ASPECTS OF TONIC ACCOMMODATION AND TONIC VERGENCE

BY

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SUMMARY

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Under conditions of reduced visual stimulation, the systems of accommodation and vergence tend towards physiological resting states that are intermediate within their functional range. The terms tonic accommodation (TA) and tonic vergence (TV) are used in the study to describe these stimulus-free, intermediate adjustments and to represent the systems as being in a state of innervational tonicity. The literature relating to TA and TV and the various experiments of this thesis are reviewed.

Methodology has been developed enabling the determination of TA and TV under conditions of total darkness: laser optometry for TA and vernier-alignment for TV. The thesis describes a series of experiments designed to investigate various aspects of TA and TV, and their role in ametropia, binocular vision and their adaptation to sustained visual tasks. Measurements of TA were also utilised to investigate the effect of various autonomic effector drugs on the ciliary muscle.

The effects of ethanol on binocular function are shown to be directly proportional to the initial level of TV; which is itself unaffected. These results support the concept of TV as the reference point for normal vergence responses. The results of the pharmacological investigations indicate the presence of a small but significant, beta-receptor mediated inhibitory sympathetic input to the ciliary muscle, and that the wide distribution in TA is a consequence of inter-observer variations in parasympathetic, rather than sympathetic tone.

Following interaction with visual tasks of 15mins duration, the levels of TA and TV are found to be biased in the direction of, and proportional to, the task position: except during near-task viewing where the task-to-TA stimulus-distance exceeds 1.5D (for TA) and 3.5deg (for TV). Under these conditions the expected level of bias is attenuated. Adaptive models are discussed, proposing TA and TV as the reference points of the accommodative and vergence systems.

Key Words:
Tonic accommodation - tonic vergence - oculomotor stress - autonomic pharmacology - tonic adaptation

I would like to dedicate this thesis to my wife, Susan.

Thankyou for everything.

"If I have seen further
it is by standing on the shoulders of giants."

Sir Isaac Newton, (in a letter to Robert Hooke, 5th feb. 1675.)

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GENERAL INTRODUCTION

The information processing demands of a temporally and spatially dynamic visual environment, require of the human visual system, the ability to maintain an optimally focussed and binocularly-fixated image of the visual stimulus on the retina of each eye, in order that the optimum visual information is obtained. The retinal image of each eye is transduced into coded electrical signals and conveyed to the visual cortex via the visual pathway. At various stages along this system, the electrical signals representing the retinal images are compared, contrasted and eventually combined, in order that optimal perception of the visual stimulus is achieved and the appropriate response initiated.

If the information content of the retinal image can be improved (by the alteration of ocular focus), the refractive power of the eye is increased or decreased, as required (via a closed-loop feedback system). The process by which the refractive power of the eye is altered is termed 'accommodation'.

If the object of regard appears diplopic, the eyes will be horizontally rotated, with respect to each other, until an image of the object is projected on to the fovea of each eye, thereby effecting single binocular perception. A subsequent change in the linear distance of the visual stimulus will produce retinal disparity, which requires a further adjustment of the angle between the visual axes until binocularity is restored. A subsequent change in the lateral position of the visual stimulus (remaining at a constant linear distance), requires the visual axes to rotate horizontally by the same angle until fixation is restored. The process by which the angle between the visual axes of the eyes is altered is termed 'vergence', whilst the process by which the visual axes are changed by the same angle is termed 'version'.

Under normal visual conditions, a synkinesis exists between the responses of the accommodative and vergence systems (e.g., Davson, 1980; Semmlow and Hung, 1983), such that, when a visually normal observer transfers his binocular fixation from a visual task at one distance to a further visual task at a second distance, the necessity of maintaining optimal image definition and of preserving single binocular vision, requires an appropriate alteration in both, refractive power and vergence angle: a near visual task requires an increase in both refractive power and vergence angle, whereas a far visual requires a decrease in both refractive power and vergence angle.

Stimulus-dependency of the accommodative response.

A modification of the nervous input to the ciliary muscle, in response to an accommodative stimulus, induces a mechanical change in the shape of the crystalline lens and thus its focal length. Previous research has shown that the magnitude and accuracy of this response may be dependent upon such stimulus characteristics as: contrast (Charman and Tucker, 1978a; Owens, 1980; Raymond et al. 1984); spatial frequency (Charman and Tucker, 1977; Charman and Heron, 1979; Bour, 1981); stimulus luminance (Wald and Griffen, 1947; Campbell, 1954; Johnson, 1976); and colour (Fincham, 1951; Charman and Tucker, 1978b; Wolfe and Owen, 1981); together with various temporal factors, such as the latency of response (Campbell and Westheimer, 1960; Shirachi et al., 1978; Tucker and Charman, 1979) and microfluctuations (Campbell et al., 1959; Millodot, 1968; Denieul, 1982); perceived stimulus distance (Hofstetter, 1942; Ittelson and Ames, 1950; Johnson, 1976) and perceived stimulus size (Alpern,1958b; Benel,1980; Kruger and Pola, 1983; 1984).

The accommodative response may be further modified by inherent ocular factors such as: pupil diameter and the depth of focus (Campbell, 1957; Ogle and Schwartz, 1959; Tucker and Charman, 1975; Hennessy et al. 1976); chromatic aberration (Fincham, 1951, 1953; Campbell and Westheimer, 1959; Millodot and Sivak, 1973) and spherical aberration (Campbell and Westheimer, 1959; Jenkins, 1963; Charman et al., 1978). The accuracy of the accommodative response is also dependent on such observer-related factors as: age (Hamasaki et al. 1956; Braddick et al. 1979; Simonelli, 1979); refractive condition (Ramsdale, 1978; 1982; Simonelli, 1979; Maddock et al. 1981); vergence-accommodation relationships (Fincham and Walton, 1957; Semmlow and Hung, 1981; Kersten and Legge, 1983); volitional control (Marg, 1951; Randle, 1970; Provine and Enoch, 1975); level of awareness (Malstrom and Randle, 1976; Kruger, 1980) and fatigue (Berens and Sells, 1944, 1950; Malstrom et al. 1981; Miller et al. 1983).

The high stimulus dependency exhibited by the accommodative system, is a function of the potential enhancement in retinal image content that may be illicited by an accurate response to a stimulus that is rich in visual information. A visual task with strong stimulus characteristics will therefore, illicit a more accurate response than a visual task with degraded stimulus characteristics. This 'stimulus-dependency' explains the observations of a "lag" and "lead" in the accuracy of the accommodative response, under certain visual conditions (Morgan, 1944a).

Much previous research has shown that the the accommodative response to a poor accommodative stimulus, is biased towards an intermediate position (e.g. Johnson, 1976; Charman and Tucker, 1977; Owens, 1980). This phenomenon has, in the past, been given various descriptive titles such as, "night-myopia", "empty-field-myopia" or "dark-focus". Throughout this thesis, however, the term "tonic accommodation" (TA) will be adopted. The distribution of TA encompasses the near and far points of the ocular accommodative system and for a group of observers and takes a 'normal' gaussian form, with a mean of 76 cm from the eye (Owens and Leibowitz, 1980).

Stimulus-dependency of the vergence response.

Horizontal vergence movements are produced by the the medial and lateral recti muscles and result in rotation of the eyes about the vertical axis of the centre of rotation. Vergence movements can be produced voluntarily (Eskridge, 1971); in response to stimuli such as retinal disparity of the image (Westheimer and Mitchell, 1956, 1969); changes in the level of accommodation (Tait, 1951; Westheimer, 1955; Alpern, 1958); and perceived distance or size (Hofstetter, 1942; Alpern, 1955, 1958).

The accuracy of the vergence response is also dependent upon the quality of the stimulus characteristics of the visual task (Westheimer and Mitchell, 1969; Frisby and Mayhew, 1979); and can be modified by age (Provines, 1971; Slater and Findlay, 1975); stimulus luminance (Ivanoff and Bourdy, 1954; Fincham, 1962; Owens and Leibowitz, 1980); temporal factors, such as latency of response (Allen, 1953; Phillips et al. 1972); retinal eccentricity (Ogle et al. 1949; Francis and Owens, 1983; Hampton and Kertesz, 1983); oculomotor stress (Adler, 1945; Westheimer, 1963; Hogan and Linfield, 1983); fatigue (Malstrom et al. 1981) and adaptive processes (Ebenholtz and Fisher, 1982; Schor, 1983).

As is found with accommodation, the vergence system will respond concomitantly with the stimulus requirements: the error in response has similarly been found to be biased towards the physiological position of rest or tonus. The term "tonic vergence" and its abbreviation "TV" have been adopted in this thesis to represent the physiological resting position of the vergence system. Tonic vergence is intermediate between infinity and the near point of convergence and is an example of a gaussian distribution with a mean of 116 cm from the eye (e.g. Owens and Leibowitz, 1980).

It is evident therefore, that the response and synchronization of the accommodative and vergence systems are dependent not only on the inherent accommodation-vergence interaction, but also on the stimulus characteristics of the visual task. The complexity of these characteristics preclude simple investigation of the roles of accommodation and vergence in visual cognizance under normal visual conditions; although it is acknowledged that systems have been developed which have enabled measurements of accommodation, vergence and pupil size to be monitored objectively (e.g. the "Triple-function ocular monitor" of O'Neill and Stark, 1968). Such systems, however, invariably require accurate calibration and head-positioning which thus makes the application to normal visual environments cumbersome.

Stimulus-free measurements of TA and TV.

It is known that under degraded visual conditions the responses of the accommodative and vergence systems are biased towards their respective tonic positions, TA and TV. Knowledge of the magnitude of TA and TV would provide information on the 'steady-state' levels of the accommodative and vergence systems, whilst free from the complications and constraints of stimulus-dependency. It would seem pertinent therefore, to explore the advantages of stimulus-free measurements of the accommodative and vergence systems.

The most convenient stimulus-free visual environment is found under conditions of total darkness. It is obvious however, that standard optometric techniques may not be used to measure both the accommodative and vergence systems under such conditions and it is evident, therefore that a methodology is required that will enable investigation of the accommodative and vergence systems in total darkness, whilst not itself interfering with their function.

The quantification of TA, TV and TP

Consideration will be given (in chapter 3) to the methodological design and control of the measurement of TA and TV under conditions of total darkness, whilst use is made of the technological developments in such fields as laser-optometry (Knoll, 1966; Baldwin and Stover, 1968; Inglestam and Ragnarsson, 1972), use of light emitting diodes (Brown, 1974; Nygaard and Frumkes, 1982) and microcomputing.

a) Measurement of TA - Laser optometry is a relatively simple subjective procedure, that is readily adapted for the measurement of TA (Hennessy and Leibowitz, 1970; 1972). The technique has several advantages: there is no reliance on subjective estimate of blur (Hennessy and Leibowitz, 1970); the whole of the pupil is used; and the head position remains relatively unrestrained (see section 3.1)

b) Measurement of TV - Nonius-alignment techniques have previously been used to determine the horizontal positions of the eyes under various luminance conditions (Ivanoff and Bourdy, 1954; Ivanoff, 1955; Hebbard, 1962; Owens and Leibowitz, 1976a). Adaption of this technique using oppositely-polarised light emitting diodes (LEDs) for the subjective measurement of TV in total darkness is further developed (see section 3.2).

c) Measurement of tonic pupil size (TP) - It is known that the accommodative response can be influenced by pupil diameter and associated changes in the depth of field (Ripps et al., 1962a; Hennessy et al., 1976). It is also acknowledged that accommodation, vergence and pupil diameter are interdependant within a synkinesis in the response to vision at near (Duke-Elder, 1973; Burian and Von Noorden, 1974 and Davson, 1980). Measurement of pupil diameter (TP) under the stimulus-free conditions of total darkness may reveal further information concerning the interaction of TA and TV and also provide additional information regarding ocular pharmacology. The technique of infra-red photography will be adapted for the measurement of pupil diameter (see section 3.2).

Methodological considerations.

The mean latency of response of the accommodative system has been shown to be 380 msec (Campbell and Westheimer, 1960). Previous investigations of TA have, however, used laser-speckle presentation times of 500 msec, as recommended by Hennessy and Leibowitz (1970). An early consideration of this thesis will therefore, be an investigation into the effect of reduction of this presentation time on the variance of TA (see section 3.5A). An investigation will, similarly be carried out (in section 3.5B) into the latency of the vergence response; this has been demonstrated to be 125 msec (Westheimer and Mitchell, 1956) and has been the presentation time utilised by previous investigations using similar methodology (Owens and Leibowitz, 1980). The longitudinal stability of TA and TV will also be monitored (see section 3.5D).

Previous laser-optometric assessements of TA, using a He-Ne laser, have typically applied a chromatic aberration correction factor of +0.33 D (e.g. Leibowitz and Owens, 1978; Heron et al., 1980). The parameter of TA is ideally suited to the estimation of the chromatic aberration factor, as it is independent of factors that affect the accuracy of the accommodative response to a stimulus, including pupil size. Measurements of TA at various wavelengths will be employed to deduce the appropriateness of this factor (see section 3.5C). The application of a single arbitary correction for chromatic aberration may, however, prove inaccurate; especially in view of the observation that the wavelength of light in focus on the retina varies with the state of accommodation (Millodot and Sivak, 1973). The magnitude of the correction would therefore depend on the choice of reference wavelength.

Many of the subjects participating in the experiments will be women, it will be necessary, therefore, to evaluate the potential physical and psychological influences of menstruation on TA and TV (see sections 3.5E).

THE USE OF TA AND TV AS INVESTIGATIVE PARAMETERS OF THE ACCOMMODATIVE AND VERGENCE SYSTEMS.

Baseline, normativedata.

Once the methodology, experimental design, data monitoring procedure for the measurement of TA, TV and TP has been established, they will be used as indexes of the accommodative and vergence response to various conditions and situations. The initial aim will be their quantification for a large group of observers, which will provide a database of normative values. This data will be used to investigate the relationships between TA, TV, TP and refractive error, and oculomotor balance will be investigated.

The effect of stress on the oculomotor balance.

Although much of our practical and theoretical understanding of the vergence system has been developed from the uni-directional model of additive components of vergence (as proposed by Maddox, 1893), subsequent research and the application of bio-engineering control theory has led to the development of alternative opponent-process models (Toates, 1974; Krishnan and Stark, 1977).

It has been known for many years that under conditions of oculomotor stress, subjects develop an increasing esophoria for distance vision together with increasing exophoria for near vision. The effects have been observed to occur with anoxia (Adler, 1945); barbiturates (Westheimer, 1963); nitrous oxide (Amos, 1976); and ethanol (Hogan and Linfield, 1983), and appear qualitatively analogous to the effects of degraded visual conditions. It has been hypothesised that under such conditions, the vergence system is biased towards its tonic position TV (Hogan and Linfield, 1983; Owens and Leibowitz, 1983).

This thesis includes a study (in chapter 5) designed to investigate this hypothesis, by monitoring the effects of oculomotor stress on the oculomotor balance and TV. It hypothesised that, although oculomotor stress may induce distance-esophoric and near-exophoric changes in heterophoria, TV will be unaffected and furthermore, that the magnitude of the induced distance and near heterophoric change should be proportional to the pre-stress level of TV. If valilated, this will suggest that TV functions as the "bias position" of the vergence system.

Autonomic innervation of the ciliary muscle

The traditional theory of accommodation (Helmholtz, 1909; Duke-Elder, 1970) maintains that at rest, accommodation would be focussed for infinity, requiring an increase in input from the parasympathetic division of the autonomic nervous system to increase accommodation; thus enabling the eye to focus for a near object. The existence of a sympathetic innervation was neither required nor sought and consequently lay unrecognized for many years. In 1937, Cogan postulated a system whereby the radial fibres of the ciliary muscle respond to sympathetic impulses and the circular fibres to parasympathetic. Although Helmholtz, many years earlier, had considered a dual function of the ciliary muscle, he considered it "highly improbable" because the muscle fibres were "much too interwoven". Morgan (1946; 1957) proposed that the sympathetic system provided a "tonal background" against which the parasympathetic acted. The anatomical, physiological and pharmacological studies of Ruskell (1973); Tornqvist (1966, 1967); Kern (1970); Van Alphen (1976); and Wax and Molinoff (1984) have provided evidence for the presence of a sympathetic input to the ciliary muscle, mediated by inhibitory Beta-adrenoceptors.

There is growing evidence to support the hypothesis that TA is a consequence of dual innervation. Consequently, the object of Chapter 6 will be to examine this hypothesis, by monitoring the effects of adrenergic and cholinergic pharmacological agents on TA in total darkness. If the hypothesis is validated, then blocking the inhibitory sympathetic receptors should induce a myopic shift in TA, whilst stimulating the sympathetic receptors or blocking the parasympathetic should both induce a hyperopic shift.

The adaptive properties of the accommodative and vergence systems.

The adaptability of the vergence system was noted as long ago as 1893 by Maddox and more recently by such workers as Schor (1979a, 1979b); Henson and North (1980) and Ebenholtz (1981), etc. These workers have studied the effects of lenses and prisms on such parameters as heterophoria and fusional reserves. Many of these previous studies have relied on inferences based on either, subjective appreciation of blur (Malstrom et al., 1981) or the effect of orthoptics on the AC/A ratio (Flom and Takahashi, 1962; Ogle et al., 1967). A major problem in many of these studies has been the inherent stimulus dependency of the parameters used to monitor task-induced hysteresis[1]: e.g. it is known that measurement of the AC/A ratio by different techniques will illicit different absolute values (Hogan and Linfield, 1983).

The effects on accommodation and vergence of a short period of interaction with a visual task, at various nominal stimulus levels, will be investigated by measuring TA and TV immediately before and for a short period after the task (see Chapter 7). If the visual task induces a hysteretic effect on the accommodative and vergence systems, it would be expected that subsequent measures of TA and TV would be biased towards the position previously occupied by the task.

The central theme of this thesis will be the application of measures of TA and TV to investigations of basic functional aspects of the accommodative and vergence systems.

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[1] The use of the term "hysteresis" to describe an incomplete relaxation or a 'lagging behind' of a biological system is attributed to Fender and Julesz (1967).

CHAPTER 1

THE TONIC RESTING STATE OF ACCOMMODATION

1.1 - THE ANATOMY OF THE ACCOMMODATIVE MECHANISM

1.1A - The ciliary muscle.

The ciliary muscle is a ring of smooth muscle with its external surface lying against the inner surface of the anterior portion of the sclera. In cross section, it forms a wedge-shaped collar at the anterior rim of the posterior chamber of the eye with the apex continuous with the choroid. Early opinion divided the muscle fibres into three component-types (Salzmann, 1912): a) the longitudinal fibres or Bruck's muscle - originate in the scleral spur and run antero-posteriorly on the inner aspect of the sclera to the epichoroid; b) the circular fibres of the sphincter or Muller's muscle) - are the innermost fibres originating from the scleral spur and running circularly round the globe in a direction so oblique as to be almost parallel to the equator; and c) the radial fibres - situated more internally, they appear as an intermingled mesh connecting the circular and meridional fibres. Fincham (1937), however, considered such a discrete division of the muscle fibres to be rather too rigid.

There are a number of features that distinguish ciliary muscle from smooth muscle elsewhere in the body. Of particularly note is the ability to exert volitional control over the ciliary muscle, which is in contrast with the gut or iris. A further distinction is that the parasympathetic post-ganglionic fibres, innervating the ciliary muscle, are myelinated (Hogan et al., 1971) and larger than others elsewhere in the body (Ruskell and

Griffiths, 1979). It has been argued that these features of the parasympathetic accommodation pathway may be related to the substantial voluntary control of this faculty, which is unusual in parasympathetically controlled tissues (Warwick, 1956). This is of importance because it is known that myelinated nerve fibres conduct very much faster than non-myelinated fibres; in general, speed of conduction increases with increase in fibre diameter (Bowman and Rand, 1980). The post-ganglionic sympathetic fibres to the ciliary body are non-myelinated (Wolffe, 1976); such fibres are noted for slow and sustained nervous transmission (Bowman and Rand, 1980). Ciliary muscle has been described as a densely innervated, multi-unit smooth muscle (Ruskell and Griffiths, 1979) and is generally considered to show no spontaneous activity (Suzuki, 1983).

1.1B - The zonule of Zinn (suspensory ligament of the lens).

The Zonule consists of a series of delicate homogenous fibrils that originate in the valleys between the ciliary processes and pass forward to become continuous with the lamella of the lens capsule at the equator. The anatomy and mechanism of the zonule is highly complex: for a fuller account see Hogan et al. (1971); Rohen and Rentsch (1969); Rohen (1979) and Marshall et al. (1982).

1.1C - The crystalline lens.

The crystalline lens is a transparent, deformable, biconvex, elastic body located behind the cornea and iris. Whilst the cornea provides most of the eye's refractive power (approx. 44 Dioptres - Emsley, 1953), the crystalline lens contributes a varying supplement (from 14D in the 10 year old to less than 1D in the 52 year old), due to controlled changes in its curvature

(Hamasaki et al., 1956). Its posterior surface shares an interface with the vitreous body and is anchored into place by the zonule. The lens can be divided structurally into three components, each with unique structural and elastic characteristics (Hogan et al., 1971). The surface is formed by a basement membrane (termed the lens capsule) which is a collagen-containing structure possessing a Young's modulus of elasticity about 2000 times greater than that of the underlying lens material (Fisher, 1969a, 1971; Fisher and Wakely, 1976). The lens possesses a layered structure, with the highest refractive index (of 1.41) in the central nucleus and the lowest (of 1.38) in the outer cortical layers (Nakoa et al., 1969a + b). It thus forms a gradient - index optical element (Marchand, 1978) which, together with the aspheric form of its external and iso-index surfaces (Parker, 1972; Howcroft and Parker, 1977; Brown, 1973a) may help to reduce ocular aberrations, particularly spherical aberration. The index gradient also confers a power equivalent to that of a homogeneous lens with the same surface curvatures but with the higher index of 1.42 (Charman, 1983). The cortex is composed of layers of continuously formed elongated flattened cells, termed fibres because of their shape. The nucleus also exhibits a laminar structure.

1.2 - ACCOMMODATION - ITS EXISTENCE AND HISTORICAL ASPECTS.

> "There is no other subject in physiological optics about which so many antagonistic opinions have been entertained as concerning the accommodation of the eye. One reason for this is that many of the decisive facts were not discovered until very recently, so that formerly there was much more room for hypotheses" (Helmholtz, 1909, p. 159).

Accommodation[1] is the process by which the refractive power of the eye is altered by changes in the dioptric power of the

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[1] The use of the word 'accommodation' in this context was first introduced by C. A. Burow in 1841.

crystalline lens. The mechanism by which the eye performs such a change has been the subject of much controversy ever since Kepler (1611) recognised the need for a system capable of adapting the focus of the eyes for objects at different distances. Scheiner (1619) demonstrated the existence of such a system with his classical 'pinhole and diplopia' experiment. Since that time many theories have been presented in explanation of this accommodative process.

It was Descartes (1677), however, who first proposed that the accommodative process may be due to a change in shape of the crystalline lens. This was subsequently proven by Porterfield (1759), following his interpretation of both Scheiner's and his own observations that the accommodative process was absent in aphakic subjects. Almost a century later, Langenbeck (1849) concluded that accommodation was produced by a change in the curvature of the lens, following his observation that the position of the Purkinje images altered on accommodation and that the lens appeared more convex for near vision. Young (1801) agreed that the lens changed shape, although he considered it to be composed of muscular fibres, the "musculus crystallinus".

Cramer (1851) used electrical stimulation at two points on opposite sides of the limbus. He found that if the iris and ciliary muscle were removed, the lens ceased to change shape on subsequent stimulation. Cramer hypothesised that contraction of the ciliary muscle pulled the choroid forwards, causing the vitreous to press on the back of the lens: he assumed the periphery of the lens was retained in place by the contracted pupil whilst the central area bulged forwards. Donders (1864), however, considered the choroid to be fixed and that contraction of the ciliary muscle pulled the base of the iris backwards, allowing it to exert pressure on the lens and vitreous behind it. Hensen and Volckers (1873) confirmed the forward pull of the contracted ciliary muscle, by observing the effect of accommodation on needles inserted through the sclera into the ciliary body of dogs. It was observed that the free ends of the needles moved backwards on accommodation, which indicated a forward movement of their buried points. The restraining action of the pupil on the lens envisaged by Cramer (1851) was disproved by Von Graefe (1860) who demonstrated the presence of a full amplitude of accommodation in a case of aniridia.

Helmholtz (1909) noted, that as the eye accommodated, the curvature of both the anterior and posterior surfaces of the lens increased (together with its thickness) resulting in a reduction in diameter. He was of the opinion that the lens was elastic and was held in a flattened state by the tension of the zonular fibres, when the ciliary muscle was not contracted; and that when the ciliary muscle was contracted, the elastic lens assumed a more convex form due to the relaxation of the zonular fibres. He proposed that, accommodation increased convexity of the anterior lens surface, via a variation in the position of attachment of the zonular fibres to the anterior and posterior surfaces of the lens. He found the anterior fibres to be more peripherally attached than the fibres to the posterior surface, and thought that contraction of the ciliary muscle would relax the tension on the anteriorally-attached fibres to a greater extent than those attached to the posterior surface. This, he felt, would result in less tension on the front surface than on the posterior surface, causing a forward bulging of the anterior surface.

Helmholtz thus postulated a theory of "double antagonism", in which the form of the lens was determined by two opposing elastic forces: this has formed the essence of the modern theories of the accommodative mechanism.

This theory was opposed by Tscherning (1909) on three main points; i) that the lens was not an elastic body; ii) that the lens consisted of two parts:

> "the nucleus, which cannot change its form, and the superficial layer which, on the contrary, possesss this faculty to a very high degree; its consistence is very nearly that of a solution of very thick gum. I call this layer the 'accommodative layer' in order to show that it is due to it that the eye can accommodate itself" (Tscherning, 1909, p.222).

and iii) that accommodation induced formation of a "lenticonus anterior" or forward bulging of the anterior surface of the lens in the region of its axis with an accompanying peripheral flattening; this, Tscherning assumed, was effected by an increase in the tension on the zonule and additional pressure from the vitreous, which would cause the "accommodative layer" of the lens to press upon the harder nucleus, resulting in a flattening of the lens periphery and the formation of the central bulging.

Fincham (1937) examined a subject (originally described by Graves in 1925) whose lens-substance of one eye had dissolved, through trauma, leaving the capsule intact. He observed that the capsule surfaces were taut, parallel and close to each other, when accommodation was relaxed, yet on accommodation the front layer bulged forward in the centre, becoming convex, whilst on either side of this it became concave. The thin posterior layer was found to become slack and sagged with no definite form. Fincham concluded that the lens consisted of a soft plastic substance enclosed in an elastic envelope or capsule, that varied in its thickness and rigidity in different zones. He considered the capsule to be very thin over most of its back surface, although thickening towards the periphery. He found the anterior capsular surface to be thicker, with a ring of increased thickness about mid-way towards the periphery. This is depicted in figure 1.1.

Fincham observed that the ciliary muscle ring reduced in diameter, when contracted, to produce a reduction in the tension of the zonule. He concluded that the elastic capsule was then able to exert tension on the lens substance, in proportion with the variation in its capsular thickness. In the anterior central area, where the capsule is relatively thin, the lens was found to bulge with a shorter radius of curvature. There was, however, little change in the central posterior surface as the capsule was found to be thinner than the anterior capsule and had relatively less variation in thickness.

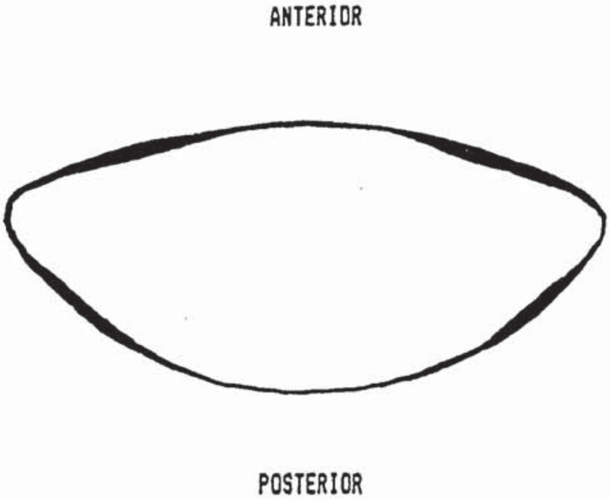

Figure 1.1 The lens capsule with its thickness exaggerated (redrawn after Fincham, 1937).

In the unaccommodated state, Fincham considered the ciliary muscle to be at rest, with the lens capsule held under tension by the zonule and vitreous. The elastic tissue in the ciliary body would tend to restrain the ciliary processes from moving towards the lens, which was subsequently stretched by the widening ciliary annulus into a comparatively flattened form.

Contrary to Fincham, Weale (1962) considered that both the external capsule and the internal lens substance were elastic, and concluded that the relationship between the elasticity of the lens capsule and lens matrix maintained the lens in its relaxed or unaccommodated form, whilst the elastic tissue of the ciliary body opposed the action of the ciliary muscle. Weale further considered that, with the ciliary muscle relaxed, the lens was held in a flattened state by both the tension of the zonule and the elastic fibres of the ciliary body; whilst with the ciliary muscle contracted, the release in tension of the zonule would allow the elastic capsule to oppose the elasticity of the lens matrix and mould the lens into its conical form.

In an experiment designed to consider the visco-elastic properties of the rabbit crystalline lens, Kikkawa and Sato (1963) applied an external compression force, in an anterio-posterior direction, to both the capsulated and uncapsulated lens. They observed a rapid deformation in shape, followed by a second phase of slower deformation. On removal of the force, a rapid partial reversal of the deformation occured, followed by a gradual restoration, although complete recovery was not achieved. They cite the results of Wanko and Gavin's (1958) work, on the relationship between individual lens fibres, in support of this observed hysteresis between lens deformation and recovery. They concluded that, on removal of the force, the lens tended to return to its original shape, by virtue of an intrinsic elasticity and that rapid and complete recovery could not be expected because the lens exhibits an "elastic after-effect". This, they assumed, would be caused by resistance between the interdigitating cell processes in the lens epithelium and equatorial portion and frictional resistance between the sliding fibres during the process of deformation.

During the late 1960's and early 1970's Fisher conducted a series of rigorously detailed experiments on freshly enucleated cat, rabbit and human eyes. He could not agree with Fincham's (1937) conclusion, that the marked increase in central curvature was "conoidal", but rather that "the properties of an ellipsoid surface fulfil the requirements found in the human eye" (Fisher, 1969b). Fisher (1969a) investigated the elastic properties of the lens and its ability to alter its shape in response to changes in ciliary ring diameter. He found that if the energy required to change the shape of the lens in accommodation was stored in its capsule, it should vary with the change in surface area of the capsule, its thickness and the value of Young's Modulus of elasticity[1].The ability of the capsule to mould the lens depends not only on surface tension but also upon the pressure which it exerts perpendicular to its surface, i.e. the lens moulding pressure; and that like the capsular surface tension, this moulding pressure also depends on the shape of the lens (Fisher, 1969b).

Coleman (1970) cites Cramer (1851) in proposing that, during accommodation the vitreous body is pushed forward thus altering the shape of the lens. Coleman had noted that, where Helmholtz failed to attribute a role to the vitreous in accommodation, Fincham (1937) implicated a supportive role of the anterior vitreous to the lens, when at rest. Coleman accepted Fincham's view of the capsule; i.e., that variations in elasticity were related to the thickness: although he hypothesised that if the vitreous played little or no part in the process of accommodation, then the posterior surface should bulge more than the anterior

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[1] It is known that the energy required to deform an elastic body is proportional to Young's Modulus of Elasticity and the square of the strain produced (Fisher, 1971).

capsular surface. Fincham (1937) had in fact observed the reverse of this hypothesis. Alpern (1969b) offered a geometrical explanation for this seemingly paradoxical situation stating:

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

Coleman reasoned however, that the lack of a posterior curvature change was a result of vitreous pressure on the back of the lens. He cites further evidence from the observation by Hess (1896) of a gravitational influence on the movement of the lens: it was found that the eye obtained a greater amplitude of accommodation in the downward position than when the eye looked up. Coleman used ultrasonography to measure the movement of the lens during accommodation in five subjects and found an average change of 0.25 mm and 0.20 mm for the anterior and posterior surfaces, respectively; and was unable to find an equivalent backward displacement as the eye looked up. He considered, therefore, that the vitreous played an active part of the process of accommodation.

