discarded.
2. Any results where the cylinder was greater than 1.00 D were ignored.
3. Any results where the mean sphere differed significantly (e.g. > 0.75) from the previous reading were ignored.

An example of a series of readings from the instrument is given below:

SPHERE	CYLINDER	AXIS	
-0.75	-0.37	97	
-1.00	-0.25	108	
ERR			(1)
-1.00	-0.25	107	
+0.50	-2.25	155	(2)
-0.87	-0.50	79	
-0.50	-1.12	82	(3)
-9.25			(4)

The above series is an uncharacteristic example in that it contains a greater percentage of results that would be rejected than would be anticipated. Result 1 is an error reading due to the subject blinking or misalignment. Reading 2 would be rejected because of the cylinder power. Although reading 3 has a mean sphere similar to that of the previous estimate it would be rejected due to the cylinder power. Reading 4 would be rejected because it differs significantly from the previous mean sphere value.

APPENDIX X

PUBLISHED SUPPORTING PAPERS

X.1. **Bullimore, M.A.,** Gilmartin, B. and Hogan, R.E. (1986a) Objective and subjective measurement of tonic accommodation. *Ophthal. Physiol. Opt.* **6**, 57-62.

X.2. Gilmartin, B. and **Bullimore, M.A.** (1986) Evidence for sympathetic innervation of the ciliary muscle during sustained near vision. Supplement to *Invest. Ophthalmol. Vis. Sci.* **25**, 81 (Abstract).

X.3. **Bullimore, M.A.,** Gilmartin, B. and Hogan, R.E. (1986b) A comparison of three methods of measuring tonic accommodation. Ophthal. Physiol. Opt. Paper presented to the Society of Experimental Optometry, July 1985, University of Aston in Birmingham. *Ophthal. Physiol. Opt.* **6**, 247 (Abstract).

X.4. **Bullimore, M.A.** and Gilmartin, B. (1986a) The effect of mental effort on tonic accommodation in emmetropes and late-onset myopes. Paper presented to the American Academy of Optometry, December 1986, Toronto. *Am. J. Optom. Physiol. Opt.* **63**, 10P (Abstract).

X.5. **Bullimore, M.A.** and Gilmartin, B. (1986b) Sympathetic inhibition modifies the effect of mental effort on near task accommodation. Paper presented to the American Academy of Optometry, December 1986, Toronto. *Am. J. Optom. Physiol. Opt.* **63**, 77P (Abstract).

X.6. Gilmartin, B. and **Bullimore, M.A.** (1987) Sustained near-vision augments sympathetic innervation of the ciliary muscle. *Clin. Vision Sci.* **1**, 197-208.

X.7. **Bullimore, M.A.** and Gilmartin, B. (1987a) Tonic accommodation, cognitive demand and ciliary muscle innervation. *Am. J. Optom. Physiol. Opt.* **64**, 45-50.

X.8. **Bullimore, M.A.** and Gilmartin, B. (1987b) The influence of retinal area stimulated on the accommodative response, in *Advances in Diagnostic Visual Optics. Proceedings of the Third International Symposium, Tirrenia, Italy, May 1-4,1986.* Eds Fiorentini, A., Guyton, D.L. and Siegel, I.M. pp. 181-185.

X.9. **Bullimore, M.A.** and Gilmartin, B. (1987c) The relationship between cognitive induced changes in tonic accommodation and ciliary muscle innervation. Paper presented to the Society of Experimental Optometry, July 1986, University of Aston in Birmingham. *Ophthal. Physiol. Opt.* **7**, 96 (Abstract).

X.10. **Bullimore, M.A.** and Gilmartin, B. (1987d) The influence of retinal target eccentricity on the accommodative response. Paper presented to the Society of Experimental Optometry, July 1986, University of Aston in Birmingham. *Ophthal. Physiol. Opt.* **7**, 97 (Abstract).

X.11. **Bullimore, M.A.** and Gilmartin, B. (1987e) Aspects of tonic accommodation in emmetropia and late-onset myopia. *Am. J. Optom. Physiol. Opt.* Accepted for publication.

X.12. **Bullimore, M.A.** and Gilmartin, B. (1987f) Retinal eccentricity and the accommodative response. *Am. J. Optom. Physiol. Opt.* Accepted for publication.

APPENDIX X

PUBLISHED SUPPORTING PAPERS

X.1. **Bullimore, M.A.,** Gilmartin, B. and Hogan, R.E. (1986a) Objective and subjective measurement of tonic accommodation. *Ophthal. Physiol. Opt.* 6, 57-62.

X.2. Gilmartin, B. and **Bullimore, M.A.** (1986) Evidence for sympathetic innervation of the ciliary muscle during sustained near vision. Supplement to *Invest. Ophthalmol. Vis. Sci.* **25**, 81 (Abstract).

X.3. **Bullimore, M.A.,** Gilmartin, B. and Hogan, R.E. (1986b) A comparison of three methods of measuring tonic accommodation. Ophthal. Physiol. Opt. Paper presented to the Society of Experimental Optometry, July 1985, University of Aston in Birmingham. *Ophthal. Physiol. Opt.* **6**, 247 (Abstract).

X.4. **Bullimore, M.A.** and Gilmartin, B. (1986a) The effect of mental effort on tonic accommodation in emmetropes and late-onset myopes. Paper presented to the American Academy of Optometry, December 1986, Toronto. *Am. J. Optom. Physiol. Opt.* **63**, 10P (Abstract).

X.5. **Bullimore, M.A.** and Gilmartin, B. (1986b) Sympathetic inhibition modifies the effect of mental effort on near task accommodation. Paper presented to the American Academy of Optometry, December 1986, Toronto. *Am. J. Optom. Physiol. Opt.* **63**, 77P (Abstract).

X.6. Gilmartin, B. and **Bullimore, M.A.** (1987) Sustained near-vision augments sympathetic innervation of the ciliary muscle. *Clin. Vision Sci.* **1**, 197-208.

X.7. **Bullimore, M.A.** and Gilmartin, B. (1987a) Tonic accommodation, cognitive demand and ciliary muscle innervation. *Am. J. Optom. Physiol. Opt.* **64**, 45-50.

X.8. **Bullimore, M.A.** and Gilmartin, B. (1987b) The influence of retinal area stimulated on the accommodative response, in *Advances in Diagnostic Visual Optics. Proceedings of the Third International Symposium, Tirrenia, Italy, May 1-4,1986.* Eds Fiorentini, A., Guyton, D.L. and Siegel, I.M. pp. 181-185.

X.9. **Bullimore, M.A.** and Gilmartin, B. (1987c) The relationship between cognitive induced changes in tonic accommodation and ciliary muscle innervation. Paper presented to the Society of Experimental Optometry, July 1986, University of Aston in Birmingham. *Ophthal. Physiol. Opt.* **7**, 96 (Abstract).

X.10. **Bullimore, M.A.** and Gilmartin, B. (1987d) The influence of retinal target eccentricity on the accommodative response. Paper presented to the Society of Experimental Optometry, July 1986, University of Aston in Birmingham. *Ophthal. Physiol. Opt.* **7**, 97 (Abstract).

X.11. **Bullimore, M.A.** and Gilmartin, B. (1987e) Aspects of tonic accommodation in emmetropia and late-onset myopia. *Am. J. Optom. Physiol. Opt.* **64**, 499-503.

X.12. **Bullimore, M.A.** and Gilmartin, B. (1987f) Retinal eccentricity and the accommodative response. *Am. J. Optom. Physiol. Opt.* **64**, 644-645.