Coleman proposed that the base of the "vitreous - lens - zonule diaphragm" advanced as the ora serrata and the choroid move forward during contraction of the ciliary muscle. This action, together with that of the reducing volume in the posterior chamber would cause the vitreous to be forced forward. This would then provide support for the posterior lens surface, whilst the elasticity of the lens and capsule produced an increase in axial thickness and a steepening of the anterior surface. This "vitreous support concept" indicates that a gradient of fluid or hydraulic pressure exists between the vitreous body, the lens and the anterior chamber.

Fisher (1982) demonstrated however, that the larger anterior polar movements of the lens compared with the small posterior polar movements were due to the "inherent elastic anisometropy" within the intact crystalline lens and zonule lenticular complex, and not to changes in vitreous pressure. He concluded that the vitreous plays a negligible role in modifying the position or shape of the lens.

Koretz and Handelman (1982) derived a mathematical representation for the lens, from the published measurements of lens curvature and curvature upon accommodation (Brown, 1973a, b) and of the elastic properties of the lens material (Fisher, 1971). The model indicates that the role of the lens capsule in accommodation is that of a force distributor, responding to external forces exerted upon it and distributing them over the anterior lens surface. It is interesting that the model also requires a contribution from the vitreous as well as the zonular apparatus. They have, however, made two assumptions: a) that the anterior lens curvature for young lens is approximated by a spherical section, and b) that the lens could be considered to be isotropic. In a subsequent paper (Koretz and Handelman, 1983) they applied Fisher's (1971) figures of the elasticity of the lens of an 11 year old human to their model, and found that their anisometropic model was little changed from the same basic considerations of their older isotropic model.

1.2A-Review of the accommodative mechanism.

In the relaxed state (see fig. 1.2B), the elastic network of the choroid retracts the ciliary muscle so that the ciliary body becomes stretched. The fulcrum or plexus of zonular tension fibres moves posterolaterally, relaxing the 'tension' fibres and allowing the pars plana zonular, or 'holding' fibres to exert traction directly on the anterior zonular fibres (Rohen, 1979). The lens capsule is stretched latero-radially, flattening the lens and decreasing its refractive power.

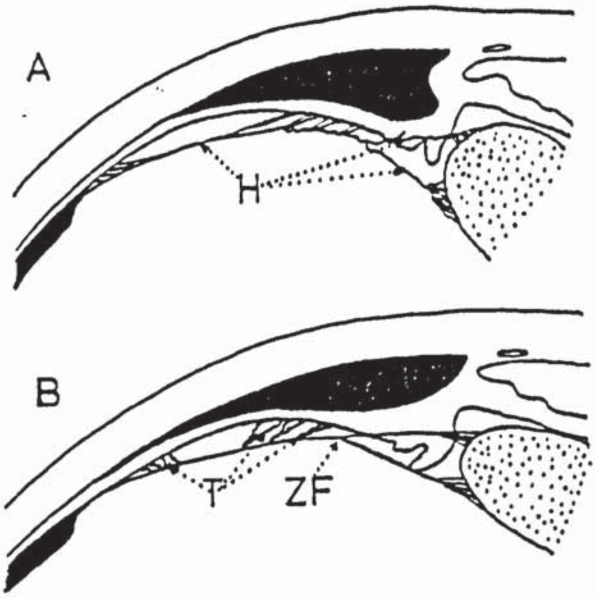

Figure 1.2 - The accommodative mechanism: (A) The accommodated state. (B) The relaxed state. The holding fibres (H) split at the zonular fork (ZF). Branching from the holding fibres are the 'tension fibres' (T), inserting into the ciliary epithelium. (redrawn after Rohen and Rentsch, 1969).

When the ciliary muscle contracts (fig 1.2A), its fibre bundles re-orientate themselves and the number of circular bundles increase (Lutjen, 1966). The ciliary body and muscle move forward and inward. The 'tension' fibre system is stretched and assumes traction of the posterior zonular fibres and the elastic network of the choroid, thereby relaxing the main 'holding' fibres together with those fibre strands anterior to the zonular fork (Rohen, 1979). The normal elasticity of the lens capsule, no longer counteracted by zonular traction, moulds the lens to a more spherical shape, thus increasing its refractive power (Fisher, 1969a; 1969b; 1971). The involvement of the vitreous, during accommodation, remains a subject of some debate, however it would seem reasonable to assume the vitreous takes a supportive role during accommodation (Coleman, 1970).

1.3 - THE NEUROLOGY OF ACCOMMODATION.

The traditional theory of accommodation (Helmholtz,1909; Fincham, 1937) maintains that, for the emmetropic eye, accommodation would be at rest when the eye is focussed for infinity and would require stimulation of the parasympathetic division of the autonomic nervous system, that innervates the ciliary muscle, to produce an increase in the refractive power; thus enabling the eye to focus for a near stimulus.

The existence of a sympathetic innervation to the ciliary muscle was neither required nor sought for and consequently lay unrecognized for many years. It is not surprising therefore that accommodation had seldom been studied in the context of dual innervation.

1.3A - The autonomic nervous system.

> "Nature thought it prudent to remove the important phenomena which it controls from the caprice of an ignorant will." (Bernard, 1878).

The autonomic nervous system governs the predominantly involuntary visceral actions of the body. It has two major divisions, the sympathetic and parasympathetic nervous systems, each differing in structure, transmitter substance and function. The main distinction is made solely on an anatomical basis of the site within the central nervous system, in which the cell body of the preganglionic autonomic axon is located. The transmitter substance for the sympathetic nervous system is mainly noradrenaline, whereas for the parasympathetic nervous system it is acetylcholine. Neither system is consistently excitatory nor inhibitory but each is usually mutually antagonistic in their influences on the viscera and organs of the body thus innervated. Thus dual-innervation is a basic homoeostatic mechanism of the human body, regulating most smooth muscles and glands.

1.3B-The afferent accommodative-pathway.

Activation of the afferent neural pathway of the accommodative 'reflex' is initiated by the image of a stimulus falling on the retinal receptors. The resultant 'signal' then passes to the lateral geniculate body via the optic nerve, chiasma and optic tract. It is then relayed to the calcarine cortex (Brodmann area 17) via the optic radiations. A further relay then passes the signal to the parastriate area or Brodmann area 18 and peristriate area or Brodmann area 19 (Alpern, 1969b; Duke-Elder, 1971). It is within the visual cortex that the visual information contained within the accommodative stimulus is processed.

1.3C - Parasympathetic innervation of the ciliary muscle.

The signal to respond to the accommodative stimulus is sent from the peristriate area of the visual cortex, to the hypothalamus in the tectal or diencephalic region, via the internal cortico-tectal tract, and thence to the Edinger-Westphal nucleus (Warwick, 1954; Loewy et al., 1978). The signal then passes along the parasympathetic fibres of the IIIrd cranial or oculomotor nerve. It is largely accepted (Behr, 1924; Kuntz, 1929; Warwick, 1954; Ruskell and Griffiths, 1979) - although not without dispute (Westheimer and Blair, 1973) - that these fibres synapse in the ciliary ganglion with the post-ganglionic fibres of the short ciliary nerve which innervate the ciliary muscle. Arrival of the nervous impulse initiates a contraction of the ciliary muscle in proportion with the stimulus requirements of the foveal image (Alpern, 1969b; Duke-Elder, 1971).

Several studies have induced ocular accommodation by electrical stimulation of various areas along the efferent pathway, such as the Edinger-Westphal nucleus (Pitts, 1964); oculomotor nerve (Morgan, 1944a); ciliary ganglion (Marg, 1954; Ripps et al., 1962a); short ciliary nerves (Olmstead, 1944); and supranuclear areas such as the nuclei interpositus (Hosoba et al., 1978) and Brodman area 19 (Jampel, 1959).

Jampel and Mindel (1967) have, in the macaque monkey, provided evidence to support Warwick's (1954) concept of the Edinger-Westphal nucleus and anteromedian nucleus forming a continuous mass as integral parts of the parasympathetic oculomotor nucleus, the centre traditionally associated with accommodative control. Lovasik and Beauchamp (1982a; 1982b) however, have reported electrical activity that is correlated with accommodative response, in the cat at least, from cells within the mesencephalic reticular formation; an area near to, but outside the Edinger-Westphal nucleus. Lovasik and Beauchamp acknowledge however, that the accommodative neurons 'tapped' in the reported study, were likely to be "sampling-fibres" linking the Edinger-Westphal nucleus to the cerebellum. This would be in agreement with the results of a study by Cohen et al. (1958) demonstrating that the projections of the cerebellar nuclei interpositus and dentatus project include the Edinger-Westphal nucleus; the area in the brain stem observed by Lovasik and Beauchamp. This led the latter authors to speculate that such areas as the nucleus interpositus may modulate ocular accommodation, at least in the cat.

1.3D - Sympathetic innervation to the ciliary muscle.

The sympathetic supply to the ciliary muscle is thought to arise from a diffuse area within the hypothalamus of the diencephalic region (Duke-Elder, 1971), from where it passes to the lower cervical and upper thoracic segments of the spinal cord, to a cell station in the spino-ciliary centre of Budge in the intermedio-lateral tract of the cord. It leaves the cord mainly by the ventral roots of the 2nd (but also 1st and 3rd) thoracic nerves. The pre-ganglionic fibres run up the cervical sympathetic chain, the majority synapsing in the superior cervical ganglion. The fibres then travel up the sympathetic carotid plexus and enter the eye as the long ciliary nerves, to reach the ciliary muscle where they become incorporated in the terminal syncytitial network around the muscle fibres (Duke-Elder, 1971).

1.3E - Receptors of the sympathetic nervous system.

The conceptual background for the understanding of adrenoceptor function is based upon the results of the experiments of Ahlquist (1948); in which he compared the relative potencies of a number of sympathomimetics including noradrenaline, adrenaline and isoprenaline. He found that the order of potency on smooth muscle that responded with contraction was adrenaline > noradrenaline > isoprenaline; whereas on smooth muscle that responded with relaxation the order of potency was isoprenaline > adrenaline > noradrenaline. The order of potency for stimulation of the heart was similar to that for relaxation of smooth muscle. In explanation of these results Alquist postulated the existence of two sub-types of receptor, which he designated "alpha" and "beta". Effector cells with alpha-adrenoceptors have a high sensitivity to adrenaline and noradrenaline but are practically insensitive to isoprenaline; whereas those with beta-adrenoceptors have a higher sensitivity to isoprenaline than to other catecholamines, and are usually more sensitive to adrenaline than to noradrenaline (Bowman and Rand, 1980).

Lands et al. (1967) divided beta-adrenoceptors into two distinct types on the basis of the differential sensitivity of various tissues to a series of beta-adrenoceptor agonists: noradrenaline, an effective stimulant of cardiac beta-adrenoceptors, has little or no ability to stimulate beta-adrenoceptors mediating vasodilation in the smooth muscle of blood vessels. The beta-adrenoceptors of the heart were designated beta_1-adrenoceptors, whilst those of bronchial, vascular and uterine smooth muscle were designated beta_2-adrenoceptors.

The alpha-adrenoceptor system has also been divided into two sub-systems, following the evidence that pre-synaptic and post-synaptic alpha-adrenoceptors were not identical (Langer, 1973). Pharmacological characterization has defined the alpha_1-adrenoceptor as being stimulated by phenylephrine but blocked by prazosin and the alpha_2-adrenoceptor as being stimulated by clonidine but blocked by yohimbine. Alpha_2 agonists decrease, whilst antagonists increase the release of the transmitter noradrenaline.

The inhibition of neurotransmission by agonists implies that feedback inhibition is a natural phenomenon (Sears, 1984). Released noradrenaline may diffuse to the same or nearby neurons to inhibit further release of noradrenaline. Pre-synaptic receptors can be activated by agonists different from the transmitter itself and can modulate the release of noradrenaline. Langer and Dubocovich (1978) have shown that beta-adrenoceptors at pre-junctional sites may exert positive feedback control of noradrenergic transmission. These are usually of the beta_2-type amd may thus respond to circulating adrenaline to augment neural release of noradrenaline. Therefore, adrenergic effects, alpha or beta, on pre- as well as post-synaptic receptors, must be considered in analyzing endogenous mechanisms or the action of exogenously administered adrenergic drugs.

1.4 - TONIC ACCOMMODATION.

The traditional theory of accommodation (Helmholtz,1909; Fincham, 1937) maintains that, for the emmetropic eye, accommodation would be at rest when the eye was focussed for infinity, requiring stimulation of the parasympathetic division of the autonomic nervous system to produce an increase in the refractive power of the eye; thus enabling the eye to focus for a near stimulus. This theory of accommodation has not been without its critics: one group of critics have challenged the single innervation hypothesis, in favour of a dual innervation to the ciliary muscle; whilst a second group point to the failure of the traditional accommodative theories to provide adequate explanation for a group of supposedly "maladaptive" conditions, often described as "the anomalous myopias", and propose that the accommodation system does not rest at infinity but rather, at some intermediate position of focus.

1.4A-Sympathetic innervation and Accommodation.

In his review, Cogan (1937) cites several studies in support of the hypothesis, that the sympathetic nervous system is responsible for adapting the eye for distance vision: e.g. Henke (1860) and Warlomont (1875) proposed that the ciliary muscle had two components; circular fibres, functioning for near accommodation and longitudinal fibres, functioning for distance. Helmholtz (1909) had considered the possibility of a dual nature of the ciliary muscle fibres, although he discounted it on two grounds: firstly, he argued that the fibres of the ciliary muscle were too intertwined to allow such discrete muscle action (a view supported more recently by Ruskell, 1975); and secondly, he noted that atropine paralysed the action of the ciliary muscle without altering the refractive condition of the emmetropic eye.

With respect to Helmholtz's first objection, Cogan (1937) argued that it was known that other organs, such as the gastro-intestinal tract or uterus, possessed intimate anatomical connections between anatagonistically acting groups of muscles and that this did not appear to interfere with their separate functions. To Helmholtz's second objection, Cogan hypothesised that the parasympathetic nervous system would be responsible for near vision alone and not distance, thus distance refraction would not be expected to be affected by atropinization, unless hypermetropic.

Cogan (1937) draws an analogy between the innervation of the ciliary muscle and the iris in that, prior to the identification of the dilatator muscle of the iris (Langley and Anderson, 1892), the pupil was generally believed to be under the sole control of the sphincter. In 1928, however, Poos had observed a consensual decrease in accommodation and an increase in pupil size, in subjects with unilateral lesions of the cervical portion of the sympathetic nervous system, following the instillation of adrenaline into the eye. He found there to be practically no affect in normal subjects, under similar circumstances. Poos also observed that cocaine affected the iris and ciliary muscle of normal subjects but had practically no effect on the iris and ciliary muscle after lesions of the cervical portion of the sympathetic chain; whereas instillation of dilute adrenaline had practically no effect on the normal iris or ciliary body but had profound effects on both muscle-systems after lesions of the cervical portion of the sympathetic nervous system. Cogan considered this to be significant, especially in view of the known sensitization of structures innervated by the sympathetic nervous system to adrenaline after lesions of the sympathetic pathway.

1.4B - Physiological evidence for sympathetic innervation of the ciliary muscle.

Morat and Doyon (1891) are generally credited as the first workers to suggest that an inhibitory sympathetic innervation may have a role in distance focussing, following their report of a flattening of canine crystalline lens on stimulation of the superior cervical spinal ganglion. Five years earlier, however, Jessop (1886) had reported systematic changes in the purkinje images, following stimulation of the long ciliary nerves of cats and dogs, previously rendered aniridic and somewhat myopic (from instillation of pilocarpine). Hess and Heine (1898) used retinoscopy to observe a 1.0 to 1.5D increase in hypermetropia in dogs, whilst utilising a stimulation technique similar to that of Jessop. Morgan et al. (1940) stimulated the sympathetic nerve in rabbits, cats and dogs and found, in each case, that accommodation shifted hypermetropically, irrespective of whether the eyes were atropinized, the IIIrd nerve cut, or the extra-ocular muscles were severed from the globe: the effect was found to amount to 1.5D, whilst stimulation of the IIIrd nerve induced myopia by a level a much as 10.0D, in the same animals. When the sympathetic nerve was severed, accommodation was found to shift myopically. Similar results have been reported in the rhesus monkey (Mohoney et al.,1942) and also for rabbits and cats (Olmstead and Morgan, 1941). In 1944 Omlstead reported:

> "...we have refracted the eyes of several animals...and have never found an exception to the rule that stimulation of the cervical sympathetic causes a change in the direction of hypermetropia (negative accommodation) ....stimulation of the oculomotor nerve, on the other hand, produces a state of myopia".

Kuntz et al. (1946), attempted to rationalize Morat and Doyon's (1891) suggestion that the action of the sympathetic nervous system on accommodation was inhibitory in nature. They proposed that the oculomotor nerve contained parasympathetic fibres with adrenergic endings, and that the cervical sympathetic nerve acted on the midbrain to inhibit the oculomotor nerve. This proposal, however, was weakened by the experimental results of Melton et al. (1955), in which the long and short ciliary nerve fibres of enucleated and perfused cats' eyes were electrically stimulated. They observed opposing patterns of ciliary muscle contraction when the two nerve-types were stimulated and concluded that, in all likelihood, the ciliary muscle had direct and dual innervation.

In 1966 Tornqvist demonstrated the presence of a beta-adrenergic inhibitory mechanism in the ciliary muscle of the cynomologus monkey, following the abolition of the hyperopic response to cervical sympathetic stimulation using propranolol, a non-selective beta-adrenoceptor antagonist: the hyperopic response was unaffected by alpha-adrenergic antagonists. He also found that in the atropinized eye, cervical sympathetic stimulation had no effect upon the refractive state. Tornqvist further demonstrated that the decrease in accommodation on sympathetic stimulation usually developed within 10 - 40sec and that the response was 2 to 4 times greater against a background of pharmacologically induced parasympathetic activity (i.e. pilocarpine or physostigmine).

In an attempt to study the influence of the sympathetic nervous system on accommodation in a more "physiological" manner, Tornqvist (1967) induced parasympathetic activity by electrical stimulation of the pre-ganglionic oculomotor nerve, rather than via the instillation of topical pilocarpine or physostigmine. He noted that an oculomotor nerve stimulation rate of 2 to 5/sec gave an accommodative response of 1 to 3D, whilst 20 to 50/sec gave a response of 6 to 11D, that was fully developed within 1 to 2 sec:

thereafter, accommodation was found to steadily decrease over the next 10 to 30sec, until a "steady state" was achieved, especially at the higher stimulation frequencies. On cessation of the stimulation, the response ended within 1 to 2sec. Tornqvist concluded that frequencies of 5, 10 and 20 stimuli/sec, gave a "physiological accommodative response" equivalent to 1.8, 3.1 and 7.1D, respectively.

He then stimulated the cervical sympathetic nerve at the continuous, "steady state" oculomotor nerve stimulation rate of 5/sec, whereupon a decrease in accommodation was recorded within 5 to 10sec, becoming maximal within 10 to 40sec, and although the response was greater against higher parasympathetic stimulation, the decrease never exceeded 1.5D. Tornqvist (1967) noted the very slow (10sec) development of the sympathetic response, compared to the 1 to 2sec required for the fully developed parasympathetic response: Campbell and Westheimer (1960) had earlier found that a stable accommodative response was achieved about 1 second from stimulus onset. Tornqvist considered such temporal dynamics to be indicative that the sympathetic nervous system may not have an important influence on accommodation under normal visual environments.

1.4C - Clinical and Pharmacological evidence for a sympathetic innervation.

There have been many reports in the literature of an increase in refractive power following lesions of the sympathetic nervous system: e.g. Cogan (1937) reported the case of a patient in whom sympathectomy of the upper dorsal and lower cervical portion of the sympathetic nervous system on the left side, resulted in a myopic shift in the amplitude of accommodation (AA) from a preoperative 6.5D in each eye to a postoperative 7.0 and 8.5D for the right and left eyes, respectively. A further example may be found in a report by Schober (1954), in which he describes a case of Horner's syndrome involving the loss of sympathetic innervation to the eye, in which extreme difficulty was experienced in accommodating for distance.

Studies by Cogan (1937), Siebeck (1953) and Biggs et al. (1959) report reductions in human AA, following sympathetic stimulation by the local instillation of sympathomimetic drugs. The latter two studies also confirmed a drug-induced increase in hypermetropia.

Some workers suggested that the sympathetic effects may have been induced via alpha-sympathetic mediated alterations in vascular volume (e.g. Morgan, 1946; and Fleming and Hall, 1959). The studies of Meesman (1952), on enucleated cat and human eyes, and of Van Alphen et al. (1965), on ciliary muscle strips from rabbit, cat and monkey eyes, however, were able to demonstrate the presence of adrenergic receptors in the ciliary muscle, whilst in the absence of an active vascular circulation. In addition, Van Alphen et al. (1965) identified the receptors in the ciliary muscle of the above species, to be of the beta-type.

Tornqvist (1966) demonstrated that the sympathetic nervous system had a direct effect on the ciliary muscle itself, rather than via an alteration in ciliary muscle vascular tone. His results showed the alpha-adrenoceptor antagonists, phentolamine and phenoxybenzamine, to have no effect on the level of accommodation induced by sympathetic stimulation, although the volume changes were found to decrease considerably. He cites the study of Bill (1962) who had earlier demonstrated the ciliary body vascular receptors to be of the alpha type. Tornqvist also demonstrated that the beta-adranoceptor antagonist propranolol abolished the accommodative response to sympathetic stimulation, although the volume changes remained.

It is interesting to note, therefore, that Chin et al. (1968) have demonstrated that the predominantly alpha agonist, phenylephrine, depressed the positive accommodative responses induced by mid-brain stimulation, although they themselves, suggested that this was most likely due to the slight beta effects of the drug. This was a view supported by Hurwitz et al. (1972b) showed that local alpha-sympathetic stimulation had no effect on positive accommodation.

Table 1.1 illustrates the distribution of the adrenergic receptors in cat, rabbit, monkey and man; Van Alphen (1976) has demonstrated that the distribution of the adrenergic receptors of the internal muscles of the human eye closely resembles that of the rhesus monkey.

	DILATATOR	SPHINCTER	CILIARY MUSCLE
CAT	mainly alpha, some beta	mainly beta, some alpha	mainly beta, some alpha
RABBIT	mainly alpa, few beta	mainly beta, few alpha	mainly alpha, few beta
MONKEY	mainly alpha, very few beta	mainly alpha, perhaps beta	exclusively beta, no alpha
MAN	mainly alpha, very few beta	alpha + beta in equal amounts	mainly beta, very few or no alpha

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

In 1973 Ruskell demonstrated the presence of small granular vesicles in primate ciliary muscle, of a type known to be present in sympathetic nerve fibre terminals (Bondareff and Gordon, 1966; Ruskell, 1967), to take up exogenous noradrenaline (Wolfe et al., 1962), and to degenerate following superior ganglion sympathectomy (Ruskell, 1967; Roth and Richardson, 1969). It was concluded that the nerve fibre terminals were, both sympathetic and that their supplying fibres originated from the superior cervical ganglion. The above observations are in agreement with those of Ehinger (1966a, 1966b 1966c and 1971); Laties and Jacobwitz (1964); and Malmfors (1965). Ruskell concluded, however, that on average, fewer than 1% of the terminal endings in primate ciliary muscle were sympathetic; although he acknowledged that this may be an underestimate due to the difficulty of retaining the dense cores of vesicles during fixation (Richardson, 1966). Such a low percentage led Ruskell to doubt a useful function for the sympathetic terminals in the neural control of the ciliary muscle contraction.

Kern (1970) compared the in-vitro effects on human ciliary muscle strips, of three catecholamines (l-noradrenaline, l-adrenaline and l-isoprenaline) and of three adrenergic blocking agents (phenoxybenzamine, priscoline and dichloroisoproterenol). He demonstrated the (almost exclusive) presence of beta-adrenergic receptors in ciliary muscle, and that the catecholamines induced relaxation of the ciliary muscle.

Hurwitz et al.(1972a) found that the depressed positive accommodative response, induced by sub-conjunctival injection of the non-selective beta-adrenoceptor agonist isoprenaline in the Ververt monkey, was prevented by pretreatment with propranolol. It was concluded that stimulation of the beta-sympathetic receptors antagonized positive accommodation, and that negative accommodation was mediated by the beta system (see also, Tornquist, 1966; Van Alphen et al., 1965; Tagawa et al., 1967). Hurwitz et al. (1972a) demonstrated that positive accommodation, induced by mid-brain electrical stimulation, occasionally appeared biphasic with a sharp transition at the 2 - 4D level - essentially the same level below which beta-antagonism ceases to be effective. Beta-stimulation appeared to selectively antagonize the second or higher component, whilst parasympathetic inhibition abolished both. Hurwitz et al. (1972a) interpreted their findings as indicative that accommodation may have two components under separate neurological control, an interpretation consistent with the observations of Ishikawa (1962) and Shigekazu (1967).

Nyberg (1976) studied the influence of single oral doses of two beta-adrenoceptor antagonists, alprenolol and propranolol, on the accommodative responses of six male subjects, but were unable to detect a significant effect of either drug on accommodation.

1.4D - Systemic autonomic balance.

It is known that pupil size is able to reflect the 'emotional content' of a stimulus and has, in the past, been used as a measure of autonomic balance (Hess, 1965). The literature would suggest that accommodation may now be considered as innervated by both branches of the autonomic system, it is of interest, therefore, to consider the possibility that ocular accommodation may also be influenced by systemic autonomic changes.

It is a traditionally held view that stress induces an increase in sympathetic activity. Cannon and de la Paz (1911) were the first to demonstrate the response of the adrenal medulla to psychological factors. They found that the venous blood of cats frightened by barking dogs, contained adrenaline which was undetectable in the blood of undisturbed cats. This response was prevented by adrenalectomy (Cannon et al., 1911) or by the sectioning of the splanchnic nerve which innervates the adrenal medulla (Hitchings et al., 1913). Cannon (1914) later suggested that the adrenal medulla responded in concert with the sympathetic nervous system, so that both systems were activated during stress thus enhancing the ability to cope better with a threatening situation via induced physiological changes, including bronchodilation and increased glucose availability.

The work of Selye (1936) indicated that the adrenal cortex was indeed involved in the stress response. Subsequent work established that adrenocorticotrophic hormone (ACTH) was released during stress from the cells of the anterior pituitary, which in turn induced secretion of the glucocorticoids from the adrenal cortex. It is now widely accepted (Mason, 1968; Maickel et al., 1967a; 1967b) that stressors activate the sympathetic nervous system, inducing it to release noradrenaline, and to activate the adrenal medulla, causing it to release adrenaline and/or noradrenaline. In common with the sympathetic response, there is an activation of the central nervous system catecholaminergic mechanisms (Stone, 1975; Anisman, 1978). Sympathetic activation has been shown to involve both peripheral and central catecholamine neurons and may include all three catecholamines, dopamine, noradrenaline and adrenaline (Dunn and Kramarcy, 1984). There is evidence to suggest that a given affective state is the result of a balance between the activities of the various amine - containing (i.e. noradrenaline, dopamine), serotonin and acetylcholine - containing neurones in parts of the brain stem and forebrain (Bowman and Rand, 1980).

1.4E - Accommodation and the systemic autonomic balance.

In 1937, Cogan reported a case, "common in his experience", of a student who reported an inability to focus adequately for near objects on the first day of his final "semester" exams. On examination, the only other physical sign was dilation of the pupils; 'normal' accommodation was found to resume within a rest period of a few hours. Olmstead and Morgan (1939) subjected rabbits to sudden taps on the nose, among other stressful situations, and found hypermetropic shifts in the accommodative response of up to 1.5D. The two studies of Morgan et al. (1940) and Olmstead (1944) both report the response of human subjects to stressful situations such as, electric shocks, hooters and pistol shots. These were found to invariably result in relative hypermetropic accommodative responses accompanied by mydriasis. It was concluded that such changes were part of a general systemic sympathetic discharge.

Conversely, Westheimer (1957) reported a myopic shift of accommodation in two subjects who were verbally insulted to the point of anger, whilst their accommodation was monitored in complete darkness. The myopic shifts lasted for several minutes; and in one instance exceeded 1D. Leibowitz (1976) also reports a 1D myopic shift in a subject who had recently been involved in a argument with a workmate. Leibowitz (1976) also measured the "dark-focus" of a doctoral candidate immediately before and after the day of the viva-voce exam. It was found that the candidate's accommodation had shifted myopically, returning to the pre-exam level the day after. Costello (1974) reports small but consistent (0.25D) shifts in the resting point of accommodation in a number of experimental subjects: inwards, following the highly stressful exposure to slides of motor-car accidents; and outwards, following a "progressive - relaxation procedure". Mason (1968) had established that the agents of the stress response can be psychological and need not involve physical stressors or pain.

Ong and Fisher (1973) set their subjects a reading task whilst wearing lenses of power varying from +2 to -2D and measured the galvanic skin response. They found that the mean amplitude of galvanic skin response increased linearly, as the accommodative stimulus produced by the lenses increased. They proposed that this may have been caused by the sympathetic compensation for the increased dioptric power of the lenses or the "averseness" of such a situation.

Miller (1978b) measured the accommodation of 21 subjects in total darkness and correlated the results to self-rated assessments of mood. It was found that in those subjects whose accommodation in total darkness was fairly consistent, there was little correlation with mood. However, in those subjects whose resting accommodation was variable, the greater was the liklihood that this was related to mood. In a subsequent study, Miller and Le Beau (1982) measured resting accommodation in 33 subjects under two conditions involving stress and no-stress: under the first, the subjects were instructed that their performance was being evaluated by the experimenter; whilst the second group had no such evaluation implied. All subjects completed a questionnaire designed to assess their level of anxiousness. It was found that resting accommodation did not shift myopically under the stress condition for every subjects, but was limited to those who demonstrated a high evaluation-anxiety as indicated by the questionnaire.

Toates (1972) presumed the anger-induced myopic shift of accommodation to be indicative of increased parasympathetic activity, whilst the fear-induced hyperopic shift was indicative of enhanced sympathetic nervous activity. He concluded that the observations (outlined above) offered support for the argument that there is a physiological differentiation between fear and anger and are also in keeping with a dual ciliary innervation. Gellhorn (1953) concluded that:

> "Fear causes reactions predominantly sympathetic, and feelings of hostility and anxiety predominantly parasympathetic discharges".

In an earlier study (Selye, 1936) it was argued that the nature of the stress response was independent of the stressor, and that the stress states induced by different stressors were indistinguishable. Mason (1971) maintains that it remains unclear whether the physiological responses during stress are specific or not.

These contradictory conclusions may be explained in terms of the duration of the stress response: Wenger et al. (1956 p. 267) states:

> "The sympathetic nervous system is the system that seems to go into action first following any intense stimulation and the parasympathetic nervous system apparently serves to counteract, or to compensate for this increased sympathetic activity. In some persons the activity of this system not only compensates for the increased sympathetic activity but, upon occasion may overcompensate".

Wenger et al. (1956 p.271) cite the phenomenon of defaecation and urination that occasionally accompany highly stressful situations as examples of "temporary overcompensation". Sternbach (1966) found that following a single intense shock, e.g. cold or the noise from a pistol shot, all the variables recorded (such as heart rate or pupil size) could be seen to return to the pre-stimulus levels and in many instances, to "overshoot" them. He has described this phenomenon as "parasympathetic overcompensation", although he has noted it for purely sympathetically innervated structures; in these cases he preferes the use of the term "rebound".

Anisman (1975) is of the opinion that exposure to stress is thought to elicit a transient catecholamine (dopamine and noradrenaline) action, followed by a cholinergic rebound together with subsequent decreased catecholamine activity. The initial catecholamine action is thought to result in behavioural excitation (Costa and Groppetti, 1970) and consequently avoidance behaviour (Breese et al., 1973). The catecholamine action in turn results in a compensatory cholinergic rebound, which produces behavioural inhibition and poor avoidance performance (Anisman and Kokkinidis, 1974). Following the initial catecholamine excitation, catecholamine activity declines, thus enhancing the compensatory effects of the cholinergic reaction. Unlike the transient excitatory catecholamine action (latency of 4 -5 sec; Porges, 1976) the cholinergic reaction is more sluggish and longer lasting.

This may explain some of the apparently paradoxical observations noted in the clinical studies. The direction of stress-induced accommodative response would depend on the time taken from the onset of the stressor that the measurement was taken. It may be that those studies showing hypermetropic accommodation changes are sampling the initial sympathetic reaction phase and studies showing myopic accommodation changes are reflecting the second, parasympathetic phase.

1.4F - The role of sympathetic innervation in the control of accommodation.

Tornqvist (1966) observed that the early pioneers of research into the influence of the sympathetic nervous system on accommodation (Morat and Doyon, 1891) found it easier to demonstrate the effects when the eye was under increased cholinergic (or parasympathetic) tone. This point has been mostly missed by subsequent investigators, although Biggs et al. (1959) noted that subconjunctival injections of adrenaline gave a greater effect at the near point than at the far point of the human eye. In explanation, they suggest that the lens is unable to flatten more than to a certain degree. However, Tornqvist (1966) considers a pharmacological explanation more likely. He considered beta-adrenergic innervation to the eye be generally inhibitory and argued that if the parasympathetic activity was abolished (by atropine), the sympathetic innervation would have nothing to inhibit and the refractive response would be unaffected. This was indeed found to be the case. Tornqvist (1967), further hypothesised that if it were impossible for an individual to naturally abolish all parasympathetic activity, there would remain a small margin against which the sympathetic system could act. A sympathetic mechanism helping distance or negative accommodation would have importance only if it could act from a state of slight myopia.

One should consider the possibiliy that there has been a development or an evolutionary element in the role of the sympathetic nervous system in the mechanism of accommodation. It is known that in lower animals the response to stimulation of the cervical sympathetic nerve have been larger than in primates and humans (Van Alphen et al., 1965) and that this is probably due to the excitatory alpha-adrenergic innervation of the ciliary muscle in these animals (Van Alphen, 1976). The review by Ehinger (1966a) discusses the variety in ciliary muscle of many species of animal from rats and mice, through to pigs, sheep and primates. One might speculate that the presence of a sympathetic innervation to the ciliary muscle is merely vestigial and that the switch from excitatory alpha-adrenergic innervation to inhibitory beta-adrenergic innervation is a consequence of evolution in, lifestyle and visual development.

In 1937 Cogan stated:

> "It appears that the sympathetic system tends to adapt the eyes for relatively distant objects and as such, opposes the parasympathetic system, which tends to adapt the eyes for relatively near objects."

Such a consideration led Luckiesh and Moss (1940) to suggest that:

> "...the eyes of the so-called emmetropic adult subject may be functionally adapted to some point less than infinity when in a state of repose."

In his literature review, Heath (1956b) proposed that the term "tonic accommodation" be used to describe the state of accommodation whilst under such a position of rest and further proposed that the terms "positive accommodation" and "negative accommodation" be used to describe the modification of ocular focus in an inwards and an outwards direction, respectively. Heath acknowledged that "positive accommodation" could be brought about by parasympathetic innervation and that "negative accommodation" could be brought about by the sympathetic innervation. This alternative hypothesis of dual innervation to the ciliary muscle was thus given a possible functional basis.

1.4G - The anomalous myopias.

1.4Gi - Night or low-luminance myopia.

It is not uncommon for the patients of an ophthalmic practitioner to report symptoms of reduced visual acuity associated with conditions of reduced illumination, such as twilight or night-time. This complaint is generally reported by such people as long-distance lorry drivers and airplane pilots, who depend upon clear vision at long range. On examination, it is found that the night acuity is indeed lower than daylight acuity and furthermore, that increased negative lens power is required to restore the vision to an acceptable level. Such a phenomena, often referred to as "night myopia", had not escaped the attention of the early scientists.

The first documented report on this subject was made in 1789 by the astronomer and Director of the Royal Greenwich Observatory, Nevil Maskelyne, during the delivery of a paper to the Royal Society, in which he reported that his night observations were facilitated by the use of negative spectacle lenses. Maskelyne's observation attracted the attention of Dr. William

Kitchiner (1824); he too, had noticed that an increase in negative power was required "in the early part of the evening when the stars first become visible" and "at large theatres".

Almost 100 years later and apparently unaware of Maskelyne's observation, Lord Rayleigh described his own observations:

> "I have found that in a nearly dark room, I am distinctly short-sighted. With concave spectacles of 36ins negative focus my vision is rendered much sharper, and is attended with increased binocular effect. On a dark night small stars are much more evident with the aid of the spectacles than without them. In moderately good light I can detect no signs of short-sightedness." (Rayleigh, 1883).

Two years later, Rayleigh (1885) published a letter in which he described a method of detecting "this peculiarity of vision" by experimental methods:

> "With the aid of a set of concave glasses it is easy to try the experiment in a room lighted with gas. The flame should be gradually burned lower and lower, so as to give the full time for the pupil to dilate, and for the eye to acquire its maximum sensitiveness." (Rayleigh, 1885).

Rayleigh's letter stimulated much interest, in particular from the ophthalmologist George Andreas Berry who, in a dicussion on the cause of myopia generally, offered an explanation of Rayleigh's findings by stating:

> ".....it is evident that (the increases in myopia) can only be due to involuntary accommodation for a nearer point than that on which attention is directed - a kind of spasmodic myopia, and, as such, would disappear when the power of accommodation was paralysed by atropine." (Berry, 1885).

This is the earliest recorded explanation of night myopia as an accommodative phenomenon. Since that time many explanations for the effect of reduced illuminance on refractive power have been proposed such as, parafoveal cupping (Ogata and Weymouth, 1918); reduced visual acuity per se (Schober, 1947); pressure on the lens from the vitreous when the the pupil is enlarged in the dark (Ronchi, 1947; 1948); Oblique astigmatism (Biessels, 1954). The most popular causal factors have, however, involved varying degrees of spherical aberration (Rayleigh, 1883; Jackson, 1883; Otero and

Duran, 1941; 1942; Le Grand, 1942; Ivanoff, 1947a; and Kooman et al., 1951), chromatic aberration and the purkinje shift (Wibaut, 1919; Wald and Griffen, 1947; Ivanoff, 1947b; and Ronchi, 1948) and eventually, ocular accommodation.

As mentioned above, the earliest documented report of accommodation as a causal element in low-luminance myopia is that of Berry (1885). Otero and Duran (1941; 1942) used subjective methods to demonstrate low-luminance myopia of up to 2.0D and found that this level was almost entirely eliminated following the installation of homatropine. Otero and Duran (1943) determined that less than 0.25 of the observed low-luminance myopia was due to chromatic aberration, less than 0.50D was due to spherical aberration and concluded that a change in lens power accounted for the remaining 1.5 D. Schober (1947) postulated that a large portion of low-luminance myopia was a result of attempting to see when no accommodative stimulus was present; he described this as "psychic accommodation".

Otero et al. (1948) used telescope eyepiece settings to measure ocular-focus under conditions of low luminance. They used monochromatic light, thus overcoming the problems of chromatic aberration, and found a mean myopic shift of 1.2D. With artificial pupils they demonstrated that no more than 0.4D of this level was due to spherical aberration. Utilising flash photography of the third purkinje image, Otero et al. (1950) was able to demonstrate a mean myopic shift in darkness in six subjects of slightly greater than 1D. Otero (1953) cites the results of a study by Carreras (1952), in which a similar technique to that employed by Otero et al. (1950) was used to measure the low-luminance myopias of 5 emmetropes (mean = -1.74D), 11 myopes (mean = -1.67D), 5 hypermetropes (mean = -1.57D), 5 presbyopes (mean = -.83D) and 5 aphakics (-0.57D). Otero argues that the low-luminance myopias of the presbyopic and aphakic groups are less than the others due to a restricted and absent accommodative ability, respectively.

Campbell (1953) used purkinje image photography and foveal scotoma fixation to demonstrate a mean increase in refractive power in darkness of 0.64D. He considered that only some of the refractive change that occured in 'night myopia' was due to an increase in the refractive power of the lens and that it was of minor importance when compared with the effects of spherical and chromatic aberration. In conclusion, however, Campbell concludes:

> "...if the fovea is deprived of visual detail .....the mechanism of accommodation takes up a position of relatively fixed focus approximately 0.75D greater than the minimum refraction of the eye."

Campbell and Primrose (1953) used purkinje image photography measurements in five subjects, in darkness and found 0.8D change in the power of the crystalline lens; this they considered to be too small a change to account for all the low-luminance myopia reported to be 1.5D. They considered accommodation and ocular aberrations to play equal roles in low-luminance myopia. In conclusion, Campbell and Primrose (1953) stated:

> "We prefer to think that what we have found is the resting position of the focussing mechanism. If one considers this mechanism as a reflex arc, when the afferent stimulus is removed as in darkness the efferent side should be in a state of repose......This interpretation of the findings implies an active flattening of the lens to focus for infinity. It may be because the change is small that the idea of a dual action by the ciliary muscle does not gain general acceptance."

Campbell (1954) measured the minimum level of light necessary to elicit an accommodative response and found it to be 1 microlambert for a test object subtending 1°; as this level was near to the lower limit of the foveal cone threshold for visibility (Mandelbaum, 1941), Campbell concluded that the receptors involved in the accommodation response were cones and that the response required twice the light energy necessary to excite sensation at the fovea. He further concluded, that if the fovea was deprived of visual detail, at any level of illumination, the mechanism of accommodation took up a position of relatively fixed focus approx. 0.6D greater than the minimum refraction of the eye. Chin and Horn (1956) used infra-red retinoscopy to demonstrate a myopic shift as darkness increased. They considered that a varying contribution of accommodation was the causal factor. Heath (1956a) attributed 1.0 to 1.25D of the typically found levels in darkness to accommodation and concluded:

> "...it is evident that a basic factor underlying nocturnal myopia and nocturnal presbyopia is not so much the reduction of illumination, as the word 'nocturnal' would imply, but rather the depression of visual acuity which inevitably accompanies such reduced illumination."

Heath (1962) employed the widely differing techniques of subjective coincidence optometry, infra-red retinoscopy, purkinje image photography (with 'white' and infra-red light) and infra-red recording optometry, to demonstrate a variable low-luminance myopia of up to 1.5D. He further demonstrated that the accommodation levels found in total darkness were in agreement with those measured whilst the observers viewed a white, unstructured visual field, i.e. a ganzfeld; he described the later situation as inducing "space-myopia". Heath concluded that enlarged pupils and enhanced spherical aberration were not a major cause of low-luminance myopia, following the observation the same level of accommodation was detected under empty-field conditions with normal or even reduced pupil sizes. Fincham (1962) measured the state of accommodation in total darkness and found that it to vary from subject to subject with a range from zero to 1.4D.

Great improvements in the level of technology and understanding of visual physiology have enabled relatively recent researchers to come to the conclusion that, under conditions of reduced luminance, the accommodative system reaches an intermediate physiological position of rest, regardless of whether it was previously focussed for a distant or a near target.

Table 1.2 illustrates the means, standard deviations and ranges of accommodation measurements in darkness and the methodology used by the more recent investigations into low-luminance myopia.

STUDY	METHODOLOGY	N	MEAN(D)	S.D.	RANGE(D)
Leibowitz + Owens, 1975a	Laser	124	1.71	0.72	0.00 to 4.00
Leibowitz + Owens, 1975b	Laser	14	1.25	0.56	0.37 to 2.28
Owens + Leibowitz, 1976a	Laser	19	1.48	0.83	0.33 to 3.21
Leibowitz + Owens, 1978	Laser	220	1.52	0.77	-0.50 to 4.00
Miller, 1978a,	Laser	21	2.76	0.36	0.39 to 4.45
Miller, 1978b	Laser	10	1.76	0.95	N.A.
Simonelli, 1979	P.V.O.	301	0.71	0.53	-0.20 to 2.80
Malmstrom et al., 1980	I/R	5	1.07	1.40	-0.50 to 2.83
Mershon + Amerson, 1980	Laser	39	1.96	0.72	N.A.
Owens + Leibowitz, 1980	Laser	60	1.32	N.A.	-0.30 to 3.66
Heron et al., 1981	Laser	93	1.66	0.80	-0.50 to 4.00
Epstein et al., 1981	Laser	163	1.01	N.A.	-0.50 to 5.00
Maddock et al., 1981,					
Cardiff study	Laser	23	0.95	0.64	-0.30 to 3.00
Davis study	Laser	40	1.43	1.03	-0.20 to 4.40
Miller et al., 1983	Laser	10	1.67	0.80	0.00 to 3.25
Smith, 1983	Laser	13	1.52	0.44	-0.12 to 2.46
		MEAN	1.49	0.75	-0.15 to 3.52

TABLE 1.2: The results of several investigations, giving the means, standard deviations (S.D.) and ranges of accommodation whilst under conditions of total darknesss. P.V.O. = Polarised Vernier Optometer (Simonelli, 1980a); I/R = Infra-red optometer (Cornsweet and Crane 1970).

While infra-red optometry has permitted a continuous and objective measurement of accommodation, it is particularly exacting in its operation, necessitating the use of a bite-bar to maintain the observer in a rigidly-fixed position; it has the added disadvantage in that it is dependent upon pupil size. This would, in part at least, explain why the majority of recent studies (with the exception of Simonelli, 1979) have opted to use the simpler, yet subjective, Badal-laser optometer (based on the design of Hennessy and Leibowitz, 1970; 1972); further advantages of this choice of technique will be discussed in Chapter 3.

One study that has been omitted from the table is that of Epstein (1983), in which he measured the low-luminance myopia of two monocular aphakic subjects. He found that in each case, the level of induced myopia in the aphakic eye was less than 0.1 D; this was in stark contrast to the levels found in the phakic eyes of 1.22 and 0.73, of his subjects respectively. He concludes that "...this study appears to provide direct experimental evidence to support the hypothesis that accommodation is the primary cause of this myopia".

1.4Gii - Empty-field or space myopia.

Since the early 1950's a phenomenon related to that of night myopia has been reported in the literature. Whiteside (1952; 1953) found that when subjects viewed a relatively bright featureless visual field, such as fog, a cloudless sky or a uniform overcast sky, the eye exibited a myopia that varied from 0.5 to 2.0 D in magnitude. This finding has been confirmed by Heath (1956a), who also found a reduction in the amplitude of accommodation. Brown (1957) was unable to improve the observational performance of his subjects under empty-field conditions by the use of "gun-sight reticles" and concluded that for purposes of air-to-air search, most improvement in performance would be gained by careful selection of personnel. Westheimer (1957) demonstrated that the level of myopia found under empty-field conditions (0.75 -1.75 D) was equivalent to the level found under conditions of darkness.

1.4Giii - Instrument or small-pupil myopia.

Instrument myopia refers to "a persistent state of overaccommodation during observation through an optical instrument, such as a telescope or a microscope" (Hennessy, 1975). Many studies have reported the presence and magnitude of instument myopia (Baker, 1966; Schober et al., 1970; Hennessy, 1975; Richards, 1976; Richards et al., 1980 and Ditchburn, 1980). Most of these studies have involved microscopy, although other studies have shown analogous effects with other instruments (Wald and Griffin, 1947; Home and Poole, 1977). The overaccommodation has been inferred from both the eye-piece and focal adjustment of the various instuments, though many of the more recent studies have monitored ocular focus during while viewing through such instuments (Hennessy, 1975; Miller et al., 1984). Though similar in effect to night and empty field myopia, instument myopia is more complicated, in that it occurs during observation of targets of high contrast and detail and it has been suggested that the mere proximity of the instrument may induce the myopia (Schober et al., 1970). A recent study (Miller et al., 1984) has demonstrated, however, that viewing through a phoropter with 2mm artificial pupils produced the expected over- and under-accommodation, but when the artificial pupils were changed for 19mm, no significant effect on accommodation was observed.

1.4H - Night Presbyopia.

The term "anomalous myopias", as a collective description of the effects of darkness, ganzfeld empty fields and increased depth of field on accommodation, is somewhat limited in that there is also evidence for a reduction in the amplitude of accommodation under these conditions (one of the earliest observations were those of Ferree and Rand, 1933).

Duran (1943) observed that the amplitude of accommodation was reduced under dim light conditions and that in almost total darkness, the eye became 'presbyopic' and concluded that he had found the "rest point" of accommodation. Wald and Griffen (1947) found that the eye in darkness, seemed unable to alter its focus for distance or for near and appeared to possess a "fixed focus". Alpern and Larson (1960) demonstrated a reduction in the amplitude of accommodation under conditions of reducing illumination. They also haploscopically measured the change in heterophoria with the change in accommodation, i.e., the stimulus AC/A ratio, but found this not to change. Heath (1956a; 1962) found that accommodation for a near target under conditions of reduced luminance also produced a "night presbyopia", though the individual levels of accommodation were fairly variable.

More recently, Johnson (1976) measured the acommodative response of 4 observers to stimuli at 5 different dioptric distances (0.0, 0.5, 1.0, 2.0 and 3.0 D) under 4 luminance levels (0.051, 0.51, 5.14 and 51.42 cd/m^2). His results indicate that as the luminance decreased, the level of accuracy of response also decreased for both the near and the distance stimuli. The accommodation range was found to diminish, as the luminance decreased, approaching a "fixed focus" that corresponded to the resting "dark focus" values for each observer.

A point of further interest concerns the level of involvement of chromatic and spherical aberration in the magnitude of night myopia. If significant, these aberrations would adjust both the far and the near points in a myopic direction. It is clear from the discussion above that this is not the case thus enhancing the argument for an accommodative element in night myopia.

1.4I Discussion on the "Anomalous myopias".

Leibowitz and Owens (1975b) found Pearson product-moment correlation values of between 0.38 and 0.86 (df, 28) when accommodation levels in total darkness were correlated with the response to distant targets varying in luminance from "daylight" to "daylight 4.2 log-units lower". The correlation value increased as the luminance decreased. Hennessy (1975) compared the measurements of "dark focus" with instrument myopia and found a correlation value of 0.78 (df, 14). Leibowitz and Owens (1975a) found correlation values of 0.84, 0.81 and 0.68 (df, 29) when the dark focus was correlated with night accommodation (at approx. 0.52 cd/m^2), empty field (153 cd/m^2) and instrument myopias, respectively.

The results of the studies carried out by Hennessy (1975), Leibowitz and Owens (1975a; 1975b; and 1978) and Smith (1983) support the intermediate resting state hypothesis; in that they show a high correlation between an individual's accommodation level under night, empty field and instrument conditions and the corresponding level in total darkness. Thus it is suggested that they are all manifestations of the same physiological phenomenon. This is a more plausible conclusion than previous attempts to explain the myopias separately and independently in terms of aberrations, psychological factors, pupil size effects and the purkinje shift. However, the lack of 'perfect' correlations and anomalous individual responses indicates that these optical and psychological factors may have a secondary influence (e.g. proximal accommodation).

Investigations of the anomalous myopias have provided much evidence to support the hypothesis that the ocular accommodative system does not usually respond accurately to an accommodative stimulus. The accommodative error is usually biased in the direction of an intermediate, or resting position of accommodation and with a magnitude that depends on a number of factors (see general introduction, p.2), but mainly on: a) the stimulus distance or dioptric vergence from the intermediate resting position

(Johnson, 1976); b) the stimulus luminance (Johnson, 1976); and c) the form or spatial frequency content of the stimulus (Charman and Tucker, 1977; Charman and Heron, 1979; amd Owens, 1980).

It follows from this intermediate resting position hypothesis that tonic accommodation represents the level of accommodation demonstrable in the absence of an effective stimulus, i.e. in total darkness or with a bright empty field.

1.5 - STIMULUS DEPENDENCY OF ACCOMMODATION.

If an object of visual regard is randomly displaced away from a point conjugate with the retina of an observer, it is reasonable to assume that the object will no longer be perceived in focus, but will appear blurred (subject to the constraints of the depth of focus). If the object was previously of sufficient visual interest to the observer, he may wish to alter his focus until the optimum visual information is restored. It would seem relevant to pose the question "What aspects of the blurred retinal image have assisted the observer's visual system to regain and retain optimal focus of the retinal image"? The answer, although outside the direct scope of this thesis, is particularly relevant in the genesis of "tonic accommodation".

Difficulties inherent in the analysis of the stimulus characteristics of blur have led investigators to utilise specific stimuli of defined spatial and contrast characteristics by which the response of the accommodative system to such stimuli may be investigated quantitatively. Study of the response of the accommodative mechanism to sinusoidal grating stimuli has proved fruitful in the interpretation of its characteristics (see the studies of Phillips, 1974; Charman and Tucker, 1977; 1978a; Charman and Heron, 1979; Owens, 1980; Bour, 1981; and Raymond et al., 1984).

1.5A - Characteristics of the accommodative stimulus.

Whatever aspect of the visual stimulus initiates and guides accommodation, it is patently clear that the stimulus rarely elicits an accurate accommodative response. Sheard (1920) had shown that the accommodative response failed to reach the expected stimulus value at near, from the results he obtained via dynamic retinoscopy and termed the difference between the response and stimulus values "accommodative lag". The studies of Morgan and Olmstead (1939) and Morgan (1944a) demonstrate that the accommodative system over-accommodates (i.e. becomes relatively myopic) for a distant object and under-accommodates (i.e. becomes relatively hyperopic) for a near object (see fig. 1.3).

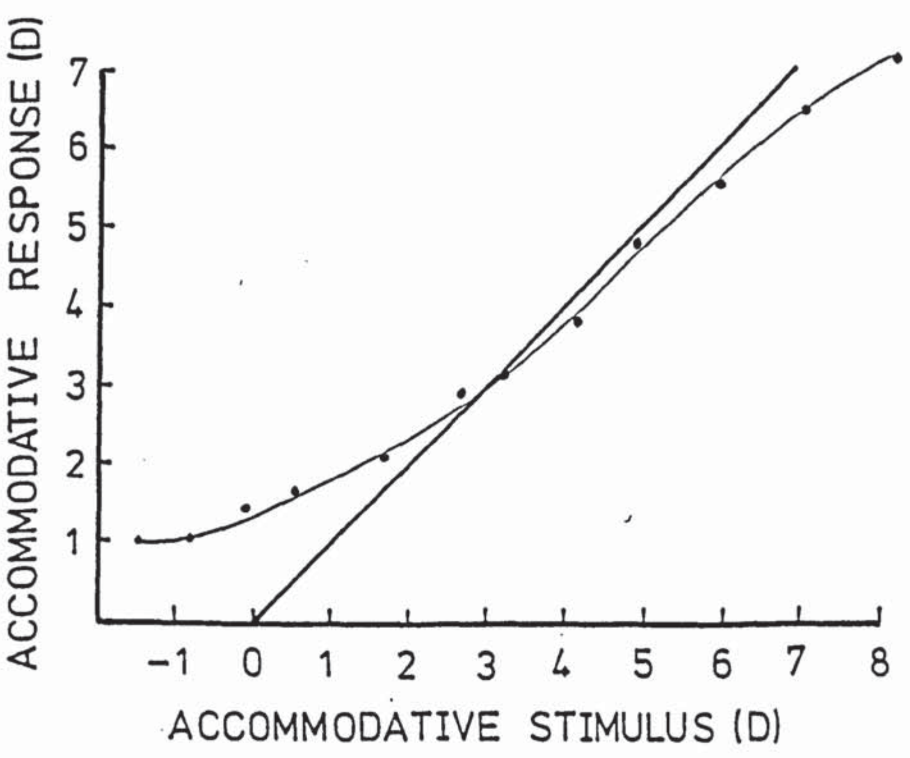

Figure 1.3. The accommodative response as a function of the stimulus to accommodation (after Morgan, 1944a).

The stimulus/response curve is sigmoidal in nature, with a definite asymptote at its lower end. Morgan found the value of the asymptote to vary with observer between 0.5 and 1.5D with an average of 0.75D. A similiar asymptote appears likely at the upper end as the limit of the amplitude of accommodation is reached. Accommodative stimulus/response curves of this type have been produced by many workers (Alpern and David, 1958; Fincham and Walton, 1957; Heath, 1956a; and more recently Ramsdale, 1979; 1982). The difference between the stimulus and response value has been considered to be a function of stimulus detail and luminance level, with the difference being larger for coarse targets (Heath, 1956a; Charman and Tucker, 1977) low luminances (Alpern, 1958a; Johnson, 1976).

In his review, Morgan (1957) proposed that the physiological resting state of accommodation was equivalent to a value of 0.75 to 1.00 D of "clinical myopia" and acknowledges Heath's (1956b) reference to this position as one of "tonic accommodation". Toates (1970) proposed that, for the normal subject, the accommodation control system has a resting point at about 1.5 D and that the resting point is equivalent to the intersection of the stimulus/response curve and the unit-ratio line of the typical "Morgan curve". Toates (1970) further suggested that the position of rest was a function of the state of the ciliary muscle and crystalline lens in the absence of any stimulus to accommodation and that increases and decreases in accommodation from the resting position would therefore require effort. He concluded that accommodation is an example of a proportional control system; i.e. fixation of a target at all positions of focus other than the rest position induces a steady-state error, thus the difference between the unit-ratio line and the stimulus/response curve at any stimulus level is known as the steady-state error. The many factors on which the accuracy of the accommodative response may rest have been outlined in the general introduction.

Clearly then, a measurement of accommodation would depend upon the level of difficulty involved in the method utilised. Until relatively recently, the only methods in which an induced-change in accommodation could be attained involved the measurement of refractive error or accommodative amplitude; visual parameters that are both highly dependent upon the stimulus requirements of the methodology. It is possible that such stimulus dependency may mask the effects of a particular experimental design, e.g. a drug or cognitive task effect. It would seem pertinent, therefore to explore the advantages of stimulus-free measurements of accommodation.

The most convenient stimulus-free environment is that of total darkness and it is obvious, therefore, that suitable methodology (such as laser-optometry) is required to enable investigation of the accommodative system via the parameter of tonic accommodation.

CHAPTER 2

THE TONIC RESTING STATE OF VERGENCE

2.1 - THE ANATOMY, NEUROLOGY AND PHYSIOLOGY OF VERGENCE

2.1A - Gross anatomy of the extraocular muscles

Each eye is located in a rigid bony orbit, together with the extraocular and levator palpebrae muscles, the orbital nerves, blood vessels, orbital fat and fibrous tissues. The latter two components serve to keep the eye reasonably well protected and fixed in place as it is rotated by the extraocular muscles. The orbit is lined with a membrane of tissue (known as the periorbita) that extends to the orbital margin where it becomes continuous with the periosteum covering the facial bones. At the apex of the orbit behind the eye a channel is formed known as the optic foramen, through which the optic nerve enters; at this foramen the periorbita thickens into a ring called the annulus of Zinn. The eyeball is covered by Tenon's capsule, which is a layer of connective tissue that is continuous with the fascial sheath that covers the extraocular muscles. Sheets of fibro-elastic tissue, called check ligaments, connect the fascial sheaths to the orbital walls to limit the degree of activity of the extraocular muscles.

There are six extrinsic ocular muscles to each eye: four rectus (lateral, medial, superior, and inferior) and two obliques (superior and inferior). The four rectus muscles arise from a common origin, the annulus of Zinn, and run forward to be inserted into the sclera anterior to the equator of the globe. The superior oblique also arises at the apex of the orbit, from the body of the sphenoid bone (and to some extent from the annulus of Zinn) and runs through a cartilaginous pulley, known as the trochlea, just behind the orbital margin at the junction of the roof and medial wall of the orbit. The superior oblique then, in the form of a tendon, turns sharply at an angle of about 54° to the vertical plane of the eyeball to run under the superior rectus to find a line of insertion lying obliquely on the upper part of the postero-lateral aspect of the sclera behind the equator. The inferior oblique originates in a short rounded tendon from the antero-medial corner of the orbital floor adjacent to the lateral aspect of the lacrimal fossa, passing posteriorally, laterally and superiorally at an angle of about 51° to the vertical plane of the eyeball. It extends beneath the inferior rectus to find an insertion in the lower part of the postero-lateral aspect of the sclera about 5mm temporal to the optic nerve. Where the muscle tendons approach the globe they do not pierce Tenon's capsule but invaginate it over themselves: For a complete anatomical description see Duke-Elder, 1961; 1973 and Wolffe, 1976.

2.1B-Minute anatomy of the extraocular muscles.

The extraocular muscles have several structural and physiological features that differentiate them from most other striated muscles. The features of interest are the unusually fine size of the muscle fibres (Kato, 1938; Lockhart and Brandt, 1938; Cooper and Daniel, 1949; Merillees et al., 1950; Cooper and Fillenz, 1955; Abou-El-Naga et al., 1963; Peachey, 1971); the unusual excess of connective tissue (Schiefferdecker, 1905; Duke-Elder, 1973); and their peculiar innervation.

2.1B i - Innervation of the extraocular muscle.

The innervation of the extraocular muscle is as yet not fully understood. Kruger (1929) described two morphological sub-types of extraocular muscle fibres; firstly the "Fibrillenstruktur", a thick, poorly staining myofibril innervated by motor nerves of large diameter with single, large plaque-like endings, with its fibrils regularly arranged and separated by abundant sarcoplasm. The second sub-type he called the "Felderstruktur", consisting of thin, poorly delineated and heavily staining fibrils which are not clearly separated but tend to be fused together in syncytial fashion within little sarcoplasm; these fibrils are innervated by nerves of small diameter with numerous grape-like endings.

Peachey and Huxley (1962) attempted to correlate the two morphological types (described above) with the electrophysiological 'fast' and 'slow' properties first described by Kuffler and Vaughan-Williams (1953a; 1953b). Muscle fibres have been classified into 'fast' or 'twitch' and 'slow' or 'tonic' categories using criteria derived from observations on frog limb muscle. Twitch or fast fibres are singly innervated, can propogate action potentials and appear to be less fatigue-resistant than the tonic or slow fibres; which are multiply innervated, typically do not conduct action potentials and develop a graded sustained contraction when stimulated.

It is true that fibres can be found in mammalian extraocular muscles that are very similar in appearance to frog "slow" muscle fibres (Hess, 1961), with similar nerve endings to the "felderstruktur" type (Dietert, 1965; Namba et al., 1968; and Harker 1972) and that possess the corresponding electrophysiological properties enabling the division into 'fast' and 'slow' types. It is also clear however, that such a division is insufficient to cover the variety of types that actually occur, e.g. up to six types of extraocular muscle fibre have been distinguished on morphological grounds alone (see Chiarandini and Davidowitz, 1979 for a review) and it is known that up to four types of so-called 'fast' fibres exist (Alvarado and van Horn, 1975).

It has been suggested that the different types might subserve different types of eye movement (Alpern and Wolter, 1956; Jampel, 1967); in that saccadic movements might be executed by the 'fast' muscle fibres and vergence movements by the 'slow' fibres. Keller (1973), however, has recorded some degree of activity in all the motorneurons he monitored from the abducens and medial rectus units of rhesus monkeys during vergence, smooth pursuit and saccadic eye movements. Thus it is reasonable to conclude that all motorneurons, and hence all muscle fibre types, are involved in vergence as well as versional eye movements. Nevertheless, the fact that motorneurons participate in all movements does not imply that all muscle fibres contribute equally to all components of the movement or fixation. Large differences would be expected between the responses of the various muscle fibre types on account of their different morphological and physiological characteristics (Mays, 1983).

2.1B ii - Pharmacological aspects.

Duke-Elder and Duke-Elder (1930) observed that mammalian extraocular muscles resembled the slow skeletal muscles of lower vertebrates in responding by contracture to acetylcholine. The receptors have been shown by Sanghvi and Smith (1969) to be mainly nicotinic.

Wolter (1954; 1955) has described three different kinds of motor endings on the thick muscle fibres: the first kind were similar to those described some years earlier by Kruger (1929) as "Fibrillenstruktur"; the second were small thin unmyelinated nerve-endings with loops in, or just outside, the main motor-end plates; the third kind were also unmyelinated and appeared to arise from the perivascular plexus, rather than the cranial nerve. Boeke (1926) had earlier noted the existence of the first two types and had regarded them as representing innervation from both the skeletal and the autonomic nervous systems. Wolter, however, attributed an autonomic function to both types of unmyelinated fibres; those that arose from the perivascular plexus he attributed to the sympathetic division while those that descended with myelinated motor nerve, he attributed to the parasympathetic division.