REFERENCES

Adams AJ. (1987) Axial length elongation, not corneal curvature, as a basis of adult onset myopia. Am J Optom physiol Opt 64:150-151.

Agababow A. (1893) Die Innervation des Ciliarokörpers. Anatomischer Anzeiger 8:555-561.

Ahlquist RP. (1948) A study of the adrenotropic receptors. Am J Physiol 153:1586-600.

Allen MJ. (1956) The influence of age on the speed of accommodation. Am J Optom Arch Am Acad Optom 33:201-207.

Alpern M. (1958a) Variability of accommodation during steady fixation at various levels of illuminance. J Opt Soc Am 48:193-197.

Alpern M. (1958b) Vergence and accommodation. 1. Can change in size induce vergence movements? Arch Ophthalmol 60:355-357.

Alpern M. (1969) Accommodation. Chapter 8, in The Eye. Vol 3 (2nd Edition) Ed. Davson H. Academic Press, London.

Alpern M and David H. (1958) Effects of illuminance quantity on accommodation of the eyes. Indust Med 27:551-555.

Alsbirk PH. (1979) Refraction in adult West Greenland Eskimos. A population study of spherical refractive errors, including oculometric and familial correlations. Acta Ophthalmol 57:84-95.

Anisman H. (1975) Time-dependent variations in aversively motivated behaviours: nonassociative effects of cholinergic and catecholaminergic activity. Psychol Rev 82:359-385.

Anisman H. (1978) Neurochemical changes elicited by stress, in Pharmacology of Aversively Motivated Behaviour. Eds. Anisman H and Bignami G. pp. 119-172.

Baker JR. (1966) Experiments on the function of the eye in light microscopy. J Royal Microscopic Soc 85:231-254.

Baker B, Brown B and Garner L. (1983) Time course and variability of dark focus. Invest Ophthalmol Vis Sci 24:1528-1531.

Baldwin WR. (1965) Accommodative characteristics of a group of myopic adults. Am J Optom Archs Am Acad Optom 42:237-243.

Baldwin WR. (1981) A review of statistical studies of relations between myopia and ethnic, behavioral and physiological characteristics. Am J Optom physiol Opt 58:516-527.

Banks MS. (1980) The development of visual accommodation during early infancy. Child Development 51:646-666.

Bedford RE and Wyszecki G. (1957) Axial chromatic aberration of the human eye. J Opt Soc Am 47:564-566.

Bedrossian RH. (1966) Treatment of progressive myopia with atropine. Proc XX Int Cong of Ophthalmology, Munich. pp. 612-617 Exerpta Medica Foundation, New York. (Cited by Young, 1975).

Behr C. (1924) Die lehre v. der pupillenbewegungen. In Graefe-Saemiisch Hanbuch der Gesamten Augenheilkunde. 3rd Edition, Berlin. (Cited by Duke-Elder, 1971).

Benel RA. (1980) Eyes and glass curtains: visual accommodation, the mandelbaum effect and apparent size. Human Factors 22:616-620.

Berens C and Sells SB. (1944) Experimental studies on fatigue of accommodation: I. Plan of research and observations on recession of near point of accommodation following a period of interpolated work on the ophthalmic ergograph. Arch Ophthalmol 31:148-159.

Berens C and Sells SB. (1950) Experimental studies on fatigue of accommodation: II. Arch Ophthalmol 33:47-58.

Berman M, Nelson P and Caden B. (1984) Objective refraction: comparison of retinoscopy and automated techniques. Am J Optom physiol Opt 61:203-209.

Biggs RD, Alpern M and Bennett DR. (1959) The effect of sympathomimetic drugs upon the amplitude of accommodation. Am J Ophthalmol 48:169-171.

Birnbaum MH. (1984) Nearpoint visual stress: a physiological model. J Am Optom Assoc 55:825-835.

Borish IM. (1970) Clinical Refraction. 3rd Edition. Professional Press Inc, Illinois.

Bour LJ. (1981) The influence of the spatial distribution of a target on the dynamic response and fluctuations of the accommodation of the human eye. Vision Res 21:1287-1296.

Bowman WC and Rand MJ. (1980) Textbook of Pharmacology. Blackwell, Oxford.

Braddick 0, Atkinson J, French J and Howland HC. (1979) A photorefractive study of infant accommodation. Vision Res 19:1319-1330.

Brodstein RS, Brodstein DE, Olson RJ, Hunt SC and Williams RR. (1984) The treatment of myopia with atropine and bifocals: a long-term prospective study. Ophthalmology 91:1373-1378.

Brown N. (1973) The change in shape and external form of the lens of the eye on accommodation. Exp Eye Res 15:441-459.

Bullimore MA and Gilmartin B. (1986a) The effect of mental effort on tonic accommodation in emmetropes and late-onset myopes. Am J Optom physiol Opt 63:10P.

Bullimore MA and Gilmartin B. (1986b) Sympathetic inhibition modifies the effect of mental effort on near task accommodation. Am J Optom physiol Opt 63:77P.

Bullimore MA and Gilmartin B. (1987a) Tonic accommodation, cognitive demand and ciliary muscle innervation. Am J Optom physiol Opt 64:45-50.

Bullimore MA and Gilmartin B. (1987b) The influence of retinal area stimulated on the accommodative response, in *Advances in Diagnostic Visual Optics*, Proceedings of the Third International Symposium, Tirrenia, Italy, May 1-4,1986. Eds. Fiorentini A, Guyton DL and Siegel IM. pp. 181-185.Springer, Berlin.

Bullimore MA and Gilmartin B. (1987c) The relationship between cognitive induced changes in tonic accommodation and ciliary muscle innervation. Ophthal physiol Opt 7:96.

Bullimore MA and Gilmartin B. (1987d) The influence of retinal target eccentricity on the accommodative response. Ophthal physiol Opt 7:97.

Bullimore MA and Gilmartin B. (1987e) Aspects of tonic accommodation in emmetropia and late-onset myopia. Am J Optom physiol Opt 64:499-503.

Bullimore MA and Gilmartin B. (1987f) Retinal eccentricity and the accommodative response. Am J Optom physiol Opt. 64:644-645..

Bullimore MA, Gilmartin B and Hogan RE. (1986a) Objective and subjective measurement of tonic accommodation. Ophthal physiol Opt 6:57-62.

Bullimore MA, Gilmartin B and Hogan RE. (1986b) A comparison of three methods of measuring tonic accommodation. Ophthal physiol Opt 6:247.

Campbell FW. (1953) Twilight Myopia. J Opt Soc Am 43:925-926.

Campbell FW. (1954) The minimum quantity of light required to elicit the accommodation reflex in man. J Physiol 123:357-366.

Campbell FW. (1957) The depth of field of the human eye. Optica Acta 4:157-164.

Campbell FW and Primrose JAE. (1953) The state of accommodation of the human eye in darkness. Trans ophthal Soc UK 73:353-361.

Campbell FW and Robson JG. (1959) High speed infra-red optometer. J Opt Soc Am 49:268-272.

Campbell FW, Robson JG and Westheimer G. (1959) Fluctuations of accommodation under steady viewing conditions. J Physiol 145:579-594.

Campbell FW and Westheimer G. (1959) Factors influencing accommodation responses of the human eye. J Opt Soc Am 49:568-571.

Campbell FW and Westheimer G. (1960) Dynamics of accommodation responses of the human eye. J Physiol 151:285-295.

Cannon WB. (1914) The emergency function of the adrenal medulla in pain and the major emotions. Am J Physiol 33:356-372.

Cannon WB. (1929) Bodily Changes in Pain, Hunger, Fear and Rage: An account of recent researches into the function of emotional excitement. Appleton, New York.

Cannon WB and de la Paz D. (1911) Emotional stimulation of adrenal secretion. Am J Physiol 28:64-70.

Carreras M. (1951) La myopia nocturna e influencia sobre la misma de la amplitud de acomodacion. Arch Soc Oftal Hisp Am 11:1443-1489. (Cited by Mellerio, 1966; Charman, 1982).

Charman WN. (1974) On the position of the plane of stationarity in laser refraction. Am J Optom physiol Opt 51:832-838.

Charman WN. (1975) Some sources of discrepancy between static retinoscopy and subjective refraction. Br J physiol Opt 30:108-118.

Charman WN. (1982) The accommodative resting point and refractive error. Ophthal Opt 22:469-473.

Charman WN. (1983) The retinal image in the human eye. Prog Retinal Res 2:1-50.

Charman WN. (1986) Static accommodation and the minimum angle of resolution. Am J Optom physiol Opt 63:915-921.

Charman WN and Heron G. (1975) A simple infra-red optometer for accommodation studies. Br J physiol Optics 30:1-12.

Charman WN and Heron G. (1979) Spatial frequency and the dynamics of the accommodative response. Optica Acta 26:217-228.

Charman WN, Jennings JAM and Whitefoot H. (1978) The refraction of the eye in relation to spherical aberration and pupil size. Br J physiol Optics 32:78-93.

Charman WN and Tucker J. (1977) Dependence of accommodation response on the spatial frequency spectrum of the observed object. Vision Res 17:129-139.

Charman WN and Tucker J. (1978a) Accommodation and colour. J Opt Soc Am 68:459-471.

Charman WN and Tucker J. (1978b) Accommodation as a function of object form. Am J Optom physiol Opt 55:84-92.

Chin NB and Horn RE. (1956) Infra-red skiascope measurements of refractive changes in dim light and darkness. J Opt Soc Am 46:60-66.

Chin NB, Ishikawa S and Lappin H. (1968) Accommodation in monkeys induced by midbrain stimulation. Invest Ophthalmol 7:386-396.

Ciuffreda KJ, Dul M and Fisher SK. (1987) Higher-order spatial frequency contribution to accommodative accuracy in normal and amblyopic observers. Clin Vis Sci 1:219-229.

Ciuffreda KJ and Hokoda SC. (1983) Spatial frequency dependence of accommodative responses in amblyopic eyes. Vision Res 12:1585-1594.

Ciuffreda KJ and Hokoda SC. (1985) Effect of instruction and higher level control on the accommodative response spatial frequency profile. Ophthal physiol Opt 5:221-223.

Ciuffreda KJ, Hokoda SC, Hung GK and Semmlow JL. (1983) Static aspects of accommodation in human amblyopia. Am J Optom physiol Opt 60:446-449.

Ciuffreda KJ, Hokoda SC, Hung GK and Semmlow JL. (1984) Accommodative stimulus/response function in human amblyopia. Doc Ophthalmol 303-326.

Ciuffreda KJ and Kenyon RV. (1983) Accommodative vergence and accommodation in normals, amblyopes and strabismics. In Vergence Eye Movements: Basic and Clinical Aspects. Eds. Schor CM and Ciuffreda KJ. pp. 101-173. Butterworths, Boston.

Ciuffreda KJ and Rumpf D. (1986) Contrast and accommodation in amblyopia. Vision Res 25:1445-1457.

Cogan DG. (1937) Accommodation and the autonomic nervous system. Arch Ophthal 18:739-766.

Cohn H. (1886) The Hygiene of the Eye in Schools, an English translation. Ed. Turnbull WP. Simpkin, Marshall, London.

Coleman DJ. (1970) Unified model for accommodative mechanism. Am J Ophthalmol 69:1063-1079.

Collins G. (1937) The electronic refractionometer. Br J physiol Optics 11:30-42. (Cited by Charman and Heron, 1975; Duke-Elder, 1970).

Cornsweet TN and Crane HD. (1970) Servo-controlled infra-red optometer. J Opt Soc Am 60:548-554.

Coulombre AJ and Coulombre JL. (1956) Role of intraocular pressure in the development of the chick eye: (i) control of eye size. J Exp Zool 133:211-225.

Curtin BJ. (1970) Myopia: a review of its aetiology, pathogenesis and treatment. Surv Ophthalmol 15:1-17.

Denieul P. (1982) Effect of stimulus vergence on mean accommodation response, microfluctuations of accommodation and optical quality of the human eye. Vision Res 22:561-569.

Donders FC. (1864) On the Anomalies of Accommodation and the Refraction of the Eye (Translated by Moore WD), pp 579-580. The New Sydenham Society, London.

Duke-Elder S. (1970) Ophthalmic Optics - Refraction. Vol V of System of Ophthalmology. Henry Kimpton, London.

Duke-Elder S. (1971) Neuro-ophthalmology. Vol XII of System of Ophthalmology. Henry Kimpton, London.

Dunn AJ and Kramarcy NR (1984) Neurochemical responses in stress: Relationships between the hypothalamic- pituitary-adrenal and catecholamine systems. Chapter 8, in Handbook of Psychopharmacology. Volume 18, Drugs, Neurotransmitters and Behaviour. Eds. Iverson LL, Iverson SD and Snyder SH. pp.455-515, Plenum Press, New York.

Ebenholtz SM. (1983) Accommodative hysteresis: a precursor for induced myopia? Invest Ophthalmol Vis Sci 24:513-515.

Ebenholtz SM. (1985) Accommodative hysteresis: relation to resting focus. Am J Optom physiol Opt. 62, 755-762

Ebenholtz SM and Zander PAL. (1987) Accommodative hysteresis: influence on closed loop measures of far point and near point. Invest Ophthalmol Vis Sci 28:1246-1249.

Ehinger B. (1966) Adrenergic nerves to the eye and to related structures in man and in the cynomolgos monkey (*Macaca irus*). Invest Ophthalmol Vis Sci 5:42-52.

Ehinger B. (1971) A comparative study of the adrenergic nerves to the anterior segment of some primates. Z Zellforsch mikrosk Anat 116:157-177.

Elliott TR. (1904) On the action of adrenalin. J Physiol 31:20P.

Epstein D, Ingelstam E, Janssan K and Tengroth B. (1981) Low-luminance myopia as measured with a laser optometer. Acta Ophthalmol 59:928-943.

Fincham EF. (1937) The mechanism of accommodation. Br J Ophthalmol Monograph suppl No VIII. Pulman, London.

Fincham EF. (1951) The accommodation reflex and its stimulus. Br J Ophthalmol 35:381-393.

Fincham EF. (1953) Defects of the colour-sense mechanism as indicated by the accommodation reflex. J Physiol 121:570-580.

Fincham EF and Walton J. (1957) The reciprocal actions of accommodation and convergence. J Physiol 137:488-588.

Fincham EF. (1962) Accommodation and convergence in the absence of retinal images. Vision Res 1:425-440.

Fisher RF. (1969a) The elastic constants of the human lens capsule. J Physiol 201:1-20.

Fisher RF. (1969b) The significane of the shape of the lens and capsular energy changes in accommodation. J Physiol. 201:21-47.

Fisher RF. (1971) The elastic constants of the human lens. J Physiol 212:147-180.

Fisher RF. (1982) The vitreous and lens in accommodation. Trans Opththal Soc UK 102:328-322.

Fisher SK, Ciuffreda KJ and Hammer S. (1987a) Interocular equality equality of tonic accommodation and consensuality of accommodative hysteresis. Ophthal physiol Opt 7:17-20.