Paralysis of the sympathetic system produces Horner's syndrome; which consists of ptosis (due to paralysis of Muller's muscle), miosis (due to paralysis of the dilator pupillae) and enophthalmos. It is this last effect that suggests that the extraocular musculature may be influenced by the sympathetic system. Kern (1968) found that isoprenaline (a non-selective beta adrenoceptor agonist) caused relaxation of tension in monkey extraocular muscle (and hence a relative exophthalmos), whilst the effect was blocked by dichloroisoproterenol (a non-selective beta adrenoceptor antagonist), indicating a beta action. He concluded that the exophthalmos that accompanies extreme fear may be due to the beta action of adrenaline secreted by the adrenal gland under these conditions ("fear, flight or fight").

2.1C - Neurophysiology of vergence.

Our knowledge of the neurophysiology of vergence movements is based on the anatomical evidence of such workers as Warwick (1953) and Buttner-Ennever and Akert (1981) and from the studies of neural activity in the ocular motor nuclei in monkeys (e.g. Keller, 1973; Keller and Robinson, 1972; Mays, 1984).

2.1Ci-The ocular motor nerves and nuclei

The motor neurones activating the eye muscles are derived from the cranial nuclei as follows:

N III. (Oculomotor nerve) - innervating the superior rectus, inferior rectus, medial rectus and inferior oblique.

N IV. (Trochlear) - innervating the superior oblique.

N VI. (Abducens) - innervating the lateral rectus.

These nerves represent essentially the axons of cell bodies collected in the grey matter of the mid-brain and pons and are known as the ocular motor nuclei, and form part of the somatic motor cranial system.

The IIIrd nerve nucleus lies in the tegmentum in the central grey matter in the upper part of the midbrain below the superior colliculus, beneath and running parallel to the aqueduct of Sylvius. It is some 5 to 6 mm long and extends between the third and fourth venticles. It is traditionally divided into a series of discrete zones, each concerned with a pair of muscles, whilst the additional median or paramedian nuclei, associated with the Edinger-Westphal nucleus, is thought to be the origin of parasympathetic innervation to the ciliary ganglion (Warwick (1955). The question of how the muscles are represented in the various different parts of the nucleus has often been a source of disagreement (for a review see Warwick, 1964; Buttner-Ennever and Akert, 1981).

The IVth and VIth nerve-nuclei are not subject to as much controversy: the IVth is a small clump of cells lying caudally to the IIIrd nucleus in the central grey matter in the floor of the aqueduct of Sylvius and at the level of the lower part of the inferior colliculus, whilst the nucleus of the VIth nerve lies in the pons, in the floor of the fourth ventricle.

2.1Cii-Motorneuron activity and vergence.

To move the eyes it is necessary to overcome the viscous drag and elastic restoring forces of the orbital supporting tissues. Robinson (1964) has suggested that the activity of the extraocular muscles might best be understood by a consideration of the properties of the viscoelastic forces occuring on the globe. He further suggests that the passive forces on the eye are such that the oculomotor plant (or effector mechanism) is an example of an overdamped mechanical system: i.e., the mechanical response to a sudden change in force is quite sluggish. A powerful contraction of the extraocular muscles is necessary to overcome the viscous resistance. Rapid movements (e.g. a saccade) require a phasic increase or burst of neural activity in the ocular motor nuclei - the pulse of innervation. Once at its new position, the eye must be held there against orbital elastic forces that tend to return it to its rest position. To hold the eye in an eccentric position requires a steady contraction of the extraocular muscles, arising from a subsequent tonic level of neural activity, descibed as the step of innervation (Leigh and Zee, 1983). When the ocular motor command signals are appropriate, the eye is thus moved rapidly and held steady in its new position.

Studies of the discharge characteristics of ocular motorneurons in monkey (Robinson, 1970) and human (Collins, 1975) confirm the presence of both the pulse and step of innervation during saccades. Vergence eye movements are comparatively slower than saccades (Rashbass and Westheimer, 1961a; Robinson, 1966), because the neural signal that produces them is a step of innervation, unaccompanied by any pulse innervation.

During vergence eye movements the medial and lateral rectus motorneurons must not receive the same signal if the eyes are to move by equal magnitudes but in the opposite direction (Westheimer and Mitchell, 1956). Activity of medial rectus and lateral rectus motorneurons has been recorded during vergence eye movements (Keller and Robinson, 1972; Keller, 1973). All abducens neurons showed a decrease firing rate for convergence and an increased rate for divergence. Conversely, all medial rectus motorneurons displayed an increase in discharge frequency during convergence and a decrease during divergence.

It is known that the internuclear neurons from the abducens carry signals to the medial rectus motorneurons for all horizontal conjugate eye movements (Highstein and Baker, 1978; Highstein, 1977; Carpenter and Batton, 1980). However, it would appear from examination of cases in which the fibres of the medial longitudinal fasciculus are damaged by injury or disease, that the vergence control signal must arrive at the medial rectus motorneurons by way of a different path. The syndrome of internuclear ophthalmoplegia results from a lesion of the medial longitudinal fasciculus between the abducens and oculomotor nuclei (Smith and Cogan, 1959) and is characterized by weakness or absence of ocular adduction for attempted gaze shifts, that is presumed to be due to the interruption of abducens internuclear fibres (Highstein and Baker, 1978); Carpenter and Batton, 1980). Adduction for attempted convergence is spared in this syndome. Carpenter and Strominger (1965) had earlier experimentally induced electrolytic lesions of the medial longitudinal fasciculus in monkeys and made similar observations. Thus, the vergence control signal must arrive at the medial rectus motorneuron by way of a pathway other than the abducens internuclear input. Since it is known that most medial rectus motorneurons carry a vergence as well as a versional signal (Keller and Robinson, 1972; Keller, 1973; Mays and Porter, 1982), vergence and version are probably combined at, rather than before, this level.

These observations would suggest that it should be possible to identify a pure vergence signal before it is combined with conjugate commands. The independant studies of Robinson (1970) and Schiller (1970) had predicted that neurons, with firing rates proportional to the angle between the eyes, might be found near to the oculomotor nucleus. Mays (1982; 1983; 1984) has conducted a series of investigations into the existence of such neurons within the mid-brain of four rhesus monkeys. He found such cells within the mid-brain reticular formation, 2mm from the medial rectus motorneuron. The activity of these cells gave: a firing rate proportional to the vergence angle, yet showed no change during version eye movements; led the vergence changes in time; had firing rates that parallel changes in vergence angle even under conditions of accommodative disparity mismatch; and had a firing pattern that is closely coupled to that of medial rectus motorneurons. Mays found that the average firing rate for the "convergences cell" increased 20.8 spikes/sec for each degree of adduction and acknowledges that this rate of change is about 4 times higher than the average vergence rate-position slope for neurons in the motor nuclei (Keller, 1973). Mays concluded that the firing range of convergence cells may be distributed across a narrow range of dysjunctive eye movement's and might explain why vergence eye movements are very precise yet limited in amplitude (when compared to saccades).

Mays (1984) also encountered cells that exibited activity during divergence within the same area of the mid-brain. These "divergence cells" were found less often and although they appeared less highly correlated with vergence, the range of their vergence angle-rate position slopes were found to be similar to the convergence cells. It is possible that divergence cells may be providing vergence signals to abducens motorneurons, since during convergence, divergence cells, like abducens motorneurons, decrease their firing rate. If this was their role, then the relative paucity of the divergence cells is puzzling.

2.1C iii - Sensory cortical pathways.

In the geniculo-striate pathway, signals from the two eyes are segregated until they reach the primary visual cortex. It is here that the input is organized into ocular dominance columns and significant binocular interaction first occurs. Binocular disparity information is probably extracted at this level. Barlow et al. (1967) found a number of neurons in the visual cortex that were sensitive to horizontal retinal disparities. More recently, Poggio and Fischer (1977) recorded from neurons in the visual cortex of alert monkeys, trained to maintain fixation of a target while an appropriate visual stimulus was moved in depth. Many binocularly driven cells in the visual cortex fired maximally when the visual stimulus was in the receptive field and at the same distance as the fixation point - these they called "tuned excitatory cells". Discharge rates decreased if the target was moved nearer or farther. Other cells fired most vigorously when the stimulus was either in front of or beyond the fixation plane - these were termed "tuned inhibitory cells". In addition to these zero-disparity cells, other cells signalled that the target was nearer ("near cells") or beyond ("far cells") the fixation plane. The near and far cells were responsive to disparities of ± 1 deg. or more, well beyond the size Panum's area (Panum, 1858). The vergence oculomotor system can also respond to large disparities (Westheimer and Mitchell, 1969). Poggio and Fischer (1977) concluded that near and far cells might be used to initiate vergence movements and that tuned excitatory cells could provide the feedback signal required to maintain fixation in the longitudinal plane. It is not inconceivable to consider that the sensory basis of accommodation may also avail itself of such a system.

Westheimer and Mitchell (1969) studied vergence movements in a "split-brain" patient, who had undergone section of the corpus callosum and anterior commissure. When a target was moved from far to near in his peripheral visual field, the subject converged to follow it. When a similar procedure was used, but this time along the mid-line and thus fixated by the subjects foveae, he did not make a convergent movement. In the first case the images of the target fell on the temporal retina of one eye and the nasal retina of the other thus both images reached the visual cortex on the same side of the retina. In the latter case, however, the retinal images shifted to the temporal retina of each eye and were thus projected to seperate cerebral hemispheres. Mitchell and Blakemore (1970) report a similar patient with a sectioned corpus callosum, who could not discriminate target depth induced by binocular disparity unless retinal signals were sent to the same cerebral hemisphere. These results suggest that the cortex is crucial for the control of the vergence system by disparity cues.

Cortical areas other than the visual cortex have also been implicated in the control of vergence eye movements. Jampel (1960) reported that the near triad (of convergence, accommodation and miosis) could be elicited by stimulation of various sites in cortical areas 19 and 22, although the responses were not always consistent. Robinson and Fuchs (1969) have, however, suggested that Jampel's results may have been due to an interaction of electrical stimulation with anaesthesia.

2.1C iv - Cortico-oculomotor pathways.

The route by which a binocular retinal disparity might be transmitted from the visual cortex to oculomotor areas is not yet known. Poggio and Fischer (1977) found that tuned excitatory cells were commonly encountered in layers V and VI of the visual cortex, which are known to project almost excusively to the superior colliculus, pulvinar and lateral geniculate nucleus (Lund et al., 1975). There is a strong anatomical projection to the superior colliculus from the visual cortex (Wilson and Toyne, 1970) and from the colliculus to the oculomotor areas (Harting, 1977) and yet, there is no evidence implicating the superior colliculus in the control of vergence eye movements.

The pretectal area has long been recognised as an important region for the control of the pupillary light reflex (Magoun and Ranson, 1935). From their examination of the connections of the pretectum, Benvento et al. (1977) concluded that the retina, superior colliculus and cortex can only influence pupillary constriction and accommodation through their projections to the pretectum. Thus coordination of the near triad may well involve pretectal nuclei, but there is as yet no direct evidence for a role for this area in the control of ocular vergence.

2.2 - VERGENCE EYE MOVEMENTS.

2.2A - The human oculomotor system.

The human oculomotor system can be considered as five functionally distinct subsystems (Robinson, 1981): a) and b) the vestibulo-ocular and optokinetic systems, serving to stabilize the eyes by compensating for head movements; c) the saccadic system, for the generation of high-velocity eye movements that can be used to aquire visual targets; d) the pursuit system, for the tracking of relatively low-velocity target motion; e) the vergence system, permitting fixation of objects at various distances from the observer.

Systems a) to d) generate conjugate eye movements, whilst system e) controls disjunctive eye movements. There is evidence to show that the vergence system is relatively independent of the conjugate eye movement control systems. Rashbass and Westheimer (1961a; 1961b) have demonstrated that pursuit and vergence eye movements can occur simultaneously with complete temporal and directional independence.

2.2B – Maddoxian considerations of vergence.

Ernest Edmund Maddox is widely credited as being the first to formalize a classificational model of vergence eye movements and, although he was primarily a clinician writing from clinical experience (rather than a visual scientist reporting the results of controlled experiments), his classification has remained to form the basis of many subsequent models (e.g. Morgan, 1968; Alpern, 1969a).

As might be expected, Maddox was clearly influenced by much of the clinical and research literature of his day and it is apparent from Maddox's book (1893) that he was familiar with the concepts of: relative accommodation (Donders), relative convergence (Donders and Landolt), latent deviations (Von Graefe and Stevens), zones of comfort (Donders, Landolt and Percival), prism dioptres (Prentice) and Variable prisms (Risley).

Maddox's first classification appeared in 1886, and it proposed that convergence was performed in three hierachical steps: underlying all vergence responses he proposed a tonic component; followed by a component induced by the action of accommodating for a near object, this he termed "accommodative-convergence"; and finally, a "fusional supplement" would be added, when necessary, to bring the eyes into alignment for single vision.

Some seven years later Maddox (1893) extended his original ideas into, what Morgan (1983) later described as, "the first complete description....of vergence eye movements". In this later model, Maddox proposed that the total vergence required to bifixate an object in visual space could be categorized into various components, each of which was related to either the "physiology of vergence", to some aspect of the stimulus pattern, or to both.

Maddox termed the initial component of the vergence response as "tonic convergence" and stated:

> "Were all the innervations to cease, the anatomical position of rest of the eye would undoubtedly be one of considerable divergence." (p. 90).

He considered that, even in the absence of visual information, the eyes were moved by "tonic convergence" from this position of anatomical rest to one that was more convergent. Maddox identified two essentially non-visual factors that could influence the magnitude of tonic vergence. The first was the tonus exhibited by living striated muscle; the second he termed "persistent activity of the converging innervation": this would be described today as the central control mechanism of vergence, which has a tonic activity of its own (Morgan, 1980). Maddox considered this latter factor to be affected such conditions as drowsiness, alcohol, anaesthetics and ultimately death. He further considered this latter factor to be influenced by knowledge of the spatial position of the object of regard and by (what may be interpreted as) a type of muscular memory due to the constant use of some degree of vergence needed for bifixation.

Maddox considered that, where the magnitude of tonic convergence was in excess or in deficit to the requirements of bifoveal fixation, compensation was provided by a supplemental vergence, which he described as the "fusional supplement" or "reflex convergence". It is immediately apparent that the term "convergence" is inappropriate where the tonic vergence element is in excess, for in this situation reflex 'divergence' would be required.

Thus, according to Maddox, bifoveal fixation is achieved for a distant object by "tonic convergence" plus the fusional supplement of "reflex convergence". In discussing fixation of a near object he states:

> "In near vision, there is an intermediate grade - the accommodative. If one eye be occluded by the hand while vision is directed first to a distant object, and then to a near one, the occluded eye deviates inwards under the hand from an impulse to convergence, which is due chiefly to a sympathy with accommodation, but also to the habit of converging where attention is directed to a near object. The second grade of convergence is therefore added on to the first or tonic grade, and its amount depends, of course, on the amount of accommodation in exercise." (p. 95).

Maddox thus recognised that the amount of accommodative convergence was due to the effort of accommodation; he observed that the magnitude of accommodative convergence was found to increase under the influence of atropine and to decrease following application of physostigmine. In addition he acknowledged the existence of individual variation.

In Maddox's model, fixation of a near object would result from the addition of the requisite amount of accommodative convergence to the level of tonic convergence. If any disparity still existed, a supplementary "reflex convergence" would be induced in order to compensate for any over or under convergence. Maddox ends his discussion with a note:

> "Strictly speaking, there are four elements of convergence, though the first and third are perhaps closely related. The four are: (1) Tonic; (2) Accommodative; (3) Convergence due to "knowledge of nearness", or in other words, "voluntary convergence", for we cannot, without special practice, converge the eyes voluntarily, under ordinary conditions, without doing so by thinking of a near object; fusion convergence. Of these four elements I have included the second and third under the name of "accommodative convergence", to simplify practical work." (p.106).

In summary therefore, Maddox considered that vergence eye movements could be analysed in terms of four components. He maintained that the first component, which he termed "tonic convergence", moves the eyes from some unknown anatomical position of rest to a more convergent position and assumed that this latter position could be determined by the distance heterophoria measurement with ametropia corrected. Maddox considered the magnitude of tonic convergence to be a function of the tonus of the extraocular muscles and the activity of the convergence control centre. Any deficit or excess of tonic convergence is compensated by another component, which he termed "reflex convergence". The stimulus to reflex convergence he considered to be both disparity and constant use. The third component is accommodative convergence, whose magnitude is related to the effort of accommodation. Maddox recognised this relationship to vary from person to person. The fourth component he identified as due to a "knowledge of nearness" or "voluntary convergence". Maddox had as much difficulty accounting for psychic, or proximal vergence in his scheme as have more recent investigators (e.g. Morgan, 1968). He considered the latter two components to be involved in the response to a near stimulus and not at all for distance vision.

2.2C - The components of the vergence system.

It is traditional to consider two primary stimuli to vergence eye movements: disparity between the the location of images on the two retinae, producing diplopia; and blur of the retinal image. These factors stimulate fusional and accommodative vergence movements, respectively. In addition, certain psychological cues, such as an awareness of the proximity of a visual stimulus may also elicit a 'proximal' vergence eye movement.

Amongst the most notable areas of debate concerning

Maddox's model is the proposal that convergence is an active process, whilst divergence merely results from the release of passive elastic forces upon the relaxation of convergence. The proposal has since been refuted following electromyographical studies of the extraocular muscles, which have demonstrated activity in the lateral recti during divergence and steady fixation (Bjork, 1952; Adler, 1953; Breinin and Moldaver, 1955; Breinin, 1957a; 1957b; 1959; Miller, 1959; Keller and Robinson, 1972; Keller, 1973). For disparity vergence to work for an outward change in target position, an efficient divergence mechanism is essential.

2.2C i - Disparity vergence.

Disparity vergence occurs when there is retinal disparity between the images of the two eyes (Westheimer and Mitchell, 1956; 1969; Stewart, 1961; Mitchell, 1970). Such movements have conventionally been known as 'fusional vergence movements' because it seems that the objective of the disparity vergence system is to obtain and maintain retinal correspondence so that the two retinal images appear fused as one. Since the stimulus to these movements is the existence of retinal disparity rather than diplopia itself (Stark et al., 1980), the movements are now referred to as disparity vergence movements of the disparity vergence system.

Current models of the disparity vergence system are based on that of Krishnan and Stark (1977), which consists of three main components; the binocular optical system, the central processor and the plant or effector mechanism (see fig. 2.1).

The binocular optical system compares the target position with the vergence position of the two eyeballs and produces the disparity signal from the retinal images of the two eyes; this process may include some neural processing. The central processor includes both the central processing and the generation of the motor controller signal. In control system terminology, the binocular optical system is thought of as a comparator and the central processor as a controller. The neural signal generated by the controller rotates the eyeballs through the action of the associated musculature; in control terminology this portion of the system is called the plant or process. The entire system operates as an automatic control system where response (actual vergence position of the eyes) is compared with reference input (appropriate vergence position as determined by the target location), and the plant is driven by the output of the controller, which in turn is processed from the error signal (retinal disparity).

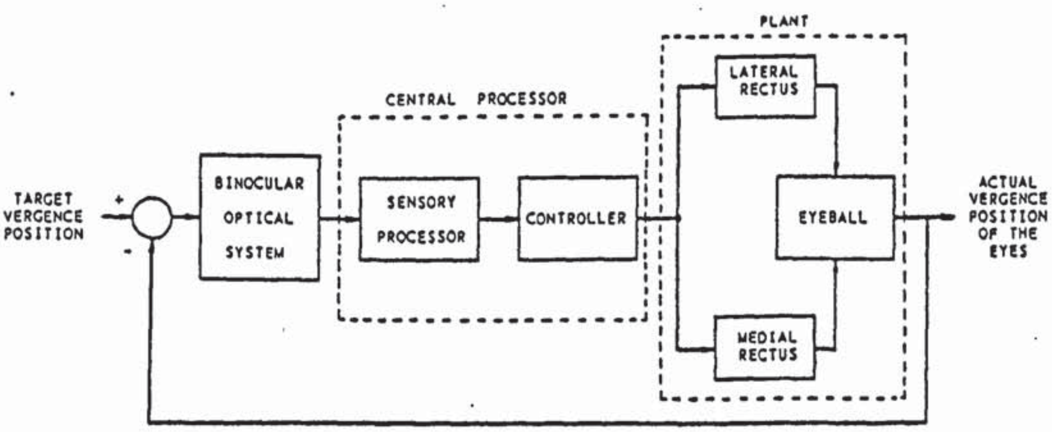

FIG.2.1 A block diagram representation of the disparity vergence system. (redrawn after Krishnan and Stark, 1977).

2.2C ii - Accommodative vergence.

Accommodative vergence refers to a blur-driven change in the horizontal alignment of the two eyes. The first acknowledged demonstration of the synkinesis between vergence and accommodation was conducted by Mueller (1843) following the observation that a target moved along the visual axis of and towards one eye will elicit a slow, nasal-ward rotation in the covered eye. This classical experiment provided the emphasis on the monocular expression of accommodative vergence. This has since been shown to be a binocular response (Semmlow and Venkiteswaran, 1976; Kenyon et al., 1978; Ono and Nakimizo, 1978). We have seen earlier that Maddox had suggested that accommodative vergence was primary and disparity vergence secondary in the usual occurrence of vergence eye movements in normal binocular vision. This appears not to be true. Fincham and Walton (1957) believed that disparity vergence provided the coarse tuning and accommodative vergence the fine tuning. It has been suggested that even with moderate disparities the accommodation system would have no effective stimulus (and thus no feedback), and it would thus be operating in open-loop mode. Evidence for this comes from Phillips (1974), who showed that the blur stimulus to accommodation (Phillips and Stark, 1977) must fall on or very near to the fovea to be effective and thus any sizeable disparity makes blur ineffective as a stimulus to accommodation (Semmlow, 1981). Disparity has been shown to be robust to blurring of the retinal image of the target secondary to accommodative error (Westheimer and Mitchell, 1969; Jones and Kerr, 1972).

Thus, the initial vergence response to a stimuli is driven by disparity; then as the target approaches the fovea, the secondary response is driven by blur, acting as a stimulus to accommodation, becomes effective. The accommodative vergence response will then be nonlinearly added (Brodkey and Stark, 1967) to the disparity vergence response. If vergence is made open-loop (e.g. by covering one eye and thus removing the disparity) the vergence system reaches a level known as the heterophoria position: the amount of vergence being appropriate to the motor state of accommodation (Morgan, 1944b; Alpern, 1950; Ono and Nakimizo, 1978). Maddox's model makes no allowance for the existence of the symmetric vergence effect on accommodation known as vergence accommodation (Morgan, 1954; Kent, 1958; Balsam and Fry, 1959; Krishnan et al., 1977). This is a disparity-induced accommodative drive that alters the amount of blur-induced drive required for a given accommodative stimulus (just as Maddox's model assumes accommodative - vergence alters the required fusional component). Its involvement in future models of the vergence system may explain the discrepancies noted between expected and empirical measurements of accommodative and fusional vergence (Semmlow and Heerema, 1979; Semmlow and Hung, 1979; Schor and Narayan, 1982).

The amount of change in accommodative vergence (expressed in prism-dioptres) per unit change in accommodation (in dioptres) results in a measure called the response accommodative convergence to accommodation (AC/A) ratio - see Morgan, 1968). The AC/A ratio is one of the most widely used measures in the assessment of binocular condition, especially in light of the presence of accommodative vergence at two months of age (Aslin and Jackson, 1979).

2.2C iii - Proximal vergence.

Proximal vergence or convergence due to a "knowledge of nearness" (Maddox, 1893), is thought to be caused by an awareness of the proximity of a stimulus (Hofstetter, 1942; Ittelson and Ames, 1950; Knoll, 1959). It has been implicated as the cause of the lack of correlation between measures of AC/A ratios determined at fixed (gradient method) and multiple (calculated method) test distances. Very high correlations would be expected were these functions solely dependent on accommodative drive to the vergence system. With disparity vergence in an open-loop state, as is true during dissociated heterophoria measurements, and accommodation monitored to account for any AC/A-related change in the angle of deviation, testing distance has been found to influence convergence (Hofstetter, 1942; Morgan, 1944b; Alpern, 1955). Closed-loop disparity testing, as in the measurement of fixation disparity, also shows a distance effect on vergence, although the available data do not exclude accommodative interaction (Ogle and Martens, 1957; Ogle et al., 1967).

Evidence for a direct perceptual effect on vergence from perceived distance has been found in investigations using presentations of playing cards varying in size (Alpern, 1958b) and overlayed so that perception of the relative distances of the cards was reversed (Morgan, 1962). Both procedures yielded convergence changes independent of accommodation, with increased size or apparent nearness associated with increased convergence.

In their review on proximal vergence, Hokoda and Ciuffreda (1983) state (p.93):

> "Proximal vergence has been regarded as small and variable in magnitude, and of being somewhat elusive by nature of its having more of a psychological than physiological basis......proximal vergence may interact with the other vergence components, so its deletion from a model may account for subtle discrepancies found between experimental and model results....we propose that proximal vergence be included in future models of the vergence system".

2.3 - TONIC VERGENCE.

2.3A - Introduction.

It was outlined earlier that Maddox (1893) considered that the vergence response of the oculomotor system resulted from the additive combination of four components of convergence that operated in opposition to the divergent bias of the eyes. Maddox maintained that tonic convergence was responsible for bringing the eyes from some indeterminable position of divergent anatomical rest to a position of physiological rest. He observed that the eyes of refractively-corrected, alert subjects did not usually diverge when viewing a distant object (with one eye occluded) but rather, maintained a parallel, or slightly convergent ocular posture. He concluded that this was the result of tonic convergence, due to both muscular tone and the involuntary action of convergent innervation.

2.3B - The anatomical position of rest.

Alpern (1969a) considered the anatomical position to be:

> "....the position of the eyes if all of the extraocular muscles were devoid of all sources of innervation....A variety of evidence from observations of eyes under deep anesthesia, in sleep, in complete ophthalmoplegia, and in fresh cadavers suggest..... that Maddox's idea - that if the eye's muscles were completely devoid of innervation the eyes would be divergent - is probably perfectly valid." (p.112).

Cogan (1956) observed that the eyes of the dead attained a position ranging between "slight" divergence and axes parallel. Breinin (1957b) argued that the true anatomical position of the eyes could be observed in a subject under deep anaesthesia. Indeed, such measurements under general anaesthesia have revealed the eyes to rest at around 15 - 25 degrees of divergence (Meyers, 1951). Duncalf and Jampel (1961) also observed a position of rest of 15 - 25 degrees of divergence following complete ophthalmoplegia induced by d-tubocurarine. Abraham (1964) argued, on the basis of a comparative analysis of orbital anatomy, that the anatomical resting position probably changes over the life span due to changes in the extraocular muscles resulting from the activity of convergence. He proposed that an infant resting position of 45 degrees would become about 20 degrees less divergent in adulthood. It is possible that Abraham may have underestimated the magnitude of the developmental involvement, as Zimmerman et al. (1933) have reported an anatomical position of 71 degrees of divergence at birth.

Whatever the numerical value of the divergence, it is clear that in deep anaesthesia or death, and therefore in the absence of any innervation, the eyes diverge to a position determined by the mechanical characteristics of orbital tissues and the eyes' suspensory system.

2.3C - The physiological resting position.

Maddox recognised that the magnitude of tonic convergence varied among individuals and that such differences may influence binocular coordination and may be related to symptoms of ocular discomfort. He claimed that excessive tonic convergence produces latent overconvergence (esophoria), and that deficient tonic convergence produces latent underconvergence (exophoria). In order to maintain single binocular vision, these tendencies must be compensated for by additional reflex (disparity) convergence, which he assumed to be potentially stressful. It is evident that Maddox considered the physiological resting position of a normal subject to be the primary position.

There is much evidence, however, to suggest the existence of a more convergent or intermediate physiological resting state. This has indicated that the functional range of vergence is reduced whenever visual performance is degraded through impoverished viewing conditions, oculomotor stress, or in the early stages of visual development. In all cases, this reduction of binocular range appears to involve increasing overconvergence for distant stimuli and underconvergence for near stimuli. When there is no fusional response, as in darkness, subjects generally appear to maintain an intermediate level of convergence that shows substantial individual variation differences.

2.3C i - The effects of reduced illumination.

Ball (1951) reported that in addition to the normal eye becoming myopic under conditions of low illumination, there is a latent tendency for the eyes to converge. Ivanoff and Bourdy (1954) used a nonius alignment technique to measure vergence responses to a large letter "M" presented at a wide range of luminances. The vergence responses remained fairly accurate until the luminance was reduced to scotopic levels, whereupon increasing fixation disparities began to appear for both near and distant stimuli. Eight of their nine subjects exhibited progressively increasing convergent (eso) fixation disparity for the distant stimuli and increasing divergence (exo) fixation disparity for the near stimulus, finally reaching a fixed intermediate adjustment for both stimuli at the lowest luminance level. The ninth subject exhibited a similar reduction in fusional amplitude, except that his responses were progressively biased towards a parallel, rather than convergent, posture at the lowest luminance levels. The mean vergence position in darkness was found to be 56cm.

Fincham (1962) utilised infra-red photography to monitor the accommodation and vergence performance of subjects whilst attempting to "look into distance" in darkness. He found that the eyes of his 10 subjects assumed a convergent posture and noted that this was unrelated to the position of accommodation in darkness. Vergence ranged from slight divergence to a position 56cm from the subject, with a mean vergence position of 197cm.

Levy (1969) used a technique involving alternatively flashed monocular stimuli on a perimeter arc and the subjective perception of the 'phi-phenomenon', to estimate the "physiological position of rest" of 16 subjects under conditions of darkness. On average, the gaze of his subjects was found to deviate downwards by 5.85 degrees and 9.6 degrees inwards, at rest.

Owens and Leibowitz (1976a; 1980) utilised a nonius alignment technique to measure the vergence position under conditions of total darkness. The distribution of results found in the 1980 study are shown in fig.2.2 ("dark vergence" are given as degrees of convergence normalized to an interpupillary distance of 65mm; "dark focus" results are also given).

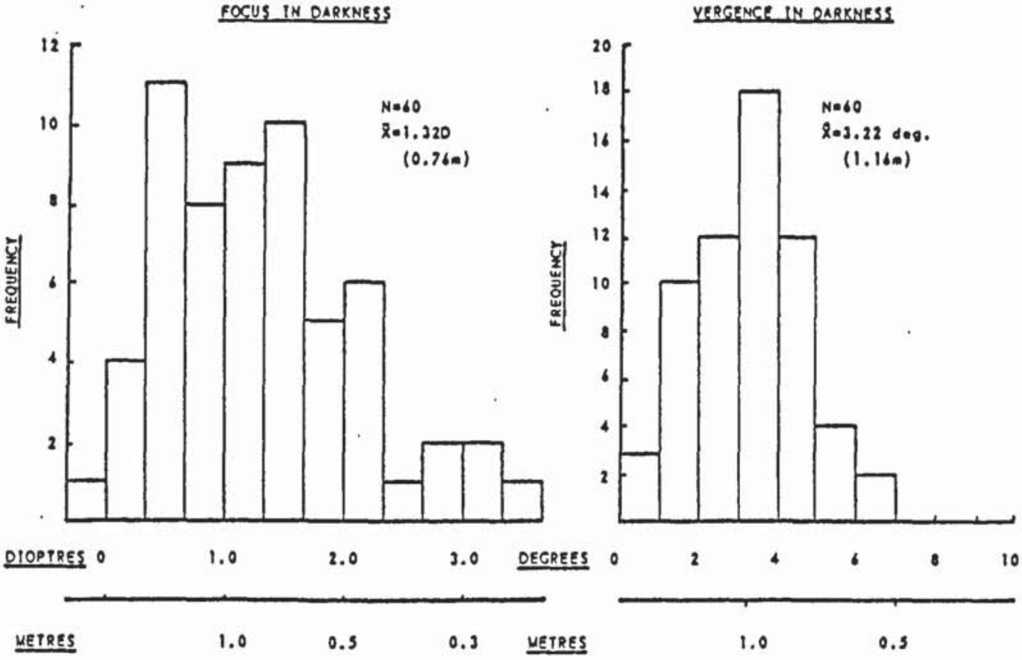

Figure 2.2 - The frequency distributions of the "dark vergence" and "dark focus of accommodation" of 60 college-age subjects (redrawn after Owens and Leibowitz, 1980)

It was found that these distributions differed in two ways. Firstly, the average values corresponded to different distances. The mean "dark focus" was 1.32 D or 76cm, while the mean "dark vergence" was 3.22 deg. or 116cm. Secondly, the "dark focus" distribution shows greater intersubject variation than the "dark vergence" distribution. In darkness, the position of ocular focus varied from low hyperopia to an equivalent distance of 28cm, whereas "dark vergence" ranged from infinity (with axes parallel) to about 50cm.

One way to interpret these results is to regard the "dark vergence" as a functional resting state toward which vergence passively returns when the stimulus is degraded (in a similar manner to that of accommodation). With the relatively high levels of stimulation in the everyday environment, the vergence response is invariably accurate. When the stimulus quality is reduced, however, the vergence response may be progressively biased toward the observer's particular resting or tonic position.

2.3C ii - The effects of oculomotor stress.

The disruption of fusional eye movements is one of the quickest and most devastating effects of physiological stress on visual performance; and is most commonly experienced as diplopia during illness, ethanol intoxication, or following injury. Several investigations (summarized in tables 2.1 and 2.2) of visual performance under physiological stress indicate that decreased fusional amplitude is the primary effect of anoxia and such drugs as nitrous oxide, barbiturates, marijuana and ethanol.

Table 2.1 - Evidence for a bias of vergence towards an intermediate tonic position under conditions of oculomotor stress.

AUTHORS	N	FACTOR	EFFECTS ON VERGENCE
Wilmer & Berens (1918)	-	Anoxia	1) reduced fusional reserves 2) recession of near point of convergence 3) increased esophoria at distance
Velhagen (1937)	-	Anoxia	1) increased esophoria at distance
Adler (1945)	8	Anoxia	1) increased esophoria at distance 2) decreased divergent fusional reserves 3) increased convergent fusional reserves
Amos (1976)	10	Nitrous oxide	1) increased esophoria at 6m 2) insignificant change in heterophoria at 33cm
Westheimer (1963a)	-	Barbiturates	1) increased esophoria at 5m 2) increased exophoria at 33cm 3) reduction of fusional reserves 4) recession of the near point of convergence 5) decreased AC/A ratio
Adams (1977)	10	Marijuana	1) increased esophoria at 6m (mean = 2 Δ)

Table 2.2 - Effects of ethanol on vergence as further evidence for an intermediate tonic vergence position.

AUTHORS	N	EFFECTS OF ETHANOL ON VERGENCE
Powell (1938)	7	1) increased esophoria at 6m 2) increased exophoria at 33cm (mean = 2_Δ) 3) recession of near point of convergence
Colson (1940)	21	1) increased esophoria at 6m 2) decreased lateral fusional reserves 3) recession of near point of convergence
Newman & Fletcher (1941)	-	1) 50% reduction of "eye coordination" 2) reduction in distance judgement 3) slight decrease in depth perception
Bietti & Giardini (1949)	-	1) increased esophoria at distance 2) increased exophoria at near 3) recession of near point of convergence
Brecher et al. (1955)	14	1) increased latency of fusion 2) increased esophoria at 6m 3) increased exophoria at 33cm 4) no change in heterophoria at ~ 60cm 5) recession of near point of convergence
Seedorff (1956)	40	1) increased esophoria at distance 2) reduced fusional reserves 3) no change in stereopsis
Masters (1964)	-	1) increased esophoria at distance 2) increased exophoria at near 3) increased latency of fusion
Wist et al. (1967)	9	1) esofixation disparity at 7m 2) stereoacuity unaffected
Cohen & Alpern (1969)	6	1) reduced AC/A ratio 2) increased esophoria at distance 3) increased exophoria at near 4) no confirmation of 60cm "position of rest"
Moskowitz et al. (1972)	-	1) increased esophoria at 6m (mean = 1.7_Δ) 2) reduced divergent fusional reserves
Adams (1977)	40	1) increased esophoria at 6m (mean = 4_Δ)
McNamee et al. (1981)	17	1) increased esophoria at distance
Hogan & Linfield (1983)	10	1) increased esophoria at 6m (mean = 2.35_Δ) 2) increased exophoria at 33cm (mean = 1.15_Δ) 3) AC/A ratio reduced by 25% 4) reduced divergent fusional reserves 5) 7 subjects developed esofixation disparity within 1 hour 6) recession of near point of convergence by 2cm 7) no change in amplitude of accommodation

Since these stressors had no appreciable effect on accommodation or conjunctive eye movements, both Adler (1945) and Westheimer (1963a) proposed that the effect is due to diminished efficiency of the central mechanism controlling vergence. According to this view, whenever these 'central processes' are depressed, the functional range of binocular vergence decreases and is biased towards an intermediate tonic position. In this case, the efficiency of the vergence system is diminished due to a physiological depression of central processes rather than to reduced information concerning the binocular registration of the retinal images, as found under conditions of degraded visual stimulation such as darkness. Thus the effects of stress and darkness on heterophoria, fixation disparity, fusional reserves, AC/A ratio and the near point of convergence can be interpreted as consequences of a common mechanism, the passive return of vergence to its intermediate tonic position.

2.3C iii - The effect of peripheral stimuli on vergence.

In 1858, Panum defined an area which can be thought of as representing the limits of accuracy within which ocular vergence must function in order to maintain single binocular vision. As long as fixation is within the limits of Panum's area, non-motor fusional processes operate to combine retinally disparate images and thus yield single binocular perception. Similar to the effects of reduced luminance, studies of vergence eye movements for peripheral stimuli indicate that fusional responses are also biased toward an intermediate tonic position as the retinal eccentricity of binocular stimuli increases.

Ogle and his co-workers conducted a series of studies which indicate that increased eccentricity of fusional stimuli results in decreased vergence accuracy (e.g. Ogle et al., 1949; Ogle and Prangen, 1949). They utilised prisms to manipulate the vergence response required to maintain fusion of dichoptic peripheral stimuli and found decreased accuracy with increased eccentricity of stimuli for both forced convergence and forced divergence.

More recently, Francis and Owens (1983) measured the accuracy of vergence responses for dim binocular stimuli that were viewed at various retinal eccentricities over distances ranging from 28.5 to 342 cm. Their results confirmed the earlier results of Ogle and his co-workers, that fixation disparity increases as fusable contours are confined to increasingly peripheral portions of the visual field. Their results also demonstrate that this reduction in vergence accuracy is obtained under conditions of "real space" as well as under the more artificial conditions of prism duction. Of greatest interest in the present context, however, is the observation that, as with reduced luminance, the fixation disparity arising from such peripheral stimulation can be characterized as a passive 'lag' and 'lead' of vergence responses towards the subjects tonic vergence position, for stimuli positioned nearer and beyond the tonic vergence position, respectively.

Ogle and his co-workers attributed their findings of the changes in fixation disparity to the increased size of Panum's areas in the periphery. Since the threshold for diplopia (Mitchell, 1966a; 1966b) increases with retinal eccentricity (Ames et al., 1932), increased fixation disparity can be tolerated without disruption of the fusion process. Mitchell (1966b) states that the variation in size of Panum's area (and therefore threshold for diplopia) "arises from difficulty in the recognition of diplopia". Therefore, in the retinal periphery there is a greater margin of error for vergence without perceptual diplopia. It is also consistent with the decreased optical resolution of images in the retinal periphery (Jennings and Charman, 1981), and with the physiological determinations of increased receptive field size with increased retinal eccentricity and the concomitant decrease in physiological resolution (Hubel and Wiesel, 1974). At the same time, the peripheral manipulations of the stimulus also degrade the sensitivity to spatial contrast, thus diminishing accommodative responsiveness (Owens, 1980) and, presumably, the strength of accommodative vergence. The overall effect is that fusional and accommodative vergence responses diminish, revealing the underlying tonic vergence.

2.3Civ-Vergence and immature visual development.

Recent studies of the development of binocular fixation in human infants have revealed parallels with the effects of stimulus degradation on the vergence responses of the visually mature. Slater and Findley (1975) photographed the eye positions of 12 neo-nates ranging from 1 to 8 days of age, as they viewed two vertical rows of lights at distances of 5, 10 and 20 inches. The vergence responses were often found to be within 0.5 of a degree of the appropriate change for the 10 and 20 inch stimuli, although not particularly stable, with standard deviations of 2.3 and 2 degrees, respectively. Even greater fluctuations were found for the 5 inch stimuli.

Aslin (1977) used video-photography to evaluate the vergence responses to dynamic stimuli for infants ranging in ages from 1 to 6 months. He demonstrated that with increased age (past 3 months) the responses became more rapid and accurate, although consistent responses were not attained until 6 months of age.

Aslin and Jackson (1981) found that the "dark vergence" position of infants corresponds to the same distance range as their most accurate vergence responses under normal visual conditions. They found that with one exception out of 18 infants, all exhibited "dark vergence" positions of less than 1 metre. This finding was replicated in two subsequent studies (Aslin et al., 1982; Aslin and Dobson, 1983), in which simultaneous estimates of the vergence and refractive states were also made under conditions of total darkness (using infra-red photography of the 1st purkinje image - for vergence, and photorefraction - for accommodation). They found only a minimal correlation between these two measures.

It is worth noting that the average tonic vergence position of the visually immature appears to be considerably more convergent than that of adults. This difference is significant when one recalls that the anatomical resting position of infants is probably more divergent than that of adults (Abraham, 1964) and would imply that the magnitude of manifest tonic vergence is much greater in infancy than in later life. Such an inference is in agreement with an earlier claim by Adler (1953) that the prevalence of concomitant esotropia in the first years of life is related to their "normally excessive" levels of tonic vergence. Aslin (1981) concluded that the development of accurate binocular fixation depends upon concomitant improvements in the infants sensitivity to retinal disparity and hence the general tendency of the vergence system to be biased towards its tonic position by an amount limited by the extent of Panum's area.

2.3C v - Conclusion.

It is evident, therefore, that the quality of the vergence response is dependent upon the quality of the stimulus, in much the same way as was found for the accommodative system. The various factors that may influence the effector characteristics of the stimulus have been outlined in the general introduction (pp. 4 - 5).

In the absence of adequate visual stimulation (e.g. total darkness) the eyes assume an intermediate tonic resting posture of about 3 degees of convergence. It would appear that under conditions of degraded or peripheral stimuli, oculomotor stress, or immature visual development and the diminishing influence of disparity and accommodative vergence, the vergence system passively tends towards an intermediate convergent position that corresponds to that attained in total darkness. It has yet to be demonstrated that the intermediate position to which the vergence system appears to be passively biased, under the various causal conditions (e.g. degraded visual stimulation, ethanol, etc.) is analagous to the tonic position found in total darkness. This aspect will be examined in more detail in Chapter 5.

CHAPTER 3

THE DEVELOPMENT OF A CENTRAL METHODOLOGY

3.1 - THE MEASUREMENT OF TONIC ACCOMMODATION

As outlined in the general introduction (p.6), knowledge of the magnitude of tonic accommodation (TA) would provide information on the 'steady-state' level of the accommodative system whilst free from the complications and constraints of stimulus-dependency. The first part of the present chapter is concerned with the methodological aspects involved in the measurement of TA.

3.1A - THE LASER OPTOMETER.

3.1A i - Laser light and speckles.

When the continuous Helium-Neon gas laser was first operated (White and Rigden, 1962) and the beam projected onto the laboratory wall, it was apparent to those present that there was something very unusual about the nature of the scattered laser light[1]. Rigden and Gordon (1962) described the phenomenon as follows:

> "The bright area of red light showed a remarkable granular or peppery nature not present in ordinary light. The granularity also appeared to scintillate since the granular pattern moved when there was relative motion between the surface and the observer."

It was observed by Rigden and Gordon that the speckles did not appear in the direct beam path, but in the reflected light and were not a purely visual phenomenon since they occured in all image

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[1] The phenomenon is present in the scattered light from lasers of other wavelengths, but had not been observed earlier. If however, conditions are suitable (e.g. with various filters), speckle may be observed in other, less coherent light forms (Palmer, 1976; Walker, 1982).

forming devices.

The speckles may be produced by reflecting laser light from a matte, diffusing surface. The random irregularities of the matte surface introduce a phase difference in the reflected laser light, such that interference fringes are produced that differ in phase, orientation, spacing and intensity; with the result that the observer perceives a random pattern of laser speckles.

3.1A ii - The use of laser light in an optometer.

Oliver (1963) observed that the particular pattern seen by the subject at any given instant is determined by the focal state of the eye. Moreover, head movements caused the "grains" to move or "flow". It was found that the pattern of speckles appeared to move "with" (i.e. in the same direction as) the head movement when the observer's retina was conjugate with a plane beyond the reflecting surface, and "against" (i.e. in the opposite direction) when the eye was conjugate with a plane in front of the reflecting surface. When the subject was focussed in the plane of the surface, the speckles were seen as randomly "boiling" and appeared to have no particular direction of flow.

This descriptions of Oliver (1963) and of Rigden and Gordon (1962), are the first documented reports that the laser could be used to determine the character of any ametropia present in the eye of an observer. Knoll (1966) incorporated the phenomenon of speckle motion into an optometer, generally known as a He-Ne laser optometer. In his apparatus, head movement was conveniently replaced by movement of the reflecting surface, a slowly rotating (1 rev/hour) cylindrical brass drum (a technical description of the optical considerations may be found by reference to, Ingelstam and Ragnarsson, 1972; Yamaguchi and Komatsu, 1977; Iwai et al., 1982; Churnside, 1982). Knoll's pioneering work showed an encouraging correlation between the results obtained with his laser optometer and those of more conventional subjective techniques. Subsequent investigators have confirmed Knoll's earlier confidence in the technique as a method of determining the position of ocular focus (e.g. see Baldwin and Stover, 1968; Dwyer et al., 1972; 1973; Jennings and Charman, 1973; Malacara, 1974; Charman and Jennings, 1976; Phillips et al., 1975; 1976; Haine et al., 1976).

3.1A iii - The plane of stationarity.

It has been shown (Charman, 1974) that the "plane of stationarity" of the speckles is a function of both the radius of the drum used and the obliquity of the incident coherent illuminating wavefront. In a later paper, Charman (1979) revised his earlier solution (based on a geometrical argument involving the optical path differences between rays of light scattered from pairs of points on the surface of the drum) evolved to better order of approximation. This was further revised (Charman and Chapman, 1980) utilising the approach of Fercher and Sprongl (1975) - originally utilised in the estimation of optical lens power. Despite certain theoretical objections raised by Bahuguna and Malacara (1983), (e.g. the effect of angle of incidence or obliquity of the laser light to the reflecting surface), the plane of stationarity may be approximated to occur one-half radius in from the reflecting surface of the drum (Charman, 1974).

3.1A iv - Correction for chromatic aberration.

Inglestam and Ragnarsson (1972) had noted a tendency for the results of Helium-neon laser refraction to be 0.25 dioptres too negative, when compared to more conventional subjective refraction. They concluded that this discrepancy was due to the effect of the longitudinal chromatic aberration of the eye on measurements made with the red light output of a laser of 632.8nm wavelength, when compared to the peak of the "daylight visibility curve" (i.e., the photopic relative luminosity curve) which they reasoned would have a maximum at 555nm. They implied that this wavelength difference corresponded to a correction of +0.32D, according to Le Grand (1956) and +0.38D, according to Ivanoff (1964). Inglestam and Ragnarsson found these figures to agree well with the observed laser refraction values when consideration was taken of the finite distance of their rotating drum (correction -0.07D).

More recent studies (e.g. Leibowitz and Owens, 1978; Heron et al., 1980) utilising laser optometry have applied a correction of +0.33D to their results, following the example set by Owens and Leibowitz (1976b), with reference to the data of Bedford and Wyszecki (1957) and correcting for a reference wavelength of 555nm.

The magnitude of correction required to account for the longitudinal chromatic aberration of the eye will be discussed at some length in section 3.5C.

3.1B The application of laser optometry to the study of ocular accommodation.

Laser optometers have also found considerable employment in the study of various aspects of ocular accommodation (e.g. Hennessy and Leibowitz, 1970; 1972; Leibowitz and Owens, 1975a+b; 1978; Hennessy, 1975; Hennessy et al., 1976; Johnson, 1976; Owens and Leibowitz, 1975; 1976a+b; 1980; Charman and Tucker, 1977; 1978a+b; Owens, 1979; 1980; Heron et al., 1981; Maddock et al., 1981; Owens and Higgins, 1983).

The application of laser optometry to the study of ocular accommodation has a number of distinct advantages over alternative techniques (e.g. infra-red):

a) the speckle-pattern perceived by the observer is formed by interference of the reflected wavefronts in the plane of the retinal receptors;

b) the end-point is independent of the pupil size. The pupil limits the potential range of angles between the interfering wavefronts responsible for the retinal image. The size of speckle is therefore, indirectly proportional to pupil size;

c) the speckle pattern contains information at all spatial frequencies and therefore, has a wide power spectrum;

d) the laser speckles will always appear in focus, regardless of the accommodative state and will therefore (theoretically) offer little accommodative stimulus;

e) the observer is merely required to describe the relative motion of a speckle pattern, which does not depend upon a stimulus-dependent and subjective assessment of blur; the observer is therefore given little or no indication of actual position of focus;

f) there is little or no restraint on head position;

g) the system is essentially "free viewing", apart from the introduction of a beam-splitting mirror; and last but not least these days,

h) the laser is relatively inexpensive.

3.1B i - Laser speckle exposure time.

It is imperative in any study of ocular accommodation that the method chosen with which to measure the accommodative state of the eye does not itself provide an alternative stimulus to the accommodative system. In the application of laser optometry to the assessment of accommodation under conditions of darkness, the only visual stimulus is the laser speckle itself. Most recent studies utilising this application of laser optometry limit the observation time of the laser speckle, via a shutter or chopper device, to exposures of 500ms and reference the choice of shutter speed to the study of Hennessy and Leibowitz (1970). This study monitored the accommodative responses of four observers to laser light presented at three intervals of 200, 500 and 1000ms, using an infra-red optometer, whilst they performed a search task through a low-powered microscope. An effect on accommodation was judged to have taken place, only if a change exceeded 0.5D for more than 300ms or rose to a level greater than 0.3D for 1000ms. Although one of the subjects was found to exhibit accommodative responses to the laser exposure (according to the regime outlined), Hennessy and Leibowitz (1970) concluded that the presentation of the laser speckle did not itself induce accommodative changes. It is interesting to note their comments:

> "Because the latency (Cornsweet and Crane, 1970) of the accommodative response is 0.4s, a laser test flash of approximately this duration would theoretically be expected to reflect the state of accommodation that existed before its introduction.......To measure accommodation, the laser light is briefly exposed (approximately 0.5s)...."

For a more complete discussion on this aspect, see section 3.5A.

3.1B ii - Application of the Badal principle.

Hennessy and leibowitz (1972) combined the laser optometer with the principle of the Badal optometer (Southall, 1933; Ogle, 1968). In this context, the Badal principle is based on the observation that if the eye is placed at the second focal point of a positive lens, the ocular accommodation required to focus the image of the drum surface varies linearly, as a function of the distance of the drum surface from the lens. When the drum surface is placed at the anterior focal plane of the Badal lens, the eye will view the image to be placed at optical infinity and is conventionally assumed to require no accommodation. The relationship between the optical distance of the surface image and the surface position is given by:

$Q = F^2u - F$........where Q = image distance (dioptres)
F = power of lens (dioptres)
u = distance between drum surface and lens (metres)

Such an arrangement effectively encompasses optical infinity within the focal length of the Badal lens: as a result, the optometer is capable of being compacted with little reduction in its range. Further advantages in the use of the Badal principle include constancy of field size and luminance.

3.1C - METHODOLOGY IN THE MEASUREMENT OF TA.

3.1C i - The Badal-laser optometer.

Tonic accommodation measurements were obtained in total darkness using a Badal-laser optometer adapted from the design utilised by Hennessy and Leibowitz (1970) and is illustrated in figure 3.1. The laser used was a He-Ne laser (Scientifica-Cook, class 2) with a stabilized output of 1mW[1], A purpose-designed and built "beam expander/collimator unit" (B.E.C. unit - for details see Appendix I) was used to diverge and collimate the output from the laser. A Uniblitz 225L electronic shutter with a 25mm aperture was utilised to present the expanded laser beam for a period of 300ms, under the control of an Apple IIe microcomputer (this exposure time was selected on the basis of the results of section 3.5A). A series of three front-surface aluminium-coated mirrors (Ealing-Beck) were used to reflect the 25mm collimated beam of laser light on to the upwards-moving surface of a 6.6cm

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[1] The level of radiation for an exposure of 300ms was measured with a U.D.T. light meter and found to be 7×10^{-8} J; a level well within the maximum permissible figure of 0.069 J, (C.V.C.P., 1978).

FIGURE 3.1

THE LASER OPTOMETER

L = 1mw He-Ne laser

E = Beam expander/collimator (BEC)

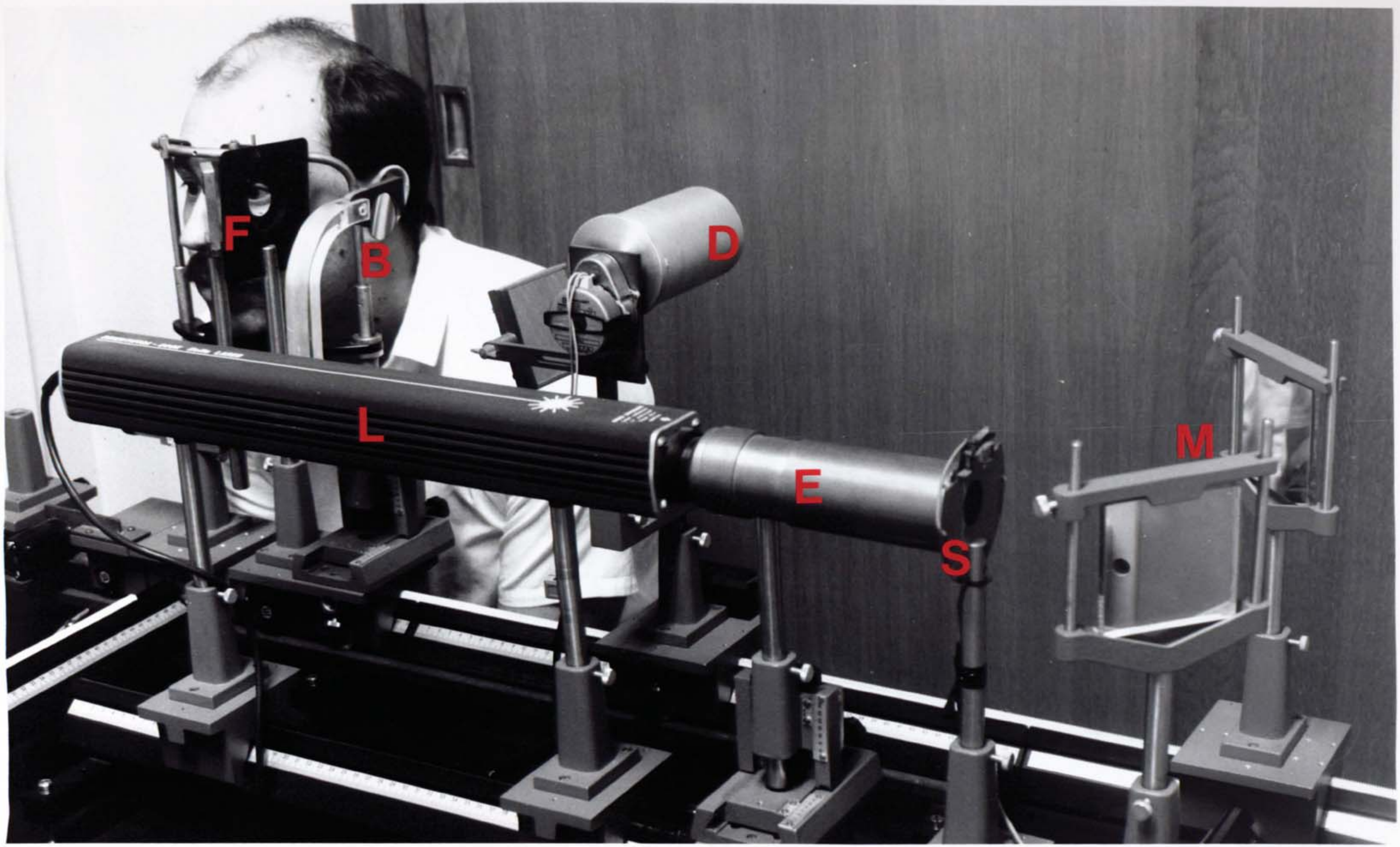
S = Shutter

D = Rotating drum

B = Badal lens

F = Field stop

M = Front-surfaced mirrors


F
B
D
L
M
E
S

diameter, slowly-rotating, cylindrical drum that had been coated with a layer of bond paper and sprayed with silver gloss paint (for a discussion on the selection of surface coating, see appendix II). A Crouzet electronic motor (type 82-344) was use to rotate the drum at 0.5 r.p.m.; corresponding to an optimal angular velocity of 3 deg/sec - for further discussion see Whitefoot (1977).

The resultant speckle pattern would be seen by the observer whilst looking straight ahead, via a beam-splitting mirror (Ealing-Beck, 50:50 semi-silvered mirror) placed in front of the observer's left eye. A +5D Badal lens was placed 216mm from the cornea of the observer - this is the distance appropriate for this power of lens within the Badal system - see section 3.1B ii). A 25mm field stop was placed between the Badal lens and the beam-splitter to reduce peripheral aberrations within the circular speckle patch; and gave an angular subtense of speckle patch of 13.4 deg. A head rest was used to maintain the observer's head in the optimal position.

The entire badal-laser optometer was mounted on Ealing-Beck Meehanite precision optical bench equipment, permitting accurate positioning of each component of the optometer via a rack and pinion system. The rotating drum was mounted on a carriage and locked onto the sliding rack, which was held within a groove on top of the optical bench system. Two further carriages were placed at each end of the rack and locked into position and the rack was moved along the groove by rotating the pinion drives of either carriage: the observer operated one pinion drive and the experimenter could operate the other. In this way, the drum could be moved away from, or towards the observer in response to his/her subjective appreciation of speckle motion. The incorporation of a prism into the observation system of the laser optometer (to assist in the assessment of the end-point), had been considered and subsequently rejected at an early stage in its development (see appendix III).

As the rack moved along the bench, it rotated a cog-wheel attached to the spindle of a micropotentiometer (output linear from 0-5volts - see Appendix IV). The output of the micropot' was fed into an Apple IIe microcomputer via a CIL PCI 6000 computer interface and displayed on the TV-monitor (situated in front of the experimenter) as a drum position in dioptres (the role of the computer in the methodological control will be further discussed in section 3.4A). The brightness output of the screen could be reduced until the read-out was just discernable and could provide no ambient illumination to the room.

3.1C ii - Procedure in the measurement of TA.

Each observer was given a full eye examination to ascertain distance refraction, oculomotor balance and visual acuity, and to check for any ophthalmological defect: in the measurement of TA he/she would wear his/her accurate distance refraction placed in a trial frame, suitably adjusted for their infinity inter-pupillary distance (I.P.D.). The observer's attention was then drawn to: the pinion drive that controlled the drum position; the footswitch that both initiated and restarted the experimental cycle (when pressed); and to the snellen letter chart that could be viewed via a mirror directly ahead of them, at the other end of room. This latter instruction was given to the observer to demonstrate that, although they would be sitting in total darkness within a relatively small room, they could still exercise their full range of accommodation. They were then asked to put on the headphones, through which they could hear "white noise", the auditory cue warnings and any additional instructions from the experimenter.

The observer would then be instructed to place his/her head in the headrest, whereupon the room lights were extinguished. After a dark adaptation period of 5 minutes, instructions would be given to press the footswitch to initiate the experimental cycle: a comfirmatory "bleep" would then be heard by both the observer and experimenter. After a period of 8 seconds, a second "bleep" would be heard: this is the auditory cue that would warn the observer that a flash of laser speckle was about to occur following a random time lapse of between 1 and 5 seconds. After the random time had elapsed, the shutter would present 300ms of laser speckle into the visual field of the observer: whose task was to distinguish the direction of motion, if any, of the laser speckles and report his decision to the experimenter. If the subject reported "up", this would indicate to the experimenter that the observer was focussed relatively myopically, with respect to the plane of stationarity of the drum, requiring an anti-clockwise rotation of the pinion drive; thus moving the drum closer to the observer. Conversely, if the observer reported "down", this would indicate that he/she was focussed relatively hyperopically, with respect to the drum, requiring a clockwise rotation of the pinion drive; thus moving the drum further away from the observer. If however, the observer reported "no motion" or "boiling" it would be apparent to the experimenter that the observer was conjugate with at the plane of stationarity of the drum and that his position of ocular focus in total darkness (i.e. TA) had been attained.

The process would be repeated, after the experimenter had randomly displaced the laser drum by ± 0.37D, until three consecutive end-points were achieved and varied by no less than ± 0.25D. This level of reproducibility was attainable after an average period in total darkness of about 7 mins, depending upon experience of the observer. The experimenter would then use the third end-point as the reference position for a subsequent staircase procedure[1]. The staircase method employed in the present study is described as follows: the experimenter randomly displaces the laser drum ± 0.37D from the reference position and then implemented a random staircase procedure in steps of 0.12D, in order to determine five transition points (i.e. an "up" to "down" response or vice-versa), the position of the drum was continuously monitored on the computer monitor. The TA value was taken to be the mean of the five transition points and recorded.

If however, a series of TA measurements were required (e.g. the monitoring of TA over a particular length of time), a series of 5 transition-point staircases would be implemented, with each subsequent trial using the last transition point of the previous trial as its reference point.

3.2 THE MEASUREMENT OF TONIC VERGENCE.

As outlined in earlier sections, the vergence system is biased towards its intermediate tonic resting state (TV) under conditions of degraded visual stimulation, oculomotor stress, or immature visual development. Knowledge of the magnitude of TV would provide information on the 'steady-state' level of the vergence system, whilst free from the complications and constraints of stimulus dependency: a convenient stimulus-free visual environment may be found under conditions of total darkness. A suitable methodology is required therefore, that will enable the measurement of TV in total darkness whilst not itself influencing the result.

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[1] The various psychophysical methods applicable to the measurement of TA have been fully discussed by Heron et al. (1981) and Miller et al. (1983).

3.2A - THE METHOD OF VERNIER ALIGNMENT.

Various methods have been used in the past to measure ocular vergence under conditions of darkness: many of these have been discussed in section 2.3C i: the method of choice in the present study is that of vernier alignment. The validity of the vernier alignment method was demonstrated by Hebbard (1962) by direct comparison of the results of objective (first Purkinje image photography) and subjective (modified haploscope) measurements of ocular vergence. It has been demonstrated to be accurate in the estimation of ocular misalignments down to 0.3 mins of arc (Duwaer et al., 1982). Using this method, the perceived misalignment of two physically aligned dichoptic stimuli - each seen by one eye only - is taken to be equal to the magnitude of ocular misalignment.

3.2B - METHODOLOGY IN THE MEASUREMENT OF TV.

3.2B i - The vernier alignment device (VAD).

Advantage is taken in the present study of the relatively recent technological advances in the field of light emitting diodes (LEDs) - for further discussion see the studies of Brown (1974); and Nygaard and Frumkes (1982). At the onset of the present study a unit was designed to monitor ocular vergence under conditions of total darkness. This unit incorporated a bank of red LEDs (of output 626nm) arranged in a single, vertical and 50mm long line, at a height of 30 cm above the optical bench (the same height as the beam-splitting mirror incorporated into the laser optometer). The upper and lower halves of the bank of LEDs were oppositely polarized, thus forming the dichoptic vernier lines. Corresponding polarized filters were placed in front of the observer's eye's, such that the left eye would see the upper half only and the right eye would see the lower half only. The LEDs were energized for

125ms (see section 3.5B).