Fisher SK, Ciuffreda KJ and Levine S. (1987b) Accommodative hysteresis and refractive error. Invest Ophthalmol Vis Sci suppl 28:103.

Fledelius HC. (1981) Accommodation and juvenile myopia. Doc Ophthalmol Proc Series 28:103-108.

Fleming DG. (1957) The role of the sympathetics in visual accommodation. Am J Ophthal. 43:789.

Fleming DG. (1959) A mechanism for the sympathetic control of accommodation. Am J Ophthal 47:585-586.

Fleming DG and Hall JL. (1959) Autonomic innervation of the ciliary body. Am J Ophthal 48:287-293.

Fleming DG and Olmsted JMD. (1955) Influence of cervical sympathetic ganglionectomy on th lens of the eye. Am J Physiol 181:664-668.

Garner LF. (1983) Mechanisms of accommodation and refractive error. Ophthal physiol Opt 3:287-293.

Garner LF, Brown B, Baker R and Colgan M. (1983) The effect of phenylephrine hydrochloride on the resting point of accommodation. Invest Ophthalmol Vis Sci 24:393-398.

Gawron VJ. (1981) Differences among myopes, emmetropes, and hyperopes. Am J Optom physiol Opt 58:753-760.

Gawron VJ. (1983) Ocular accommodation, personality and autonomic balance. Am J Optom physiol Opt 60:630-639.

Gawron VJ, Paap KR and Malmstrom FV. (1985) The effects of task performance on ocular accommodation and perceived size. Aviat Space Environ Med 56:225-232.

Génis-Gálvez JM. (1957) Innervation of the ciliary muscle. Anat Rec 127:219-230.

Gilmartin B. (1986) A review of the role of sympathetic innervation of the ciliary muscle in ocular accommodation. Ophthal physiol Opt 6:23-37.

Gilmartin B and Bullimore MA. (1986) Evidence for sympathetic innervation of the ciliary muscle during sustained near vision. Invest Ophthalmol Vis Sci suppl 25:81.

Gilmartin B and Bullimore MA. (1987) Sustained near-vision augments sympathetic innervation of the ciliary muscle. Clin Vis Sci 1:197-208.

Gilmartin B and Hogan RE. (1985a) The role of the sympathetic nervous system in ocular accommodation and ametropia. Ophthal physiol Opt 5:91-93.

Gilmartin B and Hogan RE. (1985b) The relationship between tonic accommodation and ciliary muscle innervation. Invest Ophthalmol Vis Sci 26:1024-1029.

Gilmartin B and Hogan RE. (1985c) The magnitude of longitudinal chromatic aberration of the human eye between 458 nm and 633 nm. Vision Res 26:1024-1028.

Gilmartin B, Hogan RE and Thompson SM. (1984) The effect of timolol maleate on tonic accommodation, tonic vergence and pupil diameter. Invest Ophthalmol Vis *Sci 25:*763-770.

Gimbel HV. (1973) The control of myopia with atropine. Can J Ophthalmol 8:527-532.

Glickstein M and Millodot M. (1970) Retinoscopy and eye size. Science 168:605-606.

Goldschmidt E. (1968) On the etiology of myopia Acta Ophthalmol Suppl 98:1-172.

Greene PR. (1980) Mechanical considerations on myopia- relative effects of accommodation, convergence, intraocular pressure and extra-ocular muscles. Am J Optom physiol Opt 57:902-914.

Hamasaki D, Ong J and Marg E. (1956) The amplitude of accommodation in presbyopia. Am J Optom Arch Am Acad Optom 33:3-14.

Heath GG. (1956a) The influence of visual acuity on the accommodative response. Am J Optom Arch Am Acad Optom 33:513-524.

Heath GG. (1956b) Components of accommodation. Am J Optom. 33:569-579.

Heath GG. (1962) The time course of night and space myopia. Aerospace Medical Division, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. Report Number AMRL-TDR-62-80.

Helmholtz H. (1855) Uber die Akkommodation des Auges. Albrecht v Graefes Arch Ophthal 1 Part 2:1-74.

Henke W. (1860) Der Mechanism der Accommodation fur Nahe und Ferne. Albrecht v Graefes Arch Ophthal 6 part 2:53-72.

Hennessy RT (1975) Instrument myopia. J Opt Soc Am 65:1114-1120.

Hennessy RT, Iida T, Shiina K and Leibowitz HW. (1975) The effect of pupil size on accommodation. Vision Res 16:587-589.

Hennessy RT and Leibowitz HW. (1970) Subjective measuremant of accommodation with laser light. J Opt Soc Am 60:1700-1701.

Hennessy RT and Leibowitz HW. (1971) The effect of a peripheral stimulus on accommodation. Percept Psychophys 10:129-132.

Hennessy RT and Leibowitz HW. (1972) Laser Optometer incorporating the Badal principle. Behav Res Meth Instrum 4:237-239.

Henson DB. (1983) Optometric Instrumentation pp 163-184. Butterworths, London.

Heron G, Smith AC and Winn B. (1981) The influence of method on the stability of the dark focus position of accommodation. Ophthal physiol Opt 1:79-90.

Hess C and Heine L. (1898) Arbeiten aus dem Gebiete der Accommodationslehre. Albrecht v Graefes Arch Ophthal 46:243-276.

Hess EH and Polt JM. (1964) Pupil size in relation to mental activity during simple problem-solving. Science 143:1190-1192.

Hofstetter HW. (1942) The proximal factor in accommodation and convergence. Am J Optom Arch Am Acad Optom 19:67-76.

Hogan RE. (1985) Aspects of tonic accommodation and tonic vergence. Unpublished PhD Thesis, University of Aston in Birmingham.

Hogan RE and Gilmartin B. (1984a) Aspects of tonic levels of accommodation, vergence and pupil. Ophthal physiol Opt 4:187.

Hogan RE and Gilmartin B (1984b). The choice of laser speckle exposure duration in the measurement of tonic accommodation. Ophthal physiol Opt 4:365-368.

Hogan RE and Gilmartin B. (1985) The effect of sustained visual tasks on tonic accommodation and tonic vergence. Ophthal physiol Opt 5:234-235.

Hokoda SC and Ciuffreda KJ. (1982) Measurement of accommodative amplitude in amblyopia. Ophthal physiol Opt 2:205-212.

Hope GM and Rubin ML. (1984) Night myopia. Surv Ophthalmol 29:129-136.

Howcroft MJ and Parker JA. (1977) Aspheric curvatures for the human lens. Vision Res 17:1217-1223.

Hurwitz BS, Davidowitz J, Chin NB and Breinin GB. (1972a) The effects of the sympathetic nervous system on accommodation: 1. Beta sympathetic nervous system. Arch Ophthalmol 87:668-674.

Hurwitz BS, Davidowitz J, Pachter BR and Breinin GB. (1972b) The effects of the sympathetic nervous system on accommodation: 2. Alpha sympathetic nervous system. Arch Ophthalmol 87:675-678.

Ingelstam E and Ragnarsson SI. (1972) Eye refraction examined by the aid of speckle pattern produced by coherent light. Vision Res 12:411-420.

Irving A. (1957) Ametropia at low illuminations. Unpublished MSc Thesis, University of Manchester (Technology). (Cited by Charman, 1982).

Ittleson WH and Ames AA. (1950) Accommodation, convergence and their relation to apparent distance. J Psychol 30:43-62.

Ivanoff A. (1947a) Les aberrations de chromatisme et de sphericite de l'oeil; Leur role en vision nocturne. Revue Opt Theor Instrum 26:145. (Cited by Mellerio, 1966)

Ivanoff A. (1947b) On the influence of accommodation on spherical aberration in the human eye, an attempt to interpret night myopia. J Opt Soc Am 37:730-731.

Jackson E. (1931) Norms of refraction. Trans Sec Ophth Amer Med Assoc. (Cited by Luedde, 1932).

Jenkins TCA. (1963) Aberrations of the eye and their effects on vision, parts 1 and 2. Br J Physiol Optics 20:59-91 and 161-201.

Jessop M. (1886) On the anatomy, histology and physiology of the intraocular muscles of mammals. Proc R Soc. 40478-484.

Jessop M. (1888) Physiology of the intraocular muscles. Berlin Int Ophthal Cong 7:188.

Johnson CA. (1976) Effects of luminance and stimulus distance on accommodation and visual resolution. J Opt Soc Am 66:138-142.

Johnson CA, Post RB and Tsuetaki TK. (1984) Short-term variability of the resting focus of accommodation.Ophthal physiol Opt 4:319-325.

Kern R. (1970) Die adrenergischen Receptoren der intraocularen Muskeln des Menschen. Albrecht v Graefes Arch Ophthal 180:231-248.

Kersten D and Legge GE. (1983) Convergence accommodation. J Opt Soc Am 73:332-338.

Kirschen DG, Kendall JH and Stark L. (1981) An evaluation of the accommodative response in amblyopic eyes. Am J Optom physiol Opt 58:597-602.

Koomen M, Scolnik R and Tousey R. (1951) A study of night myopia. J Opt Soc Am 41:80-90.

Korge A and Krueger H. (1984) Influence of edge sharpness on the accommodation of the human eye. Albrecht v Graefes Arch Klin Ophthal 222:26-28.

Kothe AC, Lovasik JV and Campbell MCW. (1987) Variation of dark focus of accommodation with laser speckle exposure duration. Ophthal physiol Opt 7:143-148.

Kotulak JC and Schor CM. (1986) The dissociability of accommodation from vergence in the dark. Invest Ophthal Vis Sci 27:544-551.

Krishnan VV and Stark L. (1975) Integral control in accommodation. Comput Progm Biomed 4:237-245.

Krishnan VV and Stark L. (1977b) A heuristic model for the human vergence eye movement system. I.E.E. Trans Biomed Engin BME-24:44-49.

Kruger PB (1980) The effect of cognitive demand on accommodation. Am J Optom physiol Opt 57:440-445.

Kruger PB and Pola J. (1986) Stimuli for accommodation: Blur, chromatic aberration and size. Vision Res 26:957-971.

Kruger PB and Pola J. (1987) Dioptric and non-dioptric stimuli for accommodation: Target size alone and with blur and chromatic aberration. Vision Res 27:555-567.

Krumholz DM, Fox RS and Ciuffreda KJ. (1986) Short-term changes in tonic accommodation. Invest Ophthalmol Vis Sci 27:552-557.

Kuntz A. (1929) The autonomic nervous system, pp. 317-323. Lea and Febinger, Philadelphia.

Kuntz A, Richens CA and Casey CA. (1946) Reflex control of the ciliary muscle. J Neurophysiol 9:445-451.

Lands AM, Arnold A, McAnliff JP, Ludueana FP and Brown RG, Jr. (1967) Differentiation of receptor systems activated by sympathomimetic amines. Nature 214:598-697.

Laties AM and Jacobowitz D. (1966) A comparative study of the autonomic innervation of the eye in monkey, cat and rabbit. Anat Rec 156:383-389.

Le Grand Y. (1942) Etudes sur la vision nocturne. Revue Opt Theor Instrum 21:71-87. (Cited by Mellerio, 1966)

Leibowitz HW. (1976) Visual perception and stress, in Physical Work and Effort. Ed. Borg G. pp. 25-37. Pergamon Press, New York.

Leibowitz HW and Owens DA (1975a) Night myopia and the intermediate position of relaxed accommodation. J Opt Soc Am 65:1121-1128.

Leibowitz HW and Owens DA. (1975b) Anomalous myopias and the intermediate dark-focus of accommodation. Science 189:646-648.

Leibowitz HW and Owens DA (1978) New evidence for the intermediate position of relaxed accommodation. Doc Ophthalmol 46:133-147.

Libby WL, Lacey BC and Lacey JI. (1973) Pupillary and cardiac activity during visual attention. Psychophysiol 10:270-294.

Linder K. (1944) Uben einfluss von umwelt und vererbung auf die entstehung der schulmyopie. Alb v Graefes Arch Opthal 146:336-376.

Lograno MD and Reibaldi A. (1986) Receptor-responses of fresh human ciliary muscle. Br J Pharmacol 87:379-385.

Lovasik JV. (1983) A simple continuously recording infrared optometer. Am J Optom physiol Opt 60:80-87.

Luedde WH. (1932) Monocular cycloplegia for the control of myopia. Am J Ophthalmol 15:603-609.

Lutjen-Drecoll E and Kaufman PL. (1986a) Long-term timolol and epinephrine in monkeys. 1. Functional morphology of the ciliary processes. Trans ophthalmol Soc UK 105:180-195.

Lutjen-Drecoll E and Kaufman PL. (1986b) Long-term timolol and epinephrine in monkeys. 2. Morphological alterations in trabecular meshwork and ciliary muscle. Trans ophthalmol Soc UK 105:196-207.

Maddock RJ, Millodot M, Leat S and Johnson CA. (1981) Accommodative responses and refractive error. Invest Ophthalmol Vis Sci 20:387-391.

Malmfors T. (1965) The adrenergic innervation of the eye as demonstrated by fluorescence microscopy. Acta physiol scand 65:259-267.

Malmstrom FV and Randle RJ. (1976) Effects of visual imagery on the accommodation response. Percept Psychophys 19:450-453.

Malmstrom FV and Randle RJ. (1984) Effect of a concurrent counting task on dynamic visual accommodation. Am J Optom physiol Opt 61:590-594.

Malmstrom FV, Randle RJ, Bendix JS and Weber RJ. (1980) The visual accommodation response during concurrent mental activity. Percept Psychophys 28:440-448.

Malmstrom FV, Randle RJ, Murphy MR, Reed LR and Weber RJ. (1981) Visual fatigue: The need for an integrated model. Bull Psychonom Soc 17:183-186.

Mäntyjärvi MI. (1987) Accommodation in hyperopic and myopic school children. J Paed Ophthalmol Strab 24:37-41.

Marchand E. (1978) Gradient Index Optics. Academic Press, New York.

Marg E. (1951) An investigation of voluntary as distinguished from reflex accommodation. Am J Optom Arch Am Acad Optom 28:347-356.

Matsumura I, Maruyama S, Ishikawa Y, Hirano R, Kobayashi K and Kohayakawa Y. (1983) The Design of an open view autorefractor, in Advances in Diagnostic Visual Optics. Eds. Breinin GM and Siegel IM. pp 36-42. Springer, Berlin.

Maurice DM and Mushin AS. (1966) Production of myopia in rabbits by raised body-temperature and increased intraocular pressure. Lancet 2:1160-1162.

McBrien NA. (1987) Differences in adaptation of tonic accommodation with refractive state. Invest Ophthalmol Vis Sci suppl 28:316.

McBrien NA and Barnes DA. (1984) A review and evaluation of theories of refractive error development. Ophthal physiol Opt 4:201-213.

McBrien NA and Millodot M. (1985) Clinical evaluation of the Canon Autoref R-1. Am J Optom physiol Opt 62, 786-792.