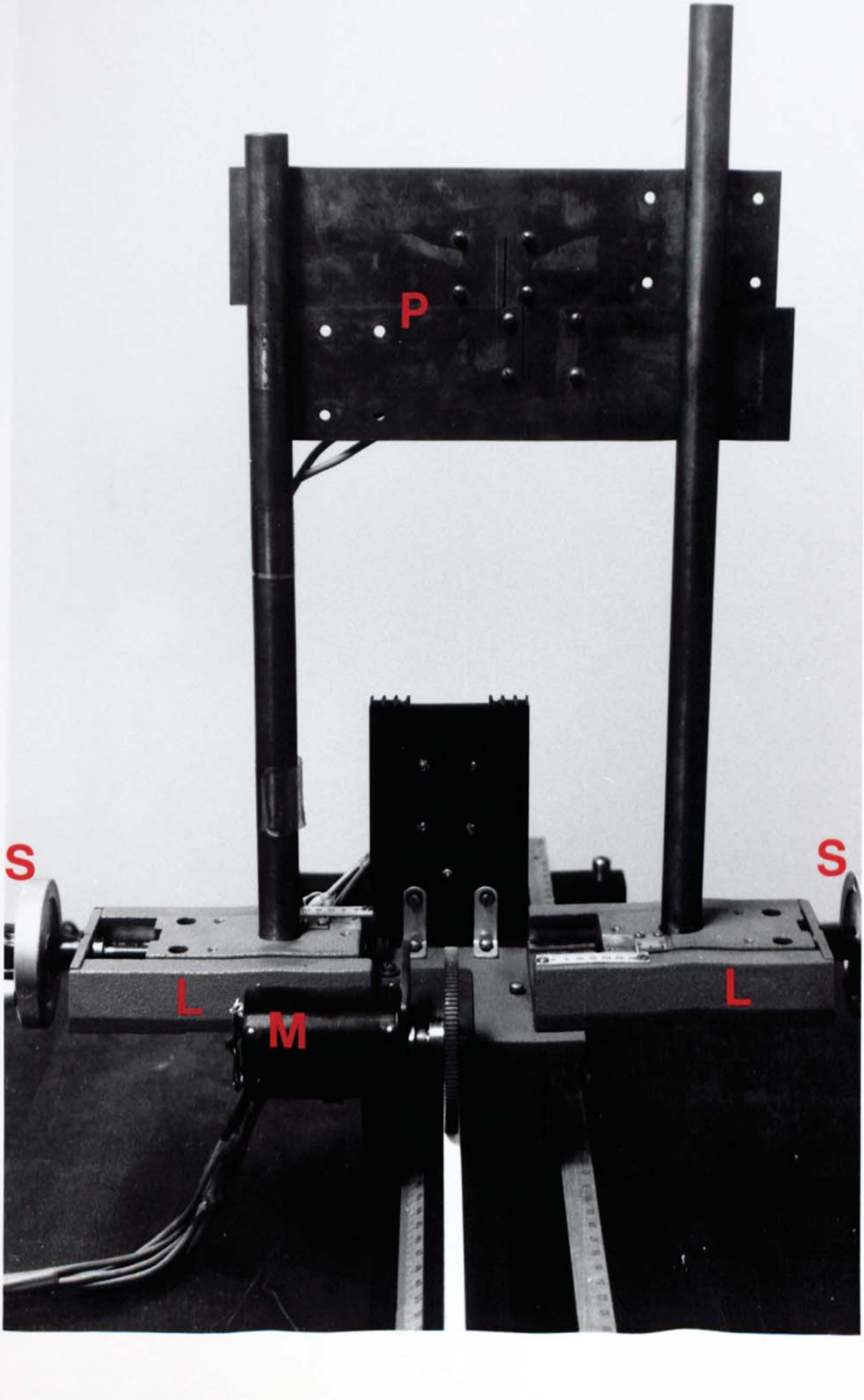
TV was measured by moving the unit along the optical bench until the observer reported apparent alignment of the vernier lines. A number of problems with this early design of unit became evident during use. The first problem was its inability to cover the range of TV measurements found in the literature (e.g. from 50cm to infinity - see fig. 2.2); a second problem became evident when the TV position differed from the TA position by more than 20cm, namely that the vernier lines were obviously blurred, thus degrading the observer's ability to accurately discriminate the state of alignment of the vernier lines.

A second unit was subsequently designed (figure 3.2) to specifically overcome the problems inherent in the earlier design. In this second vernier alignment device (VAD) a vertical line groove (25mm x 0.5mm) was cut into a metal plate, immediately behind which was arranged a bank of LEDs (of output 626nm) and their accompanying electrical circuitry. Apart from the groove, through which the light was viewed, the LEDs were sealed onto the rear of the plates. A second plate was similarly constructed and placed with its edge in contact with the edge of the first plate such that, when aligned, both grooves formed a continuous, vertical 50mm groove. Polarizing filters were arranged (as in the original design of unit) such that the left eye would see the upper bank of LEDs and the right eye would see the lower bank of LEDs: thus forming the dichoptic vernier lines. Each plate was supported by a pillar, which was independently mounted on one of two lateral-motion devices (adapted from an Ealing-Beck 22-4071, transverse slide). Both lateral-motion devices, together with their pillars and plates were mounted on a single carriage on the optical bench system. The lateral adjustment of the plates was

FIGURE 3.2

THE VERNIER-ALIGNMENT DEVICE (VAD)

P = Moveable plates with vertical grooves
(behind which are mounted the oppositely
polarized LEDs)
L = Lateral motion unit
S = Thumb-screw
M = Micropotentioneter


P
S
S
L
L
M

independently controlled by the rotation of two thumb screws, one at either side of the VAD unit. The actual separation of the grooves on the plates could be monitored to an accuracy of 0.1mm with reference to a vernier scale at the base of each pillar.

Also mounted on the carriage was a micro-potentiometer (similar to that used in the measurement of TA), arranged such that its output was proportional to the linear adjustment of the VAD unit, via a cog-wheel in contact with the fixed rack system of the optical bench (for details concerning the linearity of the micropot' see Appendix IV). The output from the micropot' was calibrated, via the programming of the microcomputer, and displayed on the monitor alongside the TA result.

3.2B ii - Procedure in the measurement of TV.

Before the measurement of TV commenced, the position of the VAD unit was altered (with reference to the video-monitor) until it coincided with the position of TA of the observer, as found earlier. This stratergy ensured that accommodation could not influence the measurement of vergence and that the vernier lines were always in focus. Thus the measurement of TV invariably followed the measurement of TA.

The observer wore the oppositely polarized filters (mentioned above) over their distance-P.D. centred refractive correction and remained with their head in the same position as for the TA measurement. The observer was then asked to press the footswitch (which this time had been programmed to initiate the experimental loop incorporating the LEDs of the VAD unit). After the random pause, the LEDs would be energized for 125ms (taking into account both the fusional response latency - Westheimer and Mitchell, 1956 - and the results of the pilot study into the effects of various exposure latencies on the variance of TV - see section 3.5B).

The observer was asked to describe the relative positions of the vernier lines in terms of the position of the top line as compared to the bottom line (i.e. "top to the left of the bottom", or "top to the right of the bottom", or "top in line with the bottom"). If the upper vernier line appeared to the left of the bottom, this indicated that the observer was over-converged in relation to the plane of the LED-grooves on the VAD. To reduce the apparent lateral separation of the two lines in this instance, the experimenter could rotate either or both thumb-wheel screws (of the lateral motion devices at the base of each pillar) in a clockwise direction. The cycle was repeated. If the upper vernier line appeared to the right of the lower vernier line, this indicated that the observer was under-converged in relation to the LED-grooves. To reduce the apparent lateral separation in this instance, the experimenter can rotate the thumb-wheel screws in an anti-clockwise manner; the cycle would then be repeated. The psychophysical procedure for determining TV was similar to that for the determination of TA (but with a step-size of 2").

3.2B iii - Calculation of TV.

At the end-point of the TV measurement with the lines apparently aligned, the actual separation between the vernier lines was indicated by the vernier scale readings at the base of each pillar on the VAD unit. TV was calculated from; the actual separation of the lines, the P.D. of the observer and the distance between him/her and the VAD unit (usually the TA distance, unless in those cases where the observer's TA was at the extremes of the range, whereupon the VAD unit would be placed as close as possible to the TA). A correction factor was applied to take account of the effects, on the position of the vernier lines, of any prismatic factors induced in those observers wearing a distance centred spectacle correction. The vergence result obtained is the position of each eye in relation to the primary position: i.e. a tonic vergence result of 3 degrees would indicate that each eye had converged by 3 degrees from the primary position under conditions of total darkness. The calculations were performed by the programming of a microcomputer: details of the program listing and accompanying notes may be found in Appendix V.

3.3 - THE MEASUREMENT OF HORIZONTAL PUPIL DIAMETER IN TOTAL DARKNESS.

It is known that the response of the pupil is interdependent with the accommodative and vergence systems within a synkinesis in the response to vision at near (Duke-Elder, 1973; Burian and Von Noorden, 1974; and Davson, 1980), and it has been shown that the accommodative response can be influenced by pupil diameter and associated changes in the depth of field (e.g. Ripps et al., 1962a; Hennessy et al. 1976). This synkinesis (inclusive of pupil) has yet to be investigated however, under conditions of total darkness. The measurement of pupil diameter under conditions of total darkness may reveal further information concerning the nature of this synkinesis. It will similarly provide additional information concerning the effect of various autonomic effector agents upon the ciliary and iris muscle structures.

3.3A - Methodology in the measurement of pupil diameter.

Pupillography has been performed by a variety of techniques (reviewed by Hakerem, 1967; Taylor, 1977), ranging from the simple and subjective pupillometers (e.g. Moss, 1932; Clark-Jones, 1939), to the complex and objective infra-red television video systems (e.g. Lowenstein and Loewenfeld, 1958; Green and Maaseidvaag, 1967).

In this study, pupil diameter will be measured in total darkness; this clearly inhibits the use of subjective techniques, for obvious reasons. Although the television-based systems are capable of excellent accuracy and time-resolution, they are relatively complex and expensive. For these reasons, it was decided to make use of the comparatively less complex and less expensive (yet objective) technique of infra-red photography in the measurement of pupil diameter. This technique has only one major disadvantage; in that it involves some delay because of the processing and measurement stages. At best, results are available only after a delay of up to 4 hours. However, as the measurement of pupil could almost be described as secondary to the measurement of TA and TV, this delay was deemed to be the acceptable result of a compromise between expense, accuracy and convenience.

3.3A i - Instrumentation.

The principle employed in infra-red photography of the pupil is to simultaneously illuminate and photograph the iris using an infra-red light source and camera, respectively.

The Infra-red light source was obtained by placing an infra-red filter (Kodak-Wratten 87C) over the output of a standard electronic flashgun (Vivitar 285 thyrister)[1]. The flashgun was mounted on the hotshoe of a 35mm reflex camera body (Nikon FM) to which was attached a 500mm cata-dioptric lens (Tamron SP) and 2x teleconverter (Tamron flat-field). This arrangement of lenses effectively gave a 1000mm lens system. The image of the iris and pupil were recorded on black and white film sensitive to infra-red light (Kodak HIE 135-36, 25 ASA). A motordrive (Nikon MD-12) and

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[1] This provided an infra-red energy output of 22mJ during the full exposure of the flashgun.

remote cord (Nikon MC-10) enabled the film to be wound-on, and the camera to be triggered under the test conditions of total darkness via the control of the microcomputer. A data-back (Nikon MF-12) was used to record the date and time within the film-frame; this formed the basis of film negative identification.The entire camera assembly was mounted on the "vergence wing" of the experimental apparatus directly ahead and at a distance of 2.5m from the observer.

The system was set at an f-stop of 8 (a constraint of the teleconverter) and the camera ASA set at 12 (rather than the 25 recommended by Kodak) to enhance the image contrast. The shutter speed was set at the flash sync-speed of the camera, at 1/125 sec.

3.3A ii - Procedure.

The camera was focussed on the pupil margin of the observer's right eye, with his/her head in position on the headrest and adjustment was made with regard to the infra-red index on the lens (thereby accounting for the induced chromatic aberration error due to the long wavelength, infra-red light).

TA and TV were then measured by the previously descibed techniques. Immediately prior to the measurement of pupil, the refractive correction and polarized filters were removed from in front of the observer's right eye: this was in order to enhance the contrast of the image and also to negate consideration of image magnification problems due to the various refractive corrections.

The camera was fired, under the control of the microcomputer, during (what the observer was told was) a repeat TA measurement cycle. The procedure was repeated after the flash recycling time and then the experiment was terminated, and the observer de-briefed.

3.3B - Measurement of pupil diameter by slide projection of the film negative

Horizontal pupil diameter was assessed via projection of the negative-image onto graph paper mounted on the surface of a wall. The distance between the projector and graph paper was calibrated such that the image of a ruled scale (in mm), photographed by the same system and at the same distance as the pupil photographs, was magnified and projected in order that a 1mm on the ruled scale equated to 1cm on the graph paper (i.e. a 10x magnification). Each infra-red negative was similarly projected and the horizontal pupil diameter estimated and recorded.

3.4 - METHODOLOGICAL CONTROL.

This section describes the development of a methodological control system enabling the regulation and interfacing of the equipment for the measurment of TA, TV and pupil diameter in total darkness.

In the early stages of the development of a control methodology, much consideration was given to the assessment of various techniques such as; simple timing, the design of a purpose built "event-sequencing" unit (ESU) and finally, the interfacing and programming of a microcomputer. Although the technique of microcomputer control was originally designed as a "back-up" system, it has been used in the control of all measurements of TA, TV, and pupil diameter in preference to a custom built electronic devices. Nevertheless, production of the ESU occupied considerable time and effort: for details of the alternative techniques of simple timing and the ESU see Appendix VI.

3.4A - METHODOLOGICAL CONTROL BY MICROCOMPUTER.

3.4A i - Instrumentation.

An Apple IIe microcomputer was interfaced to the apparatus described in the previous three sections, via a CIL PCI 6000 multi-purpose interface unit. This interface unit has eight analogue inputs (accepting analogue data and converting it into digital data), four analogue outputs (converting digital data from the microcomputer into analogue data and sent to the apparatus), and four relays (used to complete electical circuits - incorporating various items of the apparatus operating at higher voltages than those used by the microprocessor of the Apple IIe). The action of the inputs, outputs and relays were under the control of the software within the microcomputer. Details of the controlling program (TVA 10) may be found in Appendix VII.

The variable output of the micropot' monitoring the movement of the sliding rack system of the laser optometer was connected to input 1, whilst the output of the micropot' monitoring the movement of the vernier alignment device (VAD) was connected to input 2. The microcomputer was programmed to convert this data into relative positions of the laser drum and VAD in units of dioptres, which were subsequently displayed on the video-monitor. The footswitch was connected to input 3, via a simple 5v circuit (all 5-volt circuits were provided by 1 amp Farnell stabilized DC-output units), such that when the footswitch was pressed, the analogue voltage of input 3 changed from zero to 5v.

A control unit was devised in order that specific sub-routines utilised in the measurement of TA or TV (within the programme TVA 10) could be selected in total darkness. This control unit consisted of three switches, each completing an individual 5v circuit connected to Interface unit inputs 4, 5 and 6, respectively[1]. The computer was programmed to continuously

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[1] The third (or right-hand) switch was not used in the present set of experiments, but was included on a contingency basis at the design stage and connected to input 6.

monitor inputs 4 and 5, in order to assess which devices had been selected for inclusion in the experimental cycle. If the left hand switch was activated (pushed away from the experimenter), the analogue data of input 4 changed from zero to 5v and was subsequently detected by the microcomputer to indicate that the measurement of TA had been selected. If the middle switch was activated, the microcomputer detected the voltage change of input 5, indicating that the measurement of TV had been selected. If both switches were activated, then the simultaneous measurement of TA and TV were selected for inclusion in the next experimental cycle. Logic was provided within the programming software (Appendix VII) for the activation of the camera simultaneously with the device(s) selected within the experimental cycle (providing the experimenter had remembered to switch the camera motordrive and flash on !).

A 5v signal was produced by interface output 0 and supplied to a bleep generator (R.S. 249 - 794). This was used to alert the observer and the experimenter of the various stages of the experimental cycle. The opening and closing of all the relays were managed by the programming of the Apple IIe, in response to the instructions provided by the control unit (described above). Relay 1 controlled the activation of the laser optometer shutter, relay 0 controlled the activation of the LEDs of the VAD and relay 2 controlled the activation of the infra-red camera system. The signal from relay 2 was sent during the activation phase of each cycle. The entire apparatus is illustrated in fig. 3.3.

Although the Apple IIe does not possess an on-board clock, time sequences can be regulated via the use of "pause-loops" of the required length within the programme TVA 10. Appendix VIII demonstrates the use of pause-loops and their linear characteristics.

FIGURE 3.3

THE EXPERIMENTAL ARRAY

L = Laser optometer

V = Vernier-alignment device (VAD)

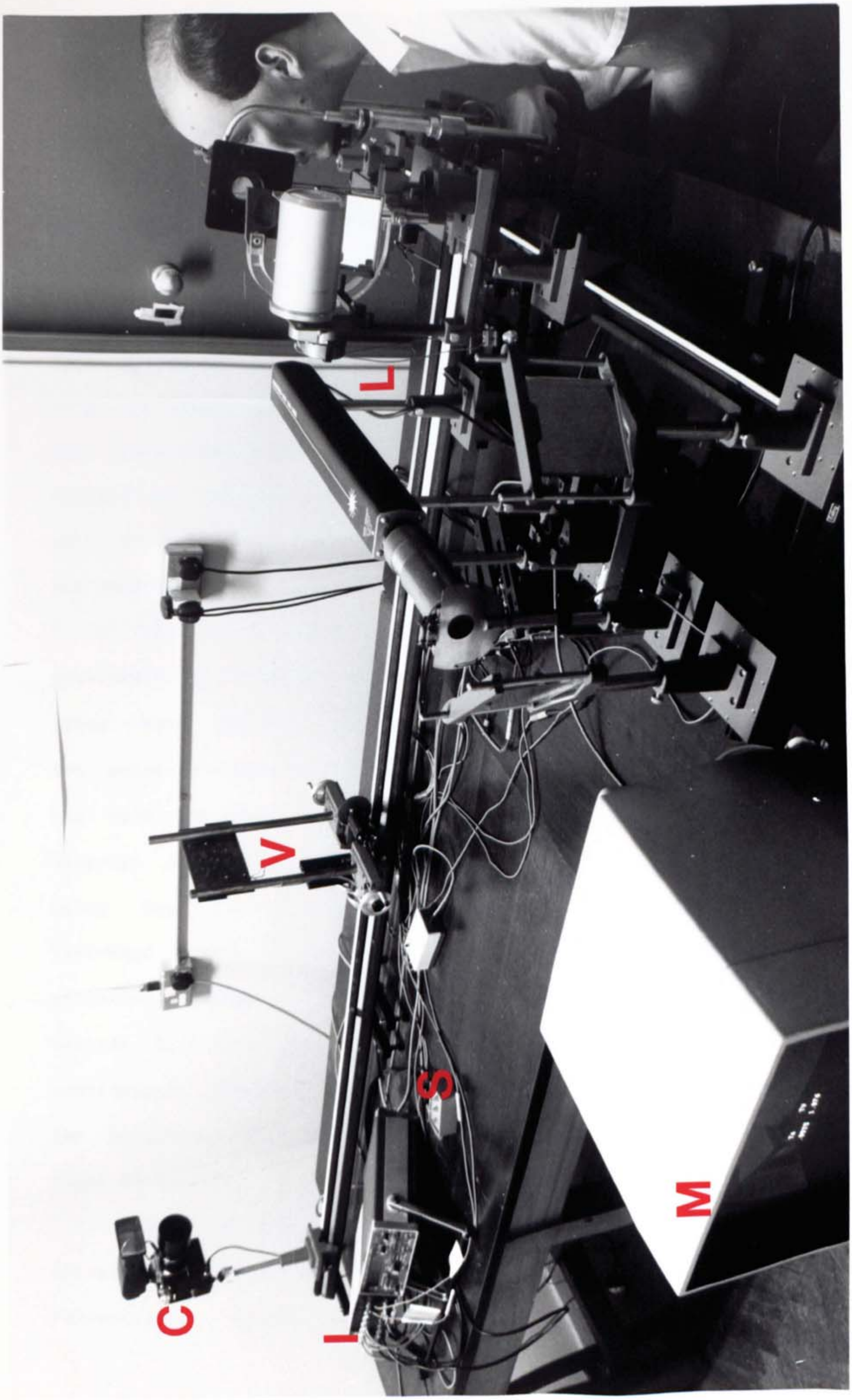
C = Infra-red camera

I = Interface unit

M = Computer monitor

S = Programme-control switch unit

The microcomputer was situated outside the room


L
V
S
M
C
I

3.4A ii - Methodological control procedure.

With the mains and all power supplies to each item of apparatus turned on, the Apple IIe was loaded with the program TVA 10 (see Appendix VII). The program was then run: one cycle of the experiment would ensue and the computer would then wait until the observer pressed the footswitch when ready. The calibration of the laser drum was checked by setting the output of its micropot' to zero (watching the monitor display) and placing the unit 18.35cm from the Badal lens (i.e. the requisite distance taking account of the plane of stationarity). The calibration of the VAD position was checked by setting its micropot' output to 1.00D and placing the unit on the bench with the plane of the LED grooves at 100cm from the observer.

The tasks were then explained to the observer (as previously outlined in the appropriate sections). He/she was then given their accurate distance corrections to wear, together with the polaroid visors and head-phones. With their head in position in the head-rest the lights would be extinguished, whereupon the observer was asked to press the conveniently placed footswitch. Using the control unit, the experimenter would select the left-hand switch (i.e. switch it up) to select the TA cycle. The procedure adopted in the measurement of TA was as described in section 3.1C ii. The change in position of the laser drum was continuously observed on the computer monitor (suitably adjusted for brightness and contrast, appropriate for the conditions of total darkness).

Once TA had been found, the experimenter would then both, select and deselect the middle and left-hand switches, respectively. Thereby selecting the cycle for the measurement of

TV. The procedure was as can be found in section 3.2B ii. Due to the unavailability of suitable electronic motorized lateral motion units, the nonius lines themselves were unable to be interfaced with the Apple IIe, as a result the positions of the nonius lines were measured directly from their position on the supporting plates.

If a pupil diameter measurement was required, the experimenter would have ensured that the camera had been focussed on the iris of the observer before the lights had been extinguished. After TA and TV had been measured, the experimenter would once again asked the observer to close their eyes for a few seconds whilst he removed the polarizing visors and any corrective lenses in front of the right eye. He would select the TA cycle and the subject would attempt to neutralise the speckle motion in the usual way (the drum position would have been altered by the experimenter). The experimenter would then switch on the flash and then (after allowing the flash to charge-up) he would switch on the motordrive. The camera would fire at the same time as the shutter during the next cycle, after which the experimenter would switch off the motordrive, allowing the flash to fully recharge before taking a further infra-red photograph. The usual TA cycle would continue until the flash had recharged and the TA/camera cycle was then repeated.

At the end of the experiment the observer would be de-briefed, thanked and (if required) a further appointment made.

3.5 - METHODOLOGICAL CONSIDERATIONS.

3.5A - LASER PRESENTATION TIME.

3.5A i - Introduction.

The reader will appreciate the importance of a technique for the measurement of TA that does not itself influence the result. In the application of laser optometry to the assessment of TA under conditions of total darkness, the only potential visual stimulus is the laser speckle itself. In view of the fact that the accommodative latency is around 360msec (see Table 3.1) it would seem reasonable to expect that, if the laser speckle was not to act as an accommodative stimulus, then its duration would have to be at or below an exposure time of this level.

With the exception of the 400- and 750-msec laser exposure times employed by Ukai et al. (1978) and Epstein et al. (1981) respectively, all other workers (e.g. Maddock et al. 1981; Heron et al., 1981) have adopted an exposure time of 500 msec, invariably citing the study of Hennessy and Leibowitz (1970) as the precedent for this choice of exposure duration. It is with relevance therefore that the comments of this latter study are repeated here:

> "Because the latency (Cornsweet and Crane, 1970) of the accommodative response is 0.4s, a laser test flash of approximately this duration would theoretically be expected to reflect the state of accommodation that existed before its introduction..... To measure accommodation, the laser light is briefly exposed (approximately 0.5s)...." (Hennessy and Leibowitz, 1970).

It would appear that these workers have chosen to use a laser exposure duration (500msec) that is 25% greater than the limit that they had set themselves (i.e. 400msec). In view of the possible ambiguity of their comments and the results of their study (in which 25% of the observers were judged to have changed their accommodative response to various exposure durations of laser speckle) and, furthermore, because an exposure of 500msec is

140msec greater than the latency of accommodation (see Table 3.1), it was decided to investigate the effect of various exposure durations on the level and variability of accommodation.

Table 3.1 - Various measurements of accommodative latency.

STUDY	MEAN (msec)	FAR-TO-NEAR	NEAR-TO-FAR
Kirchof (1940)	465	500	430
Allen (1955)	343	-	-
Carter (1962)	425 (non-repet' stim')	-	-
	220 (repet' stim')	-	-
Campbell & Westheimer (1960)	370 ± 85	360 ± 90	380 ± 80
Stark et al. (1965)	360	-	-
O'Neill and Stark (1968)	290	300	280
Cornsweet and Crane (1970)	400	-	-
Kasai et al. (1971)	441 ± 23	451 ± 19	431 ± 28
Heron (1972)	390	430	350
Phillips et al. (1972)	376	357	395
Wilson (1972)	372	365	379
Randle and Murphy (1974)	330 (pred' stim')	-	-
	317 (non-pred' stim')		
Smithline (1974)	375	-	-
Krishnan et al. (1977)	380	-	-
Shirachi et al. (1978)	379	360	398
Zulch and Krueger (1978)	250	-	-
Tucker and Charman (1979)	313 ± 100	285 ± 70	340 ± 130
Mean	358 ± 61	379 ± 70	376 ± 47

If too short a duration is selected (i.e. much shorter than the latency of accommodation) and a forced choice procedure imposed, then it would be expected that the observer would have great difficulty in perceiving both the speckle and its motion; with the consequence that the variance of a series of measurements would be high. If too long a duration is selected (i.e. longer than the latency of accommodation), then the observer would be in a position to reflexly exercise their accommodation during the excess time between the latency of accommodation and the exposure duration: this would have the effect of altering the apparent speed of speckle rotation proportionately to the alteration in accommodation (Inglestam and Ragnarsson, 1972) and therefore increasing the variance of a series of TA measurements at that duration. If, however, a duration was selected that was long enough to allow the observer to perceive the speckles and their motion, yet shorter than the latency of accommodation, one might hypothesize that the variance of TA measurements would be at a minimum.

3.5A ii - Methodological procedure.

In examining this hypothesis, five randomized measurements of TA were taken from 10 observers, at four shutter speeds (200, 300, 400 and 500msec), in total darkness, using the experimental design and procedure as described in sections 3.1C i + ii.

The different shutter speeds were controlled by the alteration of the paüse-loop length in line 420 of the controlling program TVA 10 (see Appendix VII - for the various times of 200, 300, 400 and 500msec durations the pause-loop lengths were set at 125, 190, 255 and 325, respectively - as derived from Appendix VIII).

3.5A iii - Results.

Table 3.2 - The mean ($\bar{x}$) and standard deviations (s.d.) of five randomized measures of TA (D at 632.8nm) taken from 10 observers (O).

	200		300		400		500	
O	$\bar{x}$	s.d.	$\bar{x}$	s.d.	$\bar{x}$	s.d.	$\bar{x}$	s.d.
A.M.	-	-	0.38	0.12	0.00	0.19	0.10	0.27
R.H.	1.42	0.33	1.49	0.05	2.12	0.22	2.05	0.24
R.R.	0.09	0.69	0.19	0.20	0.64	0.27	0.41	0.15
M.P.	0.99	0.23	0.74	0.14	0.62	0.24	0.66	0.12
J.W.	1.73	0.16	2.28	0.14	2.33	0.16	1.90	0.23
M.R.	1.23	0.14	1.02	0.04	1.46	0.10	1.29	0.10
B.G.	2.07	0.41	2.69	0.09	2.73	0.09	2.41	0.08
M.W.	-	-	0.89	0.05	0.79	0.23	0.77	0.18
M.F.	-	-	3.81	0.09	4.15	0.06	3.66	0.41
N.Mc.	1.10	0.08	1.47	0.06	1.25	0.12	1.17	0.16

Table 3.2 has been constructed from the means and standard deviations of 5 measurements of TA (taken at 632.8nm) from the 10 observers, at the four different shutter speeds (the full data may be found in Appendix X). As can be seen from this Table, three observers (A.M., M.W. and M.F.) were unable to perceive any speckle

motion at the 200ms shutter speed. It is for this reason that two separate analyses of variance (ANOVA) have been performed on the data. (for further details concerning the ANOVA see Appendix IX).

The first analysis concerns the seven observers able to perceive speckle motion at all four shutter speeds. The second analysis is taken from all ten observers, for the 300, 400 and 500ms shutter speeds only.

No significant differences were detected between the mean TA values for either data group (7-observer data, F = 3.01, df = 3, 18, p = n.s.; 10-observer data, F = 0.835, df = 2, 18, p = n.s.). Significant inter-observer differences were detected however, on full two-way ANOVA between observer and shutter speed for both data groups: 7-observer data, F = 49.541, df = 6, 18, $p < 0.01$; and 10-observer data, F = 82.775, df = 9, 18, $p < 0.01$. A partial ANOVA revealed a significant difference between the values of the 7-observer data between the values at 300ms to 500ms (F = 1.834, df = 1, 6, p = 0.05). A further partial ANOVA between the standard deviations obtained from the values of the 10-observer data, at the various speeds, shows significantly greater differences: for 300 and 500ms, F = 10.567, df = 1, 9, $p < 0.01$; for 300 and 400ms, F = 6.05, df = 1, 9, $p < 0.05$. Figure 3.4 illustrates the mean distribution for the 10 observers, between the change in standard deviation at the various shutter speeds. It should be noted that the mean s.d. for the 200ms shutter speed is for 7 observers only (it could be argued that the s.d. ought to be plotted at a much higher level, as three of the observers would have infinite s.d.'s).