McBrien NA and Millodot M. (1986a) The effect of refractive error on the accommodative response gradient. Ophthal physiol Opt 6:145-149.

McBrien NA and Millodot M. (1986b) Amplitude of accommodation and refractive error. Invest Ophthalmol Vis Sci 27:1187-1190.

McBrien NA and Millodot M. (1987) The relationship between tonic accommodation and refractive error. Invest Ophthalmol Vis Sci 28:997-1004.

Mellerio J. (1966) Ocular refraction at low illuminations. Vision Res 6:217-237.

Melton CE, Purnell, EW and Brecher GA. (1955) The effect of sympathetic nerve impulses on the ciliary muscle. Am J Ophthal 40:155-162.

Mershon DH and Amershon TL. (1980) Stability of measures of the dark focus of accommodation. Invest Ophthalmol Vis Sci 19:217-221.

Miller RJ. (1978a) Mood changes and the dark focus of accommodation. Percept Psychophys 24:437-443.

Miller RJ. (1978b) Temporal stability of the dark focus of accommodation. Am J Optom physiol Opt 55:447-450.

Miller RJ and LeBeau RC. (1982) Induced stress, situationally-specific trait anxiety and dark focus. Psychophysiol 19:260-265.

Miller RJ, Pigion RG, Wesner MF and Patterson JG. (1983) Accommodation fatigue and dark focus: the effects of accommodation-free visual work when assessed by two psychophysical methods. Percept Psychophys 34:532-540.

Miller RJ, Wesner MF, Pigion RG and Martin KD. (1984) Overaccommodation, underaccommodation and the clinical phoropter: A study of instrument myopia and related effects. Am J Optom physiol Opt 61:293-303.

Millodot M. (1968) Effet des microfluctuations de l'accommodation sur l'acuite visuelle. Vision Res 8:73-80.

Millodot M and Sivak J. (1973) Influence of accommodation on the chromatic aberration of the eye. Br J physiol Optics 28:169-174.

Millodot M and Thibault C. (1985) Variation of astigmatism with accommodation and its relationship with dark focus. Ophthal physiol Opt 5:297-301.

Mohan M, Rao VA and Dada VK. (1977) Experimental myopia in the rabbit. Exp Eye Res 25:25:33-38.

Mohindra I. (1975) A technique for infant vision examination. Am J Optom physiol Opt 52:867-870.

Mohindra I. (1977a) Comparison of "near retinoscopy" and subjective refraction in adults. Am J Optom physiol Opt 54:319-322.

Mohindra I. (1977b) A non-cycloplegic refraction technique for infants and young children. J Am Optom Assoc 48:518-522.

Mohney JB, Morgan MW, Olmsted JMD and Wagman IH. (1942) The pathway of sympathetic nerves to the ciliary muscles in the eye. Am J Physiol 135:759-762.

Morat JP and Doyon M. (1891) Le grand sympathetique nerf de l'accommodation pour la vision des objets eloignes. Ann Oculist Paris 106:28-30.

Mordi J, Tucker J and Charman WN. (1986) Effects of 0.1% cyclopentolate or 10% phenylephrine on pupil diameter and accommodation. Ophthal physiol Opt 6:221-228.

Morgan MW. (1944a) The nervous control of accommodation. Am J Optom 21:87-93.

Morgan MW. (1944b) Accommodation and its relationship to convergence Am J Optom Arch Am Acad Optom 21: 183-195.

Morgan MW. (1946) A new theory for the control of accommodation. Am J Physiol 23:99-110

Morgan MW. (1957) The resting state of accommodation. Am J Optom 34:347-353.

Morgan MW, Olmsted JMD and Watrous WG. (1940) Sympathetic action in accommodation for far vision. Am J Physiol 128:588-591.

Nadell MC and Knoll HA. (1956) The effect of luminance, target cnfiguration and lenses upon the refractive state of the eye. Parts 1 and 2. Am J Optom Arch Am Acad Optom 33:24-42, 86-95.

Nadell MC, Weymouth, FW and Hirsch MJ. (1956) The relationship of frequency of use of the eyes in close work to the distribution of refractive error. Am J Optom Arch Am Acad Optom 33:523-533.

Nakoa S, Mine K, Nishioka K and Kamiya S. (1969a) The distribution of refractive indices in the human crystalline lens. Jap J Clin Ophthalmol 23:41-44.

Nakoa S, Ono T, Nagata R and Iwata K. (1969b) The distribution of refractive indices in the human crystalline lens. Jap J Clin Ophthalmol 23:903-906.

Oakley KH and Young FA. (1975) Bifocal control of myopia. Am J Optom physiol Opt 52:758-764.

Ogle KN and Schwartz JT. (1959) Depth of focus of the human eye. J Opt Soc Am 49:273-280.

Olmstead JMD. (1944) The role of the autonomic nervous system in accommodation for far and near vision J nerv Ment Dis 99:794-798.

Olmstead JMD and Morgan MW. (1983) Refraction of the rabbit's eye in the unexcited and excited state. Am J Physiol 127:602-604.

Olmstead JMD and Morgan MW. (1941) The influence of the cervical sympathetic nerve on the lens of the eye. Am J Physiol 133:720-723.

Ong J and Fisher M. (1973) Effect of accommodative stimulation on the galvanic skin response. Am J Optom Arch Am Acad Optom 50:395-398.

Otero JM. (1953) The measurement of accommodation in dim light and darkness by means of purkinje images. J Opt Soc Am 43:925.

Otero JM and Duran A. (1941) Rendimiento fotometrico de sistemas opticos a baja luminosidades. Anales de Fisica y Quimica 37:459-477. (Cited by Borisch, 1970)

Otero JM and Duran A. (1942) Continuacion del estudio de la miopia nocturna. Anales de Fisica y Quimica 39:567-578. (Cited by Toates, 1972)

Otto J and Safra D. (1974) Ergenbnisse objectiver Akkommodationsmessungen an Augen mit organisch bedingtem Zentralskotom. Albrecht v Graefes Arch Klin Ophthal 192:49-56. (Cited by Charman, 1986)

Owens DA (1980) A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings. Vision Res 20:159-167.

Owens DA and Harris D. (1986) Oculomotor adaptation and the development of myopia. Invest Ophthalmol Vis Sci suppl 27:80.

Owens DA and Leibowitz HW. (1975) The fixation point as a stimulus for accommodation. Vision Res 15:1161-1163.

Owens DA and Leibowitz HW. (1976) Oculomotor adjustments in darkness and the specific distance tendency. Percept Psychophys 20:2-9.

Owens DA and Leibowitz HW. (1980) Accommodation, convergence, and distance perception in low illumination. Am J Optom physiol Opt 57:540-550.

Owens DA, Mohindra I and Held R. (1980) The effectiveness of a retinoscope beam as an accommodative stimulus. Invest Ophthalmol Vis Sci 19:942-949.

Owens DA and Wolf-Kelly KS. (1987) Near work, visual fatigue and variations in oculomotor tonus. Invest Ophthalmol Vis Sci 28:743-749.

Owens RL and Higgins KE. (1983) Long-term stability of the dark focus of accommodation. Am J Optom physiol Opt 60:32-38.

Parker JA. (1972) Aspheric optics of the human lens. Can J Ophthalmol 7:168-175.

Phillips SR. (1974) Ocular neurological control systems: accommodation and the near response triad. Unpublished PhD thesis, University of California, Berkeley. (Cited by Ciuffreda and Kenyon, 1983).

Phillips SR, Shirachi DK and Stark L. (1972) Analysis of accommodation response times using histogram information. Am J Optom 49:389-401.

Pigion RG and Miller RJ. (1985) Fatigue of accommodation: changes in accommodation after visual work. Am J Optom physiol Opt 62:853-863.

Porges SW. (1976) Peripheral and neurochemical parallels of psychopathy: A psychophysiological model relating autonomic imbalance to hyperactivity, psychopathy, and autism in Advances in Child Development and Behaviour (Vol. 11). Ed. Reese HW, pps 36-65. Academic Press, New York.

Post RB, Johnson CA and Tsuetaki TK. (1984) Comparison of laser and infra-red techniques for measurement of the resting focus of accommodation: mean differences and long-term variability. Ophthal physiol Opt. 4:327-332.

Post RB, Johnson CA and Owens DA. (1985) Does performance of tasks affect the resting focus of accommodation? Am J Optom physiol Opt 62:533-537.

Provine RR and Enoch JM. (1975) On voluntary ocular accommodation. Percept Psychophys 17:209-212.

Rabin J, Van Sluyters and Malach R. (1981) Emmetropization: a vision dependent phenomenon. Invest Ophthalmol Vis Sci 20:561-564.

Ramazzini B. (1713) Diseases of Workers. (translated by WC Wright) University of Chicago Press, Chicago. (Cited by Owens and Wolf-Kelly, 1987)

Ramsdale C. (1978) A study of binocular and monocular accommodation. Unpublished PhD thesis, University of Manchester (Technology).

Ramsdale C. (1982) Studies into some aspects of accommodation and convergence. PhD. Thesis, University of Manchester UK.

Ramsdale C. (1985) The effect of ametropia on the accommodative response. Acta Ophthal 63:167-174.

Randle RJ. (1970) Volitional control of visual accommodation. Adaptation and acclimatisation in aerospace medicine. Paper presented at the 27th Aerospace Medical Panel Meeting, Garmisch-Partenkirchen, Sept. 14-18. A.G.A.R.D. Conference proceedings No 82, pp. 20.1-20.11.

Raviola E and Wiesel TN. (1985) An animal model of myopia. New Eng J Med 312:1609-1604.

Rayleigh JWS Lord. (1883) On the visibility of small objects in bad light. Proc Cambridge Philosophical Soc 4:324. (Cited by Mellerio, 1966).

Raymond JE, Lindblad IM and Leibowitz HW. (1984) The effect of contrast on sustained detection. Vision Res 24:183-188.

Richards OW. (1976) Instrument myopia - microscopy. Am J Optom physiol Opt 53:658-663.

Richards OW, Matthews SM and Shaffer SM. (1980) Focussed apparent image position with convergent, parallel binocular and moncular microscopes. J Microscopy 122:187-191.

Richler A and Bear JC. (1980) Refraction, nearwork and education. A population study in Newfoundland. Acta Ophthalmol 58:468-478.

Ripps H, Chin N, Siegel IM and Breinin G. (1962) The effect of pupil size on accommodation, convergence and the AC/A ratio. Invest Ophthalmol 1:127-135.

Rohen JW and Rentsch FJ. (1969) Der konstructive bau des zonulaaparates beim menschen und dessen funktionelle bedeutung. Albrecht v Graefes Arch Ophthal 178:1-19.

Romer P and Dufour O. (1902) Experimentelle und kritische Untersuchungen zur Frage nach dem Einfluss des Nervus sympathicus auf den Accommodations vorgang. Albrecht v Graefes Arch Ophthal 54:491-499.

Ronchi V. (1948) Miopia notturna e accomodazione. Atti Fond Giorgio Ronchi 3:22-31. (Cited by Mellerio, 1966).

Rose L, Yinon U and Belkin M. (1974) Myopia induced in cats deprived of distance vision during development. Vision Res 14:1029-1032.

Rosenfield M and Gilmartin B. (1987a) Oculomotor consequences of beta-adrenoceptor antagonism during sustained near vision. Ophthal physiol Opt 7:127-130.

Rosenfield M and Gilmartin B. (1987b) Effect of a near-vision task on the response AC/A of a myopic population. Ophthal physiol Opt 7:225-233.

Ruskell GL. (1973) Sympathetic innervation of the ciliary muscle in monkeys. Exp Eye Res 16:183-190.

Ruskell GL and Griffiths T. (1979) Peripheral nerve pathway to the ciliary muscle. Exp Eye Res 28:277-284.

Salzmann M. (1912) The anatomy and histology of the human eyeball in the normal stat. Translated by Brown EVL. University of Chicago Press, Chicago.

Sato T. (1957) The Causes and Prevention of Acquired Myopia. Kanehara Shuppan, Tokyo. (Cited by Borish, 1970).

Schell K, Sewell S, Anzalone L, Adams AJ, Zisman F, DuVall B, Cooperman J and Vail L. (1986) Ocular components contributing to myopia progression in adults. Am J Optom physiol Opt 63:63P.

Schober HAW, Dehler H and Kassel R. (1970) Accommodation during observations with optical instruments. J Opt Soc Am 60:103-107.

Schor CM, Johnson CA and Post RB. (1984) Adaptation of tonic accommodation. Ophthal physiol Opt 4:133-137.

Schor CM and Kotulak JC. (1986) Dynamic interactions between accommodation and convergence are velocity sensitive. Vision Res 26:927-942.

Schor CM, Kotulak JC and Tsuetaki T. (1986) Adaptation of tonic accommodation reduces accommodative lag and is masked in darkness. Invest Ophthalmol Vis Sci 27:820-827.

Semmlow JL and Hung GK. (1981) Experimental evidence for separate mechanisms mediating accommodative vergence and vergence accommodation. Doc Ophthalmol 51:209-224.

Semmlow JL and Tinor T. (1978) Accommodative convergence response to off-foveal retinal images. J Opt Soc Am 68:1497-1501.

Sheard C. (1920) Dynamic skiametry. Cleveland Press, Chicago.

Shirachi D, Liu J, Lee M, Jang J, Wong J and Stark L. (1978) Accommodation dynamics 1. Range nonlinearity. Am J Optom physiol Opt 55:631-641.

Simonelli NM. (1980) Polarized vernier optometer. Behav Res Meth Instrum 12:293-296.

Simonelli NM. (1983) The dark focus of the human eye and its relationship to age and visual defect. Human factors 25:85-92.

Smith G. (1983) The accommodative resting states, instrument accommodation and their measurement. Optica Acta 30:347-359.

Sorsby A. (1967) The nature of spherical refractive errors, in Report of the Workshop on Refractive Anomalies of the Eye. N.I.N.D.B. Monograph No 5, US Department of Health, Education and Welfare, Washington, DC.

Sorsby A and Benjamin B. (1973) Modes of inheritance of errors of refraction. J Med Genet 10:161-164.

Sorsby A, Benjamin B, Davey JB, Sheridan M and Tanner JM. (1957) Emmetropia and its aberrations. Medical Research Council Special Report Series No. 293, HMSO, London.

Sorsby A, Sheridan M and Leary GA. (1962) Refraction and its components in twins. Medical Research Council Special Report Series No. 301, HMSO, London.

Stark L, Takahashi, VV and Zames G. (1965) Nonlinear servo-analysis of human lens accommodation. IEEE Trans Sys Science Cyberetics SSC-1:75-83.

Steiger A. (1913) Die Entstehung der spharischenn Refracktionen des menschlichen Auges. Karger, Berlin.

Stenstrom S. (1946) Investigation of the Variation and Correlation of the Optical Elements of Human Eyes. Translated by Woolf D. Am J Optom. Monograph 58.

Stephens KG. (1985) Effect of the sympathetic nervous system on accommodation. Am J Optom physiol Opt 62:402-406.