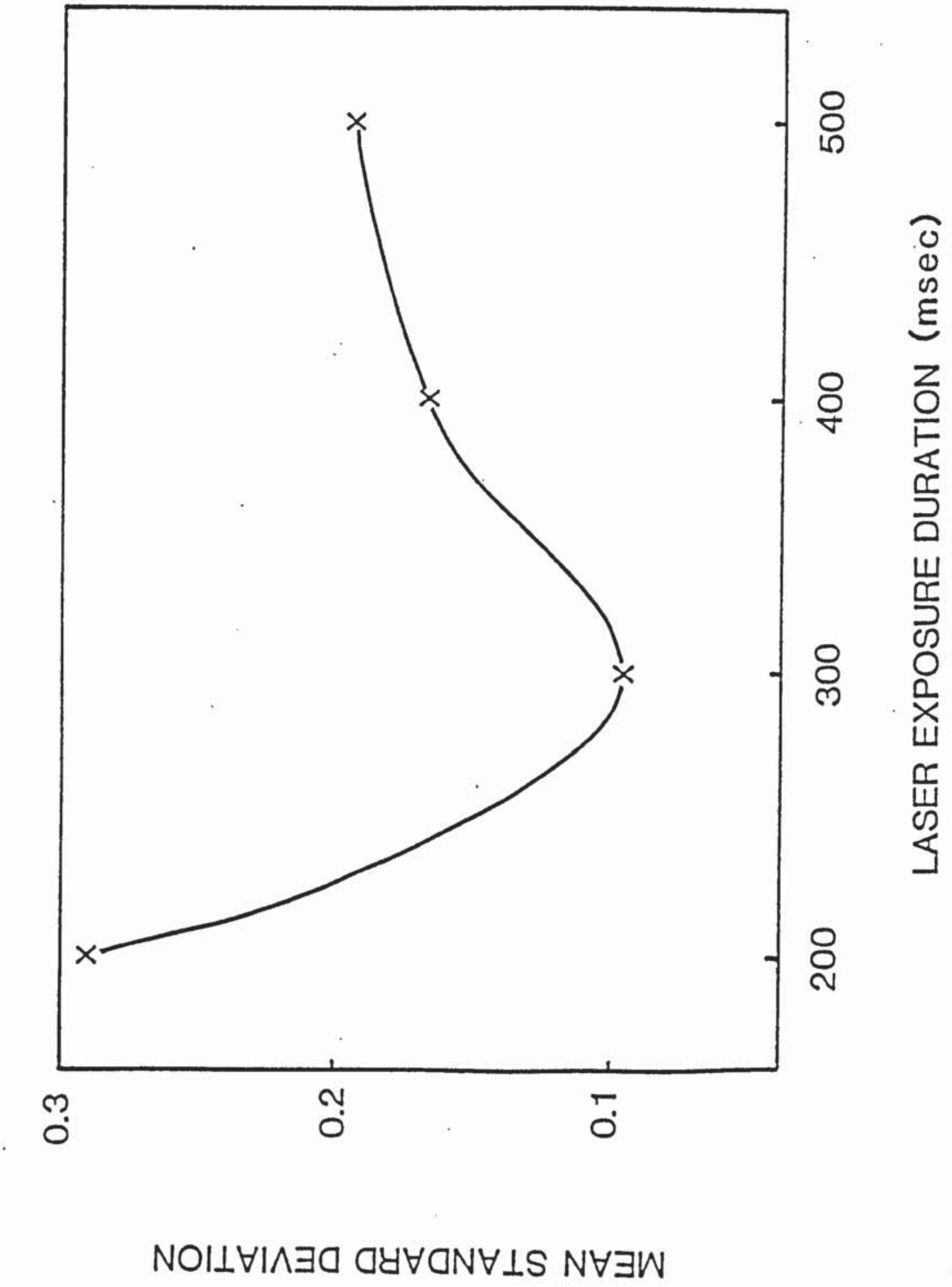


Figure 3.4 - The effect of laser exposure duration on the s.d. of measurements of TA at 632.8nm (N=10).

3.5A iv - Discussion.

At the outset of this study it was outlined that there were theoretical objections to the use of a laser speckle exposure duration (in the measurement of TA) significantly greater than the latency of accommodation (see Table 3.1). It was anticipated that too short an exposure would be insufficient to adequately perceive the direction of speckle motion and furthermore, that too long an exposure (greater than the latency of accommodation) may lead to an increase in the variation in result obtained (i.e. a larger number of measurements would be required at the slower shutter speeds to increase the probability of an accurate TA). Whilst analysis has demonstrated that the mean TA value may not differ at the various shutter speeds employed (apart from the 200msec where 3 observers were unable to make a judgement), it is clear from this study that there is greater variability about those means at the longer shutter speeds: Fig. 3.4 graphically illustrates this point and emphasizes that a shutter speed of sufficient duration, yet shorter than the acknowledged accommodative latency would elicit the smallest standard deviation (as found with a 300ms shutter speed).

The latency of accommodation is known to be normally distributed amongst the population (Campbell and Westheimer, 1960; Tucker and Charman, 1979), it will be evident therefore, that whilst half of the population have an accommodative latency longer than the mean of this distribution, the other half would exhibit an accommodative latency shorter than this mean. If research into accommodation, utilising laser speckle measurements of TA, is to include observers sampled from the majority of the population, it is imperative that exposure durations are employed at some degree faster than the mean latency of accommodation for that population.

This study has demonstrated that, not only is it possible to reduce the laser optometer shutter speed from 500 to 300ms, but that it would appear more accurate to do so (see also, Hogan and Gilmartin, 1984b). Consequently a shutter speed of 300ms will be used for all further measures of TA involved in the studies of this thesis.

3.5B - LED EXPOSURE TIME IN THE MEASUREMENT OF TV.

3.5B i - Introduction.

The latency of the fusional or disparity vergence system is somewhat shorter than that of the accommodative system, with a mean of 180ms (see Table 3.3). Previous researchers (e.g. Owens and Leibowitz, 1980) have utilised a nonius line presentation time of 125ms for the measurement of TV that is well within the mean latency period of the disparity vergence system; there is therefore much less theoretical controversy concerning this choice of presentation time in the determination of TV, than there is concerning the choice in the measurement of TA.

Table 3.3 - Reaction times of the fusional or disparity vergence system

Author/s	disparity vergence (ms)
Allen (1953)	200
Westheimer and Mitchell (1956)	150 - 200
Rashbass and Westheimer (1961a)	160 - 200
Zuber and Stark (1968)	200
Krishnan et al. (1977)	160
Semmlow and Wetzel (1979)	184 (far to near) 161 (near to far)
Mean	180 ± 16

A study was carried out, in accordance with the experimental design utilised in the previous determination of the laser speckle presentation time, to investigate the choice of an appropriate LED presentation time in the determination of TV.

3.5B ii - Methodological procedure.

Five randomized measurements of TV were taken from three observers in total darkness, using the methodology and procedure discussed in sections 3.2B i and ii at five different LED energization times (30, 75, 125, 175 and 225ms). The various LED energization times were controlled by the alteration of the pause-loop length in line 467 of the controlling program TVA 10 (see Appendix VII - for the various times of 30, 75, 125, 175 and 225ms the pause-loop lengths were set at 11, 41, 75, 105, and 137, respectively - as derived from Appendix VIII).

3.5B iii - Results and discussion.

The means and standard deviations of the five measurements of TV from the three subjects are displayed in Table 3.4 (the raw data from which the means and standard deviations have been calculated may be found in Appendix XI).

Table 3.4 - The means ($\overline{x}$) and standard deviations (sd) of the 5 randomized measurements of TV (in deg's) at 5 different LED energization times.

	LED ENERGIZATION TIME (ms)									
	30		75		125		175		225	
OBSERVER	$\overline{x}$	sd	$\overline{x}$	sd	$\overline{x}$	sd	$\overline{x}$	sd	$\overline{x}$	sd
B.G.	2.04	0.09	2.14	0.05	2.16	0.03	2.18	0.04	2.14	0.07
R.H.	1.73	0.04	1.72	0.04	1.65	0.01	1.69	0.02	1.59	0.03
J.W.	1.88	0.16	1.94	0.14	2.22	0.08	2.04	0.14	2.09	0.13

The data has been analysed in a similar manner to that of the TA measurements within section 3.5A iii. An ANOVA between the various exposure times revealed this factor to have a significant effect on the variablity of TV measurement ($F = 3.231$, $df = 2, 4$, $p < 0.05$). A partial ANOVA between the TV measurements at the various LED exposure times further demonstrates the effect: for 125ms compared to 30ms, $F = 11.032$, $df = 1, 2$, $p < 0.01$; for 125ms compared to 225ms, $F = 9.394$, $df = 1, 2$, $p < 0.01$.

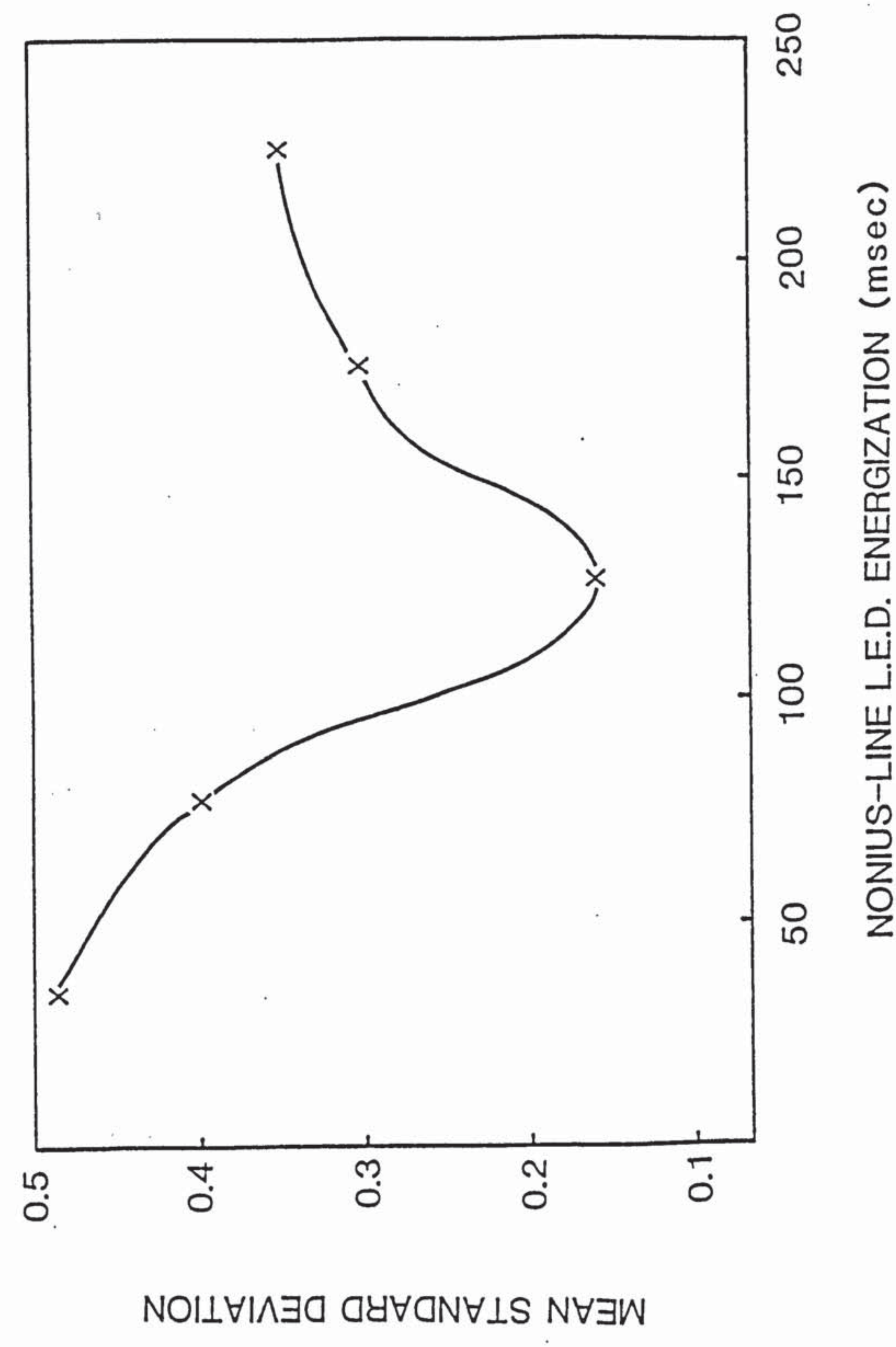


Figure 3.5 - The effect of LED exposure duration on the standard deviation of 5 randomized measures of TV (in deg's) from 3 observers.

There was no significant effect on the variablity of TV when comparing 30ms to 225ms, F = 0.988, df = 1, 2, p = n.s. As with the TA measurements, there were no significant differences between the mean values for TV at the various exposure times (e.g. comparing 125 to 225ms, F = 5.68, df = 1, 2, p = n.s.), this demonstrates (as found for TA) that although the mean value of TV is unlikely to differ at the various exposure times, the variance about that mean will change. Figure 3.5 illustrates the effect of LED exposure time on the variablity of TV measurement. It can be seen (as found for TA) that the variability of TV measurement increases significantly if the exposure time is lesser or greater than the latency of the system.

The choice of 125ms (as used by Owens and Leibowitz, 1980) in previous measurements of TV was not disputed on theoretical grounds and in fact, this study endorses its continuing usage. It is of interest to note that results of the present study support the use of the logic behind the experimental design (i.e. reliance on change in variablity) being applied for use in the previous study concerning TA measurements. Consequently an LED energization time of 125ms will be adopted for all further studies involving the measurement of TV.

3.5C - He-Ne LASER OPTOMETRIC ASSESSMENTS OF TA AND THE CHROMATIC ABERRATION CORRECTION FACTOR.

3.5C i - Introduction.

It has been reported (Ingelstam and Ragnarsson, 1972) that laser optometry measurements of ocular refraction (at 632.8nm), under normal visual conditions, yield results that are found to be approx. 0.25D too negative, when compared to those obtained under more conventional forms of subjective refraction (the reader will have been introduced to this aspect in section 3.1A iii). It was concluded that this discrepancy was due to the longitudinal chromatic aberration (LCA) of the eye, and that since the measurements of ocular refraction were made using the red, 632.8nm wavelength output of the He-Ne laser, a correction had to be applied in order to obtain results valid for the "daylight visibility curve"; which Ingelstam and Ragnarsson (1972) maintained had a maximum sensitivity at 555nm. They considered that corrections "within less than 0.25D from readings on an ordinary letter-chart" were in order, and in agreement with the LCA data of Le Grand (1956) and Ivanoff (1953).

In the more recent application of laser optometry to the measurement of TA (using a laser of output 632.8nm), most workers (e.g. Leibowitz and Owens, 1978; Heron et al., 1981) have applied a correction of +0.33D to their results, following the example set by Owens and Leibowitz (1976a). The magnitude of this correction is based on the data of Bedford and Wyzecki (1957) when corrected for a reference wavelength of 555nm[1]. It is interesting to note that various research workers have reported a proportion of refractively-corrected observers who exhibit hyperopic TA positions of up to -0.50D, even after application of the +0.33D LCA correction (see Table 1.2). These somewhat anomalous findings might be explained if one considers the possibility that the magnitude of the LCA between 632.8nm and the photopic reference wavelength had been underestimated. Recent investigations (Sivak and Mandelman, 1982; Mandelman and Sivak, 1983) have analysed the dispersion of the human ocular media and have indicated a chromatic range of 2.75D between 440 and 680nm. This range was noted to be

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[1] Bedford and Wyzecki's data was calculated for a reference wavelength of 578nm.

significantly greater than those reported from previous theoretical and psychophysical investigations (e.g. typical values found were 1.6D and 1.75 ± 0.5D by Wald and Griffin, 1947 and Bedford and Wyszecki, 1957, respectively). Mandelman and Sivak (1983) suggest that these previous theoretical estimates have failed to take full account of the exaggerated dispersion of the crystalline lens at short wavelengths, and that the differences in psychophysical estimates may be due to:

> "....variations in the choice of spectral limits and to the fact that single values reported for chromatic aberration ignore variations among individuals" (p.1557).

In 1965, Sinclair qualitatively reported the differential effect on the direction and speed of speckle motion, when observing the reflected light from the various wavelengths of laser light, produced by the tuning of a Krypton laser. He attributed this effect to the influence of the LCA of the eye and acknowledged the need for a quantitative study into the observed differential effects of various wavelengths of laser light on speckle motion.

The measurement of TA, using different wavelengths of laser light, would provide an appropriate means of measuring the LCA of the eye, whilst free from the complications and constraints of stimulus dependency, variations in pupil size and wide bandwidth chromatic stimuli. The work of Campbell (1957), Ogle and Schwartz (1959), Tucker and Charman (1975) and Charman and Whitefoot (1977) has demonstrated that the optimal refraction of the eye is independent of pupil diameter above 3mm. The mean pupil diameter of the observers used in the following studies (in total darkness) was found to be 7.02mm (sd = 0.56mm).

The present study is comprised of a series of three investigations: a) the measurement of TA using three wavelengths of laser light (488, 514.6 and 632.8nm) on 10 observers; b) the measurement of TA using an extended range of five wavelengths of laser light (457.9, 476.5, 488, 514.6 and 632.8nm); and c) the measurement of TA with three wavelengths (as used in the first investigation) on three observers, each with their ciliary muscles paralysed following the application of the cycloplegic agent, cyclopentolate 1%.

3.5C ii - The measurement of TA (N=10) at wavelengths of 488, 514.6 and 632.8nm.

Ten refractively-corrected and experienced observers were used, 6 male and 4 female with ages ranging from 18 to 37 years (mean = 23.1). TA was measured using the Badal laser optometer discussed in section 3.1C i, with the exception that, for all wavelengths other than the standard 632.8nm, a Spectra-Physics 2mW Argon air-cooled laser was used and tuned to the selected wavelength. A serial random staircase psychophysical procedure was used (as discussed in section 3.1C ii) to procure five measurements of TA at each of the three randomly selected wavelengths, 488, 514.6 and 632.8nm. Neutral density filters were used to give each wavelength of laser speckle a luminosity of 6cdm^{-2}. The means and standard deviations of the results (fully illustrated in Appendix XII) may be found in Table 3.5.

It is evident that the mean LCA for the 10 observers, over the chromatic interval from 488 to 632.8nm, can be deduced from Table 3.5, as the difference in TA measurements using laser speckle including these wavelengths: the mean LCA for the group was 1.87D with a standard deviation of 0.26 (D). Reference to the data of Bedford and Wysecki (1957) and Wald and Griffin (1947) indicates a mean LCA of 0.88D and 0.77D (sd = 0.18D), respectively for an equivalent chromatic interval. Ware (1982) found a value of approx' 1.1D for this interval, using the same apparatus as Bedford and Wysecki.

Table 3.5 - The means ($\bar{x}$) and Standard deviations (sd) of 5 measurements of TA (D) from 10 observers, using three different wavelengths of laser light 488, 514.6 and 632.8nm. The LCA (D) is given as the range between the spectral limits.

			WAVELENGTH (nm)						
			488		514.6		632.8		
OBSERVER	AGE	Rx	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd	LCA
MJ	21	+0.25	2.99	0.11	2.36	0.11	1.24	0.08	1.75
SH	20	-1.00	3.06	0.07	2.42	0.08	1.03	0.07	2.02
MR	25	-1.00	4.14	0.07	3.74	0.12	2.07	0.12	2.07
RH	27	-3.50	3.05	0.12	2.52	0.14	1.34	0.09	1.71
BG	37	-6.25	3.81	0.05	3.20	0.07	2.06	0.09	1.75
CT	24	+0.25	0.93	0.01	0.64	0.04	-0.67	0.03	1.60
MP	20	+0.50	4.30	0.02	3.91	0.03	2.45	0.35	1.86
IL	20	-0.12	1.72	0.03	1.40	0.03	0.20	0.01	1.52
MM	19	-0.50	2.80	0.03	2.35	0.06	0.85	0.07	1.94
SS	18	+0.62	4.92	0.03	4.25	0.09	2.48	0.06	2.44
MEAN			3.17		2.68		1.30		1.87
sd			1.20		1.13		1.14		0.26

It is of interest to note that there is a significant correlation ($r = 0.65$, $p < 0.05$, $df = 8$) between the observed magnitude of chromatic aberration and the level of TA (as measured using the standard He-Ne laser). The results indicate an increase in LCA of around 8% per dioptre of TA. Various studies (Nutting, 1914; Millodot and Sivak, 1973; Sivak and Millodot, 1974) have demonstrated an increase in LCA with increasing accommodative effort. Charman and Tucker (1978b) found an increase in LCA of 3% per dioptre of accommodation, which is similar in magnitude to the change expected (2% per D) from the theoretical calculations of Ivanoff (1953) and Le Grand (1967).

3.5C iii - The measurement of TA (N=4) at wavelengths 457.9, 476.5, 488, 514.6 and 632.8nm (N=4)

Mandelman and Sivak (1983) considered that the major reason their calculations have greater values for LCA was because previous studies had not taken full account of the exaggerated dispersion of the crystalline lens at wavelengths below 500nm. It would be interesting therefore to investigate LCA using a similar TA measurement technique to that used in the previous experiment and a range of laser speckle wavelengths below 500nm. The previous experiment will also be repeated with the wavelengths 514.6 and 632.8nm also included in the investigation, therefore acting as a form of check or control for the lower wavelength study.

Four refractively-corrected observers were used in the present study: each observer had participated in the previous study. TA was measured using the same technique as that used in the previous study. The additional wavelengths of 457.9 and 476.5 were provided by further tuning of the Argon laser. Once again, neutral density filters were used to provide a speckle patch luminosity of $6cdm^{-2}$.

A similar psychophysical procedure to that employed in the previous study was used to determine TA measurements at each of the five wavelengths: in this study however, each measurement of TA at each wavelength was determined on a randomized basis.

The means and standard deviations of the results (fully illustrated in Appendix XIII) may be found in Table 3.6.

Table 3.6. The means $(\bar{x})$ and standard deviations (sd) of 5 measurements of TA (D) on 4 observers at 5 wavelengths of laser speckle 457.9, 476.5, 488, 514.6 and 632.8nm. The LCA is given as the range between the spectral limits.

	WAVELENGTH (nm)										
	457.9		476.5		488		514.6		632.8		
OBSERVER	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd	LCA
SH	4.00	0.05	3.64	0.03	3.37	0.06	2.96	0.10	1.48	0.10	2.52
RH	3.60	0.01	3.03	0.18	2.56	0.08	2.13	0.15	0.86	0.09	2.73
BG	4.96	0.08	4.47	0.06	3.92	0.06	3.39	0.09	2.21	0.05	2.75
IL	3.08	0.06	2.82	0.06	2.47	0.06	1.95	0.10	0.47	0.07	2.60
MEAN	3.91		3.49		3.08		2.61		1.26		2.65
sd	0.79		0.74		0.69		0.68		0.76		0.11

Mandelman and Sivak (1983) were able to predict an LCA of 2.75 between the wavelengths of 440 and 680nm. The results of the present study would suggest a comparable LCA of 2.65D for the slightly smaller chromatic interval of 457.9 to 632.8nm. Reference to figure 3.6 demonstrates that there would indeed appear to be an increase in the LCA of the eye below 500nm.

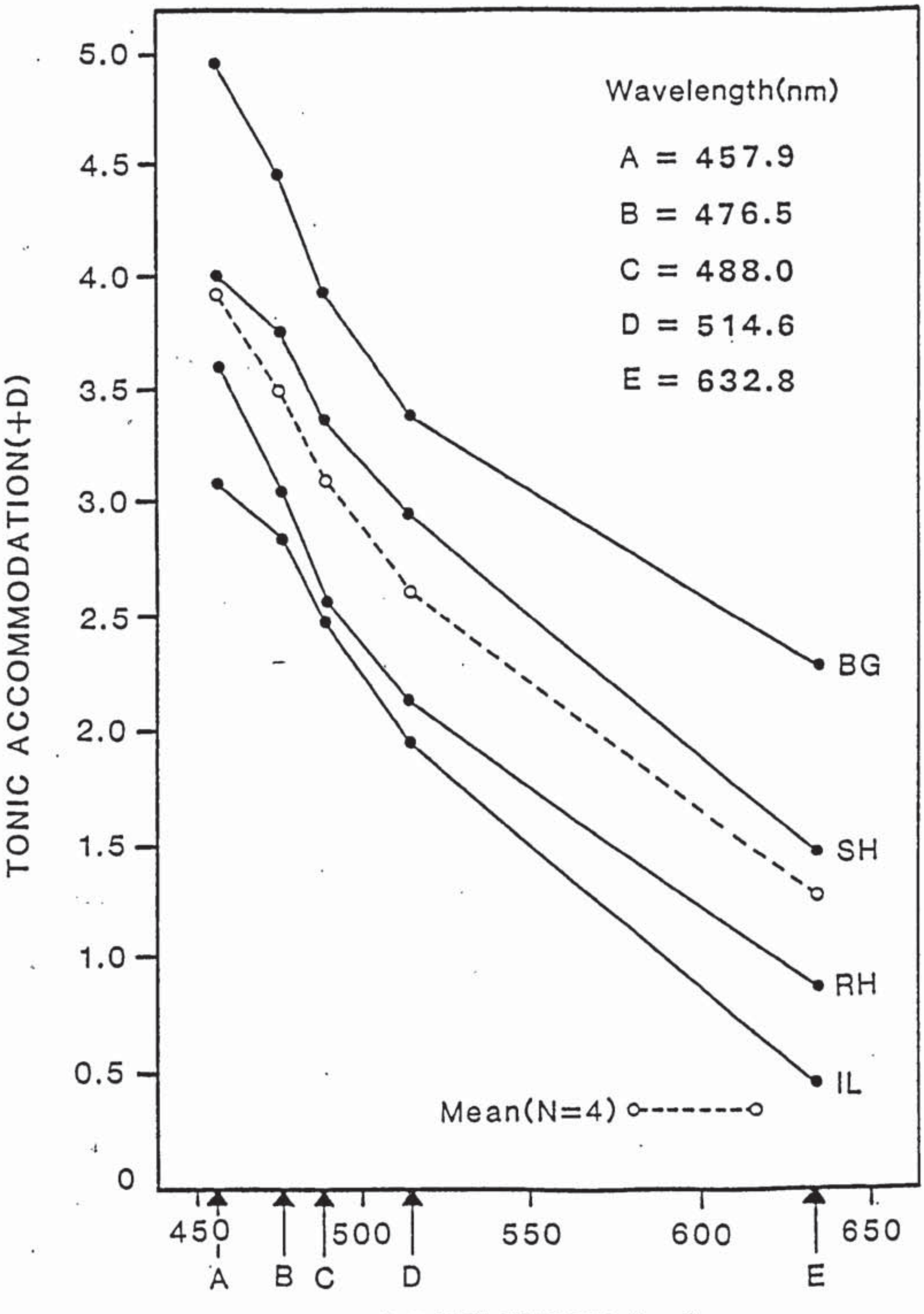

Figure 3.6 - The longitudinal chromatic aberration between wavelengths 457.9 and 632.8nm for a sub-set of 4 observers (without cycloplegia) based on the measurement of TA (D).

Figure 3.6 (together with table 3.6) demonstrates that a mean LCA of 1.82D was found for the reduced chromatic interval of 514.6 to 632.8nm which compares well with the LCA of 1.87D observed for the same interval in the previous study. The 5-wavelength study was completed at least one month after the 3-wavelength study and therefore serves as a suitable control.

3.5C iv - The measurement of TA (D) at wavelengths 488, 514.6 and 632.8nm following the instillation of a cycloplegic.

It has been reported that TA may be affected by such variables as, mood (Miller, 1978b), arousal (Westheimer, 1957; Costello, 1974; Leibowitz, 1976) and mental activity (Malmstrom et al., 1980). The effects have been attributed to an induced variation in the autonomic balance of the innervation controlling the ciliary muscle (see section 1.4E). An important aspect in the control of the present investigation (i.e. induced variation in ciliary muscle power affecting the stability of TA) would be determined by a repeat study using a subset of observers, in whom a cycloplegic agent had been topically instilled in order to paralyse the ciliary muscle and therefore eliminate the error of a potential induced variation in ocular focus.

Three of the previous observers (S.H., R.H. and B.G.) were utilised in the present study. One drop of 1% cyclopentolate was instilled into both eyes of each observer. Maximal cycloplegia (with residual amplitudes of accommodation of <0.50D) were obtained within twenty minutes. TA measurements were then taken using the same laser wavelengths and methodological procedure as that of the first investigation (see 3.5C ii). The results obtained are displayed in Table 3.7 (and the raw data may be found in Appendix XIV).

Table 3.7 - The means ($\bar{x}$) and standard deviations (sd) of 5 measurements of TA (D) taken at three wavelengths of laser light (488, 514.6 and 632.8nm), following the instillation of 1% cyclopentolate (N=3). The LCA is given as the range between the spectral limits.

	WAVELENGTHS (nm)						
	488		514.6		632.8		
Observer	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd	LCA
SH	1.43	0.12	1.00	0.17	-0.43	0.05	1.86
RH	1.41	0.07	1.05	0.01	-0.51	0.09	1.92
BG	1.48	0.15	0.98	0.08	-0.46	0.04	1.94
Mean	1.44		1.01		-0.47		1.91
sd	0.04		0.04		0.04		0.04

If excessive accommodation had been a major factor in the production of the enhanced level of LCA within the 145nm spectral range, one would have expected the cycloplegia, resulting from instillation of 1% cyclopentolate, to have significantly reduced the observed LCA. It is evident from the results of table 3.7 that, even, under the effects of cycloplegia, the mean LCA for the 145nm range is in the order of 1.91D. This figure is in fact slightly higher than the LCA values of 1.83D and 1.78D found for the same three observers in the previous two studies, respectively.

3.5C v - General conclusion.

The observed magnitude of the LCA (in sections 3.5C ii and iii) would support the predictions of the study by Mandelman and Sivak (1983). Utilising their own crystalline lens data (Sivak and Mandelman, 1982) and the schematic eye data of Hughes (1977), they were able to predict an LCA of 1.60D for the chromatic interval between 488 and 632.8nm, which compares well with the results of the present study. It is evident from the results of the cycloplegic study (section 3.5C iv), that the difference in position of TA is dependent upon the wavelength of the laser used, and not upon variations in accommodation itself.

An increased LCA would clearly be relevant to the magnitude of correction applied to laser optometer measurements of TA. The typically applied correction of +0.33 for a reference wavelength of 555nm (Owens and Leibowitz, 1976a) would (for the present data), assuming linearity between the chromatic interval of 555 to 632.8nm, increase to +0.91D. For reference wavelengths of 578 and 589 the correction would be +0.62D and +0.50D, respectively. Although the assumption of linearity for this magnitude of interval will introduce a slight error, it is clear that the +0.33D correction would be a significant underestimate. It is interesting to note that the hyperopic TA values of Table 2.1 would be accounted for by the application of the appropriate correction factor for LCA. It is proposed that the discrepancy between the results of the present study and those reported in the previous literature are associated with the advantages of the laser measurement technique (see also Gilmartin and Hogan, 1985d).

The choice of chromatic aberration correction applied to laser optometry measurements of accommodation depends, not only upon the magnitude of the chromatic aberration of the eye, but also upon the point chosen within the spectrum as the reference wavelength for photopic conditions. The choice of this reference wavelength, as observed in the literature, has varied from 555nm (Inglestam and Ragnarsson, 1972) to 589nm (Le Grand, 1967). In view of both the high (and presumably controversial) chromatic aberration data observed in the present study, and the variance in opinion concerning the reference wavelength, it is proposed that, until these issues are resolved, all future laser optometry measures of TA be stated in the uncorrected state and accompanied by the wavelength of the laser used.

3.5D - TEMPORAL STABILITY STUDIES.

3.5D i - Introduction.

In 1919, Wibaut estimated that night myopia took several minutes to develop to its maximum level. Many years later, Heath (1962) using an infra-red optometer, found that accommodation took from 1 to 5 minutes to reach a "rest" position in the dark. Phillips (1974) measured the time course of accommodation under the reduced-stimulus conditions of darkness, ganzfeld and pinhole and found that the accommodative system reached a common steady-state level dependent upon the individual's accommodative bias, despite the observation that the various conditions exhibited differing time constants of 4, 6 and 10 seconds, respectively[1]. He concluded that this demonstrated how residual information content may affect the dynamics of response but not the final resting state. Baker et al. (1983) measured the time course of night myopia and found that accommodation drifted to its resting state resembling an exponential decay function with a time constant of 1 - 3 seconds, and that the recovery of accommodation to the prior level after visual stimulation is restored suddenly, has a time constant of 200 - 400 msec.

These observations offer some explanation for the reports of Johnson et al. (1982; 1984), which describe fluctuations in the resting state of accommodation (measured by i/r optometer) during the first six minutes under conditions of total darkness. The fluctuations vary from observer to observer and appear to be related to the individual steady-state level of the resting focus of accommodation.

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[1] The time constant is the time necessary for the response to change to 63% of its final steady-state value. For its application in the assessment of accommodation response times, see Shirachi et al. (1978).