Sternbach RA. (1966) Principles of Psychology. Academic Press, New York.

Stevenson RWW. (1984) The development of myopia and its relationship with intraocular pressure. In Charman WN (Ed), Transactions of the First International Congress, "The Frontiers of Optometry", Vol 2, pp 43-50. British College of Ophthalmic Opticians, London.

Stone EA. (1975) Stress and catecholamines, in Catecholamines and Behaviour, Vol. 2, Neuropsychopharmacology. Ed. Friedhoff AJ. pp. 31-72. Plenum Press, New York.

Straub M. (1909) Uber die Aetiologie der Brechungsonomalien des Auges und den Ursprung der Emmetropie. Albrecht v Graefes Arch Ophthal 70:130-199.

Suzuki R. (1983) Neuronal influence on the mechanical activity of the ciliary muscle. Br J Pharmacol 78:591-597.

Tan RKT. (1986) The effect of accommodation response on the dark focus. Clin Exp Optom 69:156-159.

Tan RKT and O'Leary DJ. (1986) The stability of the accommodative dark focus after periods of maintained accommodation. Invest Ophthalmol Vis Sci 25:1414-1417.

Toates FM. (1970) A model for accommodation. Vision Res 10:1069-1076.

Toates FM. (1972) Accommodation function of the human eye. Physiol Rev 52:828-863.

Tokoro T. (1970) Experimental myopia in rabbits. Invest Ophthalmol 9:926-934.

Törnqvist G. (1966) Effect of cervical sympathetic stimulation on accommodation in monkeys. Acta physiol scand 67:363-372.

Törnqvist G. (1967) The relative importance of the parasympathetic and sympathetic nervous systems for accommodation in monkeys. Invest Ophthalmol 6:612-617.

Tucker J and Charman WN. (1975) The depth of focus of the human eye for Snellen letters. Am J Optom physiol Opt 52:3-21.

Tucker J and Charman WN. (1979) Reaction and response times for accommodation. Am J Optom physiol Opt 56:490-503.

Tucker J and Charman WN. (1987) Effect of target content at higher spatial frequencies on the accuracy of the accommodation response. Ophthal physiol Opt 7:137-142.

Tucker J, Charman WN and Ward PA. (1986) Modulation dependence of the accommodation response to sinusoidal gratings. Vision Res 25:1693-1707.

Ukai K, Ishii M and Ishikawa S. (1986) A quasi-static study of accommodation in amblyopia. Ophthal physiol Opt 6:287-295.

Van Alphen GWHM. (1961) On emmetropia and ametropia. Ophthalmologica Suppl 142:1-92.

Van Alphen GWHM. (1976) The adrenergic receptors of the intraocular muscles of the human eye. Invest Ophthalmol Vis Sci 15:502-505.

Van Alphen GWHM. (1986) Choroidal stress and emmetropization. Vision Res 26:723-734.

Van Alphen GWHM, Kern R and Robinette SL (1965) Adrenergic receptors of the intraocular muscles. Arch Ophthal 74:253-259.

Van Buskirk EM. (1980) Adverse reactions from timolol administration. Ophthalmology 87:447-450.

Von Euler US. (1946) A specific sympathomimetic ergone in adrenergic nerve fibres. (Sympathin) and its relations to adrenaline and nor-adrenaline. Acta physiol scand 12:73-97.

Wald G and Griffin DR. (1947) The change in refractive power of the human eye in dim and bright light. J opt Soc Am 37:321-336.

Wallman J, Turkel J and Trachtman J. (1978) Extreme myopia produced by modest change in early visual experience. Science 201:1249.

Ward PA. (1987) The effect of stimulus contrast on the accommodation response. Ophthal physiol Opt 7:9-15.

Ward PA and Charman WN. (1985) Effect of pupil size on steady-state accommodation. Vision Res 25:1317-1326.

Ward PA and Charman WN. (1986) Measurements of cycloplegia and mydriasis induced by three common ophthalmic drugs. Clin Exp Optom 69:62-70.

Ward PA and Charman WN. (1987) On the use of small artificial pupils to open-loop the accommodation system. Ophthal physiol Opt 7:191-193.

Warwick R. (1954) The ocular parasympathetic nerve supply and its mesencephalic sources. J Anat 88:71-93.

Warwick R. (1956) Oculomotor organisation. Ann Royal Coll Surg 19:36-52.

Wax M and Molinoff PB. (1987) Distribution and properties of ß-adrenergic receptors in human iris/ciliary body. Invest Ophthalmol Vis Sci 28:420-430.

Wenger MA, Jones FN and Jones MH. (1956) Physiological Psychology, pp 258-271. Henry Holt & Co., New York.

Wertheim T. (1891) Peripheral visual acuity. Translated by Dunsky IL(1980) Am J Optom physiol Opt 57:915-924.

Westheimer G. (1957) Accommodation measurements in empty visual fields. J Opt Soc Am 47:714-718.

Westheimer G and Blair SM. (1973a) The parasympathetic pathways to the internal eye muscles. Invest Ophthalmol 12:193-197.

Westheimer G and Blair SM. (1973b) Accommodation of the eye during sleep and anaesthesia. Vision Res 13:1035-1040.

Whiteside TC. (1952) Accommodation of the human eye in a bright and empty visual field. J Physiol 118:65P.

Whiteside TC. (1957) Problems of vision in flight at high altitude. London: Butterworths.

Wibaut F. (1919) Refractitoeneming in schemerdonker. Ned Tijdschr Geneesk 55:1437-1441.

Wiesel TN and Raviola E. (1977) Myopia and eye enlargement after neonatal lid fusion in monkeys. Nature 266:66-68.

Willemsen EW. (1974) Understanding statistical reasoning. W.H. Freeman & Co. San Francisco.

Wolf KS, Ciuffreda KJ and Jacobs SE. (1987) Time course and decay of the effects of near work on tonic accommodation and tonic vergence. Ophthal physiol Opt 7:131-135.

Wolfe JM and O'Connell KM. (1987) Adaptation of the resting states of accommodation. Invest Ophthalmol Vis Sci 28:992-996.

Wolfe JM and Owens DA. (1981) Is accommodation colorblind? Focussing chromatic contours. Perception 10:53-62.

Wolffe E. (1976) Anatomy of the Eye and Orbit. 7th edition. Lewis, London.

Wolter JR. (1953) Berichte u.d. 58. Zusammenkunft der Deutschen Ophth. Gesellsschaft in Heidelberg (cited by Melton *et al.*, 1955).

Wood ICJ and Tomlinson AT. (1975) The accommodative response in amblyopia. Am J Optom physiol Opt 52:243-247.

Young FA. (1961) The effect of restricted visual space on primate eyes. Am J Ophthalmol 52:799-806.

Young FA. (1965) The effect of atropine on the development of myopia in monkeys. Am J Optom 42:439-449.

Young FA. (1967) Present state of knowledge regarding the mechanisms giving rise to refraction anomalies., in Report of the Workshop on Refractive Anomalies of the Eye. N.I.N.D.B. Monograph No 5, US Department of Health, Education and Welfare, Washington, DC.

Young FA. (1975) Development and control of myopia in human and subhuman primates. Contacto 19:16-31.

Young FA, Leary GA, Box RA, Baldwin WR, West DC, Harris E and Johnson C. (1969) The transmission of refractive errors within Eskimo families. Am J Optom 46:676-685.

Young FA, Singer RM and Foster D. (1975) The psychological differentiation of male myopes and non-myopes. Am J Optom physiol Opt 52:679-686.