Much of the available literature indicates that the tonic resting state may be considered as a longitudinally stable parameter of the accommodative system. Miller (1978a) reported that the dark focus was consistent in his 21 subjects over his 2 - 3 week investigation and noted that there were no apparent cyclic or diurnal variations. Mershon and Amershon (1980) found that the mean dark focus varied by less than 0.3 D for 20 subjects, when measured over a 1-week interval. Heron et al. (1981) monitored dark focus in 30 subjects over an average period of 12 weeks and found the test-retest slope to be significantly related to a slope of unity fitted to the data. They conducted both a diurnal and a day-to-day study and found the results to be "impressively consistent". Owens and Higgins (1983) monitored the tonic resting states of 5 subjects over a 12-month period and found the average difference over this interval to be 0.21 D, with a maximum change of only 0.66 D. They too could find no evidence of any apparent cyclic variation. Miller et al. (1983) monitored the "dark focus" of accommodation in 10 subjects over a three hour session in total darkness using a Badal-laser optometer. They were unable to detect any significant changes in the individual magnitude of "dark focus" over this time period, although it was observed that the female subjects (N=5) exhibited a tendency to be more variable than the males. Post et al. (1984) used an i/r optometer to measure TA in 47 observers and found test-retest correlations for period separations over minutes, one day, one week and two weeks, of 0.98, 0.72, 0.75 and 0.76, repectively.

It may be concluded from the results of the above studies that measures of tonic resting accommodation may be utilised as an adequately stable parameter for the investigation of the accommodative system.

There are very few documented reports concerning the longitudinal stability of vergence under conditions of total darkness. Those that are available (Cornsweet, 1956; Nachmias, 1961; Fiorentini and Ercoles, 1966; Skavenski and Steinman, 1970; and Matin et al., 1970) are concerned principally with the involvement of an extra-retinal mechanism in the control of eye position. In all these reports, monocular eye position was recorded in total darkness whilst attempting to hold the eye steady, in the direction of, and following brief exposure to, a fixation target. Most studies recorded eye position for periods of 3s only, following onset of darkness; Cornsweet (1956) and Skavenski and Steinman (1970) used recording periods of 12s and 120s, respectively. All studies reported variable and inconsistent effects on eye position. The significance of these reports is somewhat limited (in the present context of the resting state of the vergence system) by the obvious involvement of a voluntary element found in the above studies, for the maintenance of directional position, and also by the brevity of their sampling periods.

There is little evidence regarding the temporal dynamics of the vergence system following the removal of the stimulus. Krishnan and Stark (1977) suggest that the system takes approximately 16sec for a prior steady-state vergence level to drift back to the resting position of the eyes.

Although provision for the study of long-term longitudinal stability of TA and TV was not included in the main experimental program of this thesis, information concerning this aspect may be obtained from the cross-referencing of data from those individuals who participated in more than one experiment. Additionally, information concerning the short-term longitudinal stability of TA and TV (i.e. over a period of < 1hr) may be inferred from the control studies within certain pharmacological experiments (e.g. Timolol, see Chapter 6). An example of typical data will follow for both the short- and long-term longitudinal stability of TA and TV.

3.5D ii - Short-term stability of TA and TV.

The data provided within Table 3.8 is an example of the longitudinal stability of TA and TV, for a typical subject (BG), over a 35min period.

Table 3.8 - An example of the short-term longitudinal stability of TA (D) and TV (deg) in a typical subject (BG) over a 35 minute period, giving the mean ($\bar{X}$) and standard deviation (sd).

	TIME (min)							
	10	15	20	25	30	35	$\bar{X}$	sd
TA	2.11	2.27	2.21	2.20	2.25	2.19	2.21	0.06
TV	2.21	2.22	2.30	2.28	2.27	2.26	2.26	0.04

It will be evident from Table 3.8 that the mean and standard deviation of the measures of TA and TV, over the 35min period were 2.21 and 0.06D, and 2.26 and 0.04D, respectively. These results are in agreement with those (results for TA) of Miller et al. (1983) and Post et al. (1984) and would indicate that both TA and TV are sufficiently stable for use as parameters in the short-term investigation of both the accommodative and vergence systems.

3.5D iii - Long-term stability of TA and TV.

As outlined earlier, the long-term longitudinal stability of TA and TV may be inferred from observation of the results of those subjects who had participated in more than one experiment, over a period extending over several months. The results of such an observer (MJ) may be found in Table 3.9.

Table 3.9 - Measures of TA (D) and TV (deg) from a typical subject (MJ), the mean values ($\bar{X}$) and standard deviations (sd), over a period of 7 months.

DATE	TA	TV
22/11/82	1.46	1.91
3/2/83	0.99	2.22
4/2/83	1.46	2.06
9/2/83	1.17	2.12
10/2/83	1.31	1.98
11/2/83	1.44	2.15
14/2/83	1.12	1.93
16/2/83	1.02	2.01
17/2/83	1.27	1.88
7/3/83	1.17	1.52
8/3/83	1.44	1.84
15/3/83	1.24	1.95
7/6/83	1.33	1.87
14/6/83	1.33	1.91
	$\bar{X}$ = 1.27	$\bar{X}$ = 1.95
	sd = 0.16	sd = 0.17

Over the 7 month period observer MJ had a mean TA of 1.27D with a standard deviation of 0.16. The maximum and minimum TA measurements were 1.46D and 0.99D, respectively, with a difference therefore, of 0.47D. It is interesting to note the results of Owens and Higgins (1983).- see section 3.5D i.

The maximum and minimum TV measurements (for MJ, over the same period) was 2.22 and 1.52 deg., respectively. This gave a mean TV of 1.95 deg. with a standard deviation of 0.17.

3.5D iv - Discussion.

These results for TA are in accordance with those of other workers (cited above), in that the level of stability diminishes slightly with increase in time between retest sessions; a similar pattern would appear to emerge for measures of TV. The work of Post et al. (1984) and others would suggest that objective measures of TA reveal a level of accommodative fluctuation not exhibited by those measures obtained by the subjective technique of laser optometry. The mean position of rest, as measured by both techniques would appear to be identical for most observers[1] which would suggest that the psychophysics involved in the technique of laser optometry might influence the variation in TA estimates without affecting the mean result. It is interesting to note that Post and his co-workers used a laser shutter-speed of 500msec; this has also been shown to induce a greater level of variation in TA measurements than a speed lower than the latency of accommodation (see section 3.5A and Hogan and Gilmartin, 1984b).

3.5E - THE EFFECT OF MENSTRUATION ON THE LONGITUDINAL STABILITY OF TA AND TV.

3. E i - Introduction.

If the observers that participated in all of the experimental aspects of this thesis were divided on the basis of gender alone, there would be a ratio of approximately 3:2, male to female. Such a division was not arranged by design (most subjects were selected on a randomised basis) but may reflect the sex-ratio existing at that time within the student population of the Vision Sciences Department at Aston. This level of female involvement is not unusual within a 'life-science' student population, and it is conceivable therefore that many physiological-based research projects, unless otherwise designed, would involve a similar proportion of female subjects. Assuming this female population to be of typical student age and, therefore menstrually active, it becomes increasingly necessary to monitor for any variation in response, unwittingly incorporated due to the fluctuations that occur in the blood-hormone levels throughout the menstrual cycle.

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[1] Post et al. (1984) only used 5 observers, 3 gave identical laser and i/r results.

It is with this potential error variation in mind that the decision was taken to monitor any menstrual cyclic effect on measurements of both TA and TV on female subjects over a normal 28 day cycle.

Opinion on the effect of the menstrual cycle on performance efficiency within cognitive and/or psychomotor tasks is separated into two opposing camps. The traditional view has been that women are significantly affected, both physically and mentally, by the phase of their menstrual cycle (Dalton, 1969; 1977); specifically at some point in the paramenstruum[1]. In contrast, the alternative position considers the alleged effects to be attributed to menstrual folklore, mythology and cultural stereotypes, rather than to the menstrual cycle per se (Paige, 1971; Parlee, 1974). The largely negative results reported for the effects on task performance (reviewed by Sommer, 1973) have often been interpreted as lending support to the latter claim. Such an interpretation has to be viewed with caution however, as research in this area is fraught with methodological weaknesses; such as poor experimental control, low sample size and lack of consistency in menstrual phase definition (see Jensen, 1982).

The menstrual cycle is typically divided into four phases:

a) the menstrual phase - the start of menstruation is generally taken to be day 1 and usually lasts from 5 to 7 days; b) the pre-ovulatory phase - which is equivalent to days 8 to 13 of the 28 day cycle, during which the level of oestrogen is known to increase (Billings et al., 1972). Release of follicular stimulating hormone, from the anterior pituitary, at the start of this phase initiates the secretion of oestrogen from the ovaries; c) the

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1. The term "paramentsruum" refers to the period comprised by the four days preceeding and following the onset of menstrual flow.

ovulatory phase - usually day 14, when the level of oestrogen is at a maximum, which stimulates the the anterior pituitary to increase secretion of Luteinizing hormone, which in turn stimulates release of the ovum from the follicle; d) the pre-menstrual phase - commences from the time of ovulation and ends with the onset of menstruation. Within this phase, the empty follicle develops into the corpus luteum from which progesterone is secreted in order that proliferation of the uterus lining may occur, in readiness for the potential implantation of the fertilised oocyte. The level of progesterone reaches a maximum level at about day 21, plasma oestrogen levels also increase slightly at this time (Smith, 1983).

The division of the menstrual cycle is as not always as fixed as the above phases would suggest, in that its characteristics may be affected dramatically in response to a wide range of physiological and psychological variables.

It has been shown that the menstrual cycle is able to affect many aspects of the basic cognitive, sensory and physiological processes of female behaviour (for reviews see Southam and Gonzaga, 1965; Dan et al. 1981; Komnenich et al., 1981; and Parlee, 1982 and the study of Jensen, 1982). It is conceivable therefore, that ocular function, involving as it does the autonomic, somatic and cortical neuromuscular systems, may similarly be affected by the variable hormone levels that are known to occur in the female body, over the 28 day cycle.

Ocular effects have been recorded: e.g. significant changes were reported in visual thresholds (Diamond et al., 1972; Barris et al., 1980; Scher et al., 1981). All these studies reported an increase in sensitivity immediately following ovulation. Speculation as to this cause has ranged from changes in corneal thickness (Leach et al., 1971; Feldman et al., 1978; Soni, 1980;

and Keily et al., 1983) as the cause of changes in performance on a complex vision detection task (Ward et al, 1978), to the effects of a central nervous system "clock" (Diamond et al., 1972) influencing the detection criterion (DeMarchi and Tong, 1972).

Millodot and Lamont (1974) were able to detect a significant decrease in corneal sensitivity corresponding with the paramenstruum. This effect was not detected in women taking oral contraceptives, or in a control study of men. Following the reports of Dalton (1967) - of an increase in intraocular pressure (IOP) during the paramenstruum; and of Boberg-Ans (1955) - that an increase in IOP may cause a reduction in corneal sensitivity; Millodot and Lamont speculated that both factors, the increase in IOP and the known water retention at the onset of this period, may somehow contribute to this variation in corneal thickness.

Bergin (1955) has reported an increase in the dioptric power of the eye (0.26D) in six of his seven observers during the paramenstruum, presumably due to an increase in corneal curvature due to oedema (outlined above). Apart from this study, there is a relative paucity in the literature regarding a menstrual effect on accommodation and binocular vision. It may come as no surprise therefore to find that the author was unable to detect any reference to an effect on TA or TV. The nearest to a menstrual effect on TA was the report by Miller et al. (1983) of a "nearly significant" tendency ($F = 3.96$, $p = 0.08$, $df = 1, 8$) for measurements of TA over a 3 hour period, to be more variable in females than males.

3.5E ii - Methodology.

Daily measures of TA (see section 3.1C ii) and TV (see section 3.2B ii) were taken from three, refractively-corrected, trained, female observers, over a 28 day period. None of the observers were taking oral contraceptives and none reported any abnormal menstrual symptoms. The experimental sessions were conducted at different, but constant times of the day for each observer.

3.5E iii - Results.

Table 3.10 gives the measures of TA and TV over the 28 day period.

Table 3.10 - Measures of TA (D), TV (deg), their means ($\bar{X}$) and standard deviations (sd) from three female observers, over a 28 day period.

	SS		SH		MM		$\bar{X}$	
DAY	TA	TV	TA	TV	TA	TV	TA	TV
1	1.88	2.61	1.21	1.86	0.95	2.23	1.35	2.23
2	1.64	2.65	1.14	1.84	0.97	2.11	1.25	2.20
3	1.40	2.43	1.12	1.78	1.03	2.06	1.18	2.09
4	1.36	2.21	1.15	1.71	0.99	2.06	1.17	1.99
5	1.36	2.04	1.19	1.59	1.03	1.99	1.19	1.87
6	1.25	2.00	1.26	1.51	1.06	2.07	1.19	1.86
7	1.11	2.01	1.24	1.46	1.02	2.02	1.12	1.83
8	1.03	2.03	1.30	1.35	0.99	2.10	1.11	1.83
9	1.29	2.39	1.11	1.34	0.96	2.18	1.12	1.97
10	1.61	2.71	0.93	1.35	0.75	2.13	1.10	2.06
11	1.52	2.37	1.09	1.31	0.55	2.19	1.05	1.96
12	1.46	1.71	1.27	1.24	0.57	2.14	1.10	1.70
13	1.30	1.83	1.21	1.39	0.61	2.27	1.04	1.83
14	1.23	1.82	1.10	1.55	0.64	2.31	0.99	1.89
15	1.11	1.95	1.02	1.66	0.68	2.40	0.94	2.00
16	1.36	2.26	1.47	1.62	0.72	2.57	1.18	2.15
17	1.49	2.14	1.84	1.44	0.86	2.49	1.40	2.02
18	1.72	2.87	1.78	1.43	0.65	2.51	1.38	2.27
19	1.66	2.31	1.80	1.45	0.45	2.61	1.30	2.12
20	1.60	1.75	1.76	1.41	0.39	2.42	1.25	1.86
21	1.57	1.87	1.75	1.38	0.32	2.15	1.21	1.80
22	1.47	1.93	1.41	1.28	0.21	1.89	1.03	1.70
23	1.44	2.04	1.65	1.54	1.03	2.17	1.37	1.92
24	1.46	2.15	1.84	1.59	0.29	2.78	1.20	2.17
25	1.45	2.45	1.86	1.77	0.54	2.71	1.28	2.31
26	1.45	2.61	1.64	1.94	0.74	2.86	1.28	2.47
27	1.49	2.65	1.79	1.88	0.76	2.61	1.35	2.38
28	1.61	2.72	1.76	1.86	0.81	2.44	1.39	2.34
$\bar{X}$	1.44	2.25	1.42	1.57	0.73	2.30	1.20	2.03
sd	0.19	0.35	0.31	0.20	0.25	0.26	0.13	0.21

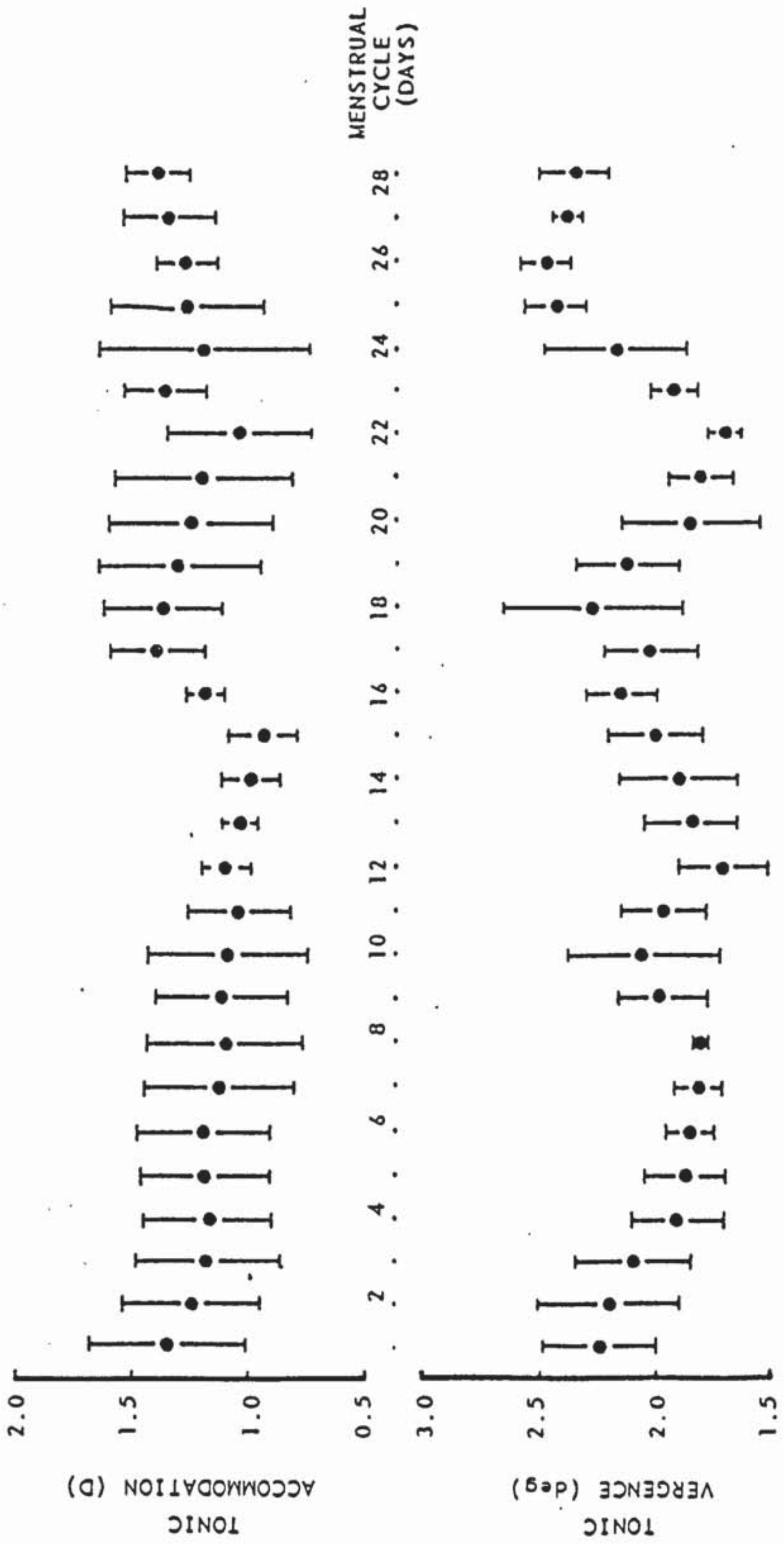

Figure 3.7 - Illustrating the effect of the 28 day menstrual cycle on daily measures of TA (D) - upper graph, and TV (deg) - lower graph; plotted as a function of this time period for three female observers. The error bars represent the standard deviation of the mean differences for each observer.

Although each observer commenced the study at different phases of their individual cycles, the results have been rearranged so that the onset of menstrual bleeding (day 1) coincides in each case.

The effect of the menstrual cycle on the stability of measures of TA and TV is illustrated in fig. 3.7; the data points plotted represent the mean TA and TV values (upper and lower graph, respectively) for the three observers. The error bars either side of these mean values, represent one standard deviation of the pooled differences between the daily TA and TV measurements and the means for each individual observer.

It is known that large differences in both TA and TV measurements exist between observers (see fig. 2.2): it is for this reason that analyses of variance (ANOVA) have been performed on the pooled and "normalised" differences between each measurement and the individual mean values, over the 28-day cycle[1]. It is largely because of this strategy therefore, that no significant differences were found between subject for either TA (F=0.01, df=2, p=ns) or TV (F=0.23, df=2, p=ns). There was a significant effect due to time, over the 28-day cycle (for TA, F=4.65, df=13, $p<0.01$: for TV, F=8.83, df=13, $p<0.01$). It would appear however, that the effects on TA (due to "time of month") were not significantly different to those effects on TV (F=0.38, df=1, p=ns).

It is possible to perform partial ANOVA on the data in order that the different characteristics of the various phases of

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[1] Restrictions in the factor level capacity of the ANOVA statistical package used - see Appendix IX - have limited the analysis to the pairing of the data of consecutive days (e.g. day 1 with day 2). This explains why the df values for the time factor are 13 (i.e. 14 minus 1) rather than 27 (i.e. 28 minus 1).

the 28-day cycle may be analysed and compared. It can be shown that there are significant day-to-day effects during days 1 to 6, the menstrual phase (F=34.36, df=2, 13, p<0.01), but that these effects on TA were not significantly different to those of TV (F=1.04, df=1, p=ns). No significance was found in the day-to-day variation in TA and/or TV over days 7 to 12, the pre-ovulatory phase, (F=1.694, df=3, 13, p=ns); whilst the day-to-day effect during days 13 to 15, the ovulatory phase, only just managed to reach significance at the 5% level (F=5.89, df=1, 13, p=0.05). There was a significant day-to-day effect demonstrable during days 17 to 28, the pre-menstrual phase, (F=8,874, df=5, 13, p<0.01), although there was no significance in the difference in the effect's between TA and TV (F=0.01, df=1, p=ns).

3.5E iv - Discussion.

If the three observers used in this study are representative of the female population as a whole, it would appear that women exhibit a slight variation in the levels of both TA and TV, as a function of the 28-day menstrual cycle. Those measurements taken during the pre-menstrual and menstrual phases are the most variable, with the ovulatory phase measurements varying only at the 5% level, whilst the variation in those measurements taken during the pre-ovulatory phase fail to reach significance even at this level. It is unlikely that each observer ovulated at exactly the same time (there was certainly a day or so difference between the observers in the cessation of menstrual flow), so it is important to understand therefore that some overlap in phase was unavoidable and that the phase boundaries have been artificially imposed.

The standard deviations of individual TA and TV measurements ranged from 0.19 - 0.31D and 0.20 - 0.35 deg, respectively; although the standard deviations of the mean TA and

TV measurements over the 28-day cycle was 0.13D and 0.21 deg, respectively. If these results are compared to those obtained from data taken over a similar period from a typical male observer (data from table 3.9) it is evident that the standard deviation of TA and TV is slightly less at 0.15D and 1.93 deg, respectively. This would indicate that females were slightly more variable observers than males.

The above raises the question "Should account be taken of the time of month in those studies involving longitudinal measurements on female observers?" An answer based on the results of this study alone would have to be tempered in the knowledge of the low number of observers used, but it would appear from the results that the answer would have to be in the affirmative. Fortunateley, the other studies of this thesis, in which female observers have participated, involve measurements of TA and TV taken from individuals over a time period of an hour or less.

The current interpretation regards the physiological changes that occur during the cycle as producing a state of psychological tension which pre-disposes women to perform abnormal behaviour. Warren et al. (1979) suggest that the psychological changes are due to imbalances in the levels of progesterone and oestrogen occurring during the pre-menstrual phase and may account for the phenomenon of "pre-menstrual tension" or P.M.T. It is thought that the changes in the levels of progesterone and oestrogen produce changes in brain amine levels (via the monoamineoxidase pathways) and therefore, changes in C.N.S. transmitter substances; this would have the effect of eliciting changes in perceptual and emotional behaviour. It is unlikely, from the present results, that the variation is due to oestrogen alone as maximum levels are achieved at ovulation. It is possible however, that some combination of influences is responsible to account for the increased variation towards the end of the cycle.

It is interesting to note that at no phase in the cycle was there a significant difference in the effect on TA to that on TV. This observation might be accounted for if the physiological effects of the variation in hormonal influence over the cycle, had a central effect on the midbrain, as well as elsewhere. Furthermore, the observation may be of significance with respect to the question of a correlation between TA and TV (see chapter 4 for further discussion on this topic).

CHAPTER 4

OBSERVATIONS ON THE RELATIONSHIP BETWEEN TONIC ACCOMMODATION, TONIC VERGENCE, TONIC PUPIL, THE OCULOMOTOR BALANCE AND AMETROPIA.

4.1 - INTRODUCTION.

This chapter is essentially concerned with the measurement of resting levels of accommodation (TA), vergence (TV) and pupil size (TP) for a relatively large group of observers (N=60). This information will provide a reference database of normative values for a series of further investigations involving the measurement of these parameters. It is known that under the normal stimulus conditions of a spatially and temporally dynamic visual environment, a synkinesis is found to exist between accommodation, vergence and pupil size. It will be interesting to ascertain whether or not this synkinesis is maintained under the astimulus conditions of total darkness. It will be of further interest to investigate how TA and TV inter-relate with other parameters involved in the maintenance of the oculomotor balance. There have been some reports in the recent literature of a relationship between TA and ametropia; this aspect will be reviewed and investigated in an attempt to rationalise the role of TA within the accommodative system.

4.1A - The N=60 database.

Sixty observers (comprising 37 males and 23 females) were randomly selected from the student population of the Department of Vision Sciences, University of Aston in Birmingham. The ages of the observers ranged from 18 to 36 yr with a mean and standard deviation of 21.6 and 3.0 yr respectively. All sixty observers were screened for any ophthalmological and binocular visual defect, refracted and had measurements recorded of relevant optometric and oculomotor parameters: each observer was required to achieve a visual acuity of 6/6 in each eye.

4.2 - TONIC ACCOMMODATION.

A brief review of the literature on the subject of tonic accommodation has been provided within section 1.4 (and particularly within sub-sections 1.4G, 1.4H and 1.4I). The results from a typical selection of recent studies from this literature are represented in Table 1.2; the mean range of TA values encountered by these studies can be shown to be from 0.15D of hyperopia to 3.52D of myopia, with a mean of 1.49D and mean standard deviation of 0.75D.

4.2A - The measurement of TA for the N=60 database.

Details of the laser optometer have been provided in sub-section 3.1C i, of the methodologiocal procedure in sub-section 3.1C ii and of the methodological control in section 3.4.

TA measurements were taken from the left eye of each observer under two refractive conditions: i) with the infinity refractive correction in place (TA+Rx); and ii) without any refractive correction in place (TA-Rx).

4.2B - Results and discussion of the measurement of TA.

The results for the measurement of TA are tabulated in Appendix XV. Where the results of measures of TA are discussed in the text, it is to be assumed (unless otherwise stated) that the infinity-balanced refractive correction (Rx) was worn by each observer.

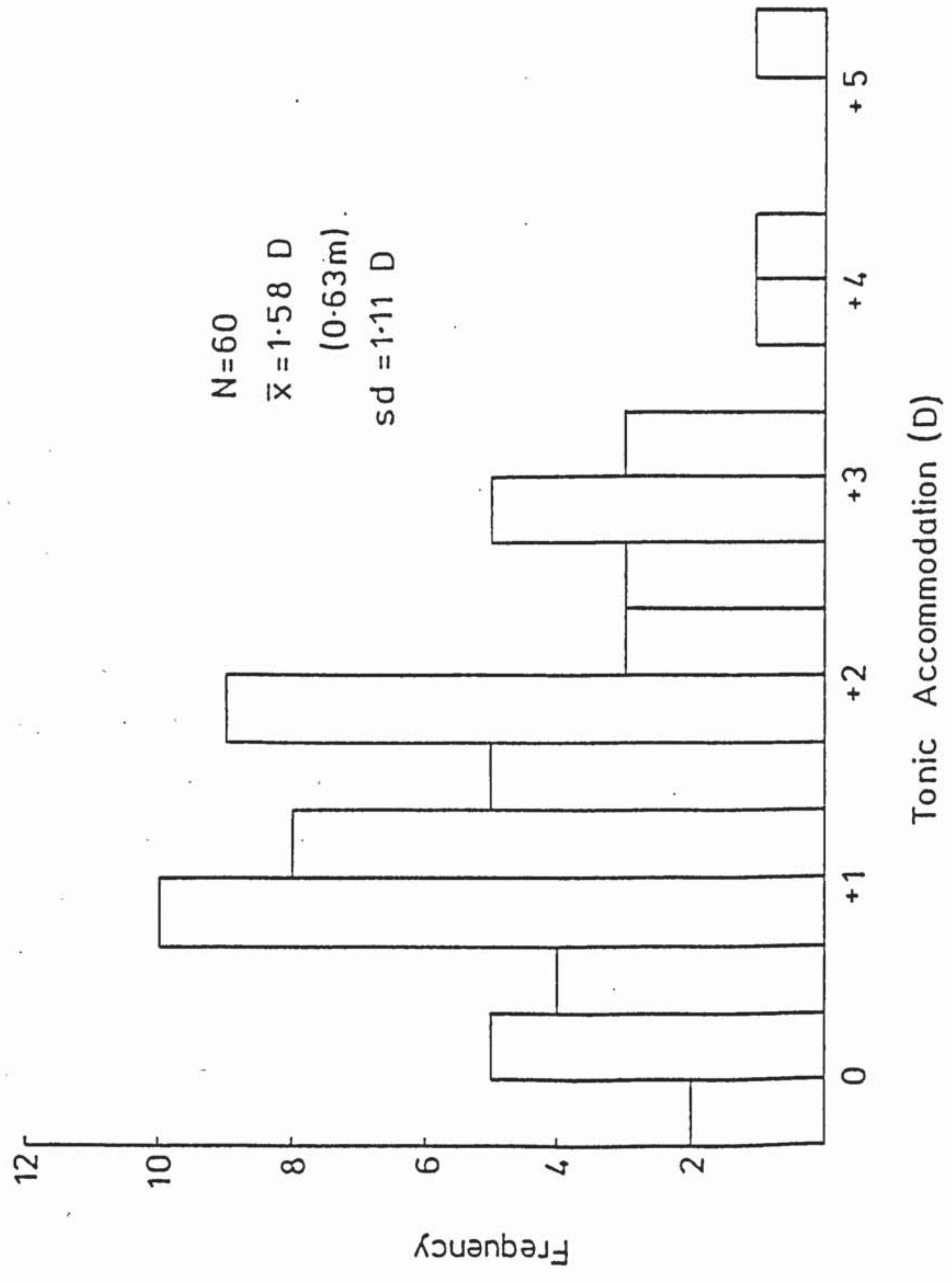

Figure 4.1 - Illustrates the frequency distribution of TA measurements (in D, at 632.8nm) for the N=60 observer-group. The positive values on the abcissa refer to an increase in the ocular power.

The mean value for TA for the N=60 database was found to be 1.58D of myopia (see fig 4.1). This value is slightly larger than the mean value for TA given in Table 1.2; especially when one considers that these studies (where appropriate) have included a correction of +0.33D for chromatic aberration, whereas the present results do not (for a discussion see section 3.5C). It is considered that most of this discrepancy can be accounted for by the low number of subjects used during some of the earlier studies, together with an inadequate control over their refractive condition. A number of the studies applied an inclusion/exclusion bar on their subjects based on visual acuity alone: e.g. Owens and Leibowitz (1976a) set a limit of "20/35" and accepted subjects who "wore their normal refractive corrections" - in other words, these subjects were not necessarily wearing a current, accurate refractive correction and it is possible therefore, that a number may have been hyperopic, which would have resulted in a relatively reduced mean TA value.

The standard deviation of TA for the N=60 database was found to be 1.11D, this is slightly larger than the mean standard deviation of 0.75D as given by the studies of Table 1.2. This difference may be accounted for by the increased range of TA values encompassed in the present study (-0.18D of hyperopia to 5.27D of myopia) in comparison to the mean range of the studies given in Table 1.2 (-0.15D of hyperopia to 3.52D of myopia).

The difference between measures of TA, taken with and without Rx in place, will be discussed in section 4.7.

4.3 - TONIC VERGENCE.

A brief review of the relevant literature has been provided in section 2.3. This included discussions on the anatomical and physiological positions of rest (sub-sections 2.3B and 2.3C, respectively), and outlined the evidence for a return of vergence towards a mean intermediate position of rest under the effects of: a) reduced illumination and total darkness (sub-section 2.3C i); b) oculomotor stress (sub-section 2.3C ii); c) eccentric or peripheral stimulation (sub-section 2.3C iii); and d) immature visual development (sub-section 2.3C iv).

4.3A - The measurement of Tonic vergence for the N=60 observer-group.

Measurements of TV were taken from the same database group of 60 observers used in the TA study above. The theory behind the nonius alignment technique of eye position assessment has been outlined in section (3.2A). Details have been provided, of the instrumentation used in the measurement of TV in the present study (in section 3.2B i), of the methodological procedure employed (in sections 3.2B ii + iii), and of the methodological control (in section 3.4).

4.3B - Results and discussion.

The results for the TV measurements have been calculated in terms of the degrees of ocular rotation (TV-deg) and the distance to which the visual axes intersect (TV-cm) and are incorporated in Appendix XV. The mean TV-deg for the N=60 database was found to be 2.18 deg (with a standard deviation of 1.03 deg), whilst the mean TV-cm was found to be 108cm (with a standard deviation of 58.24cm).

This data is illustrated in Figure 4.2.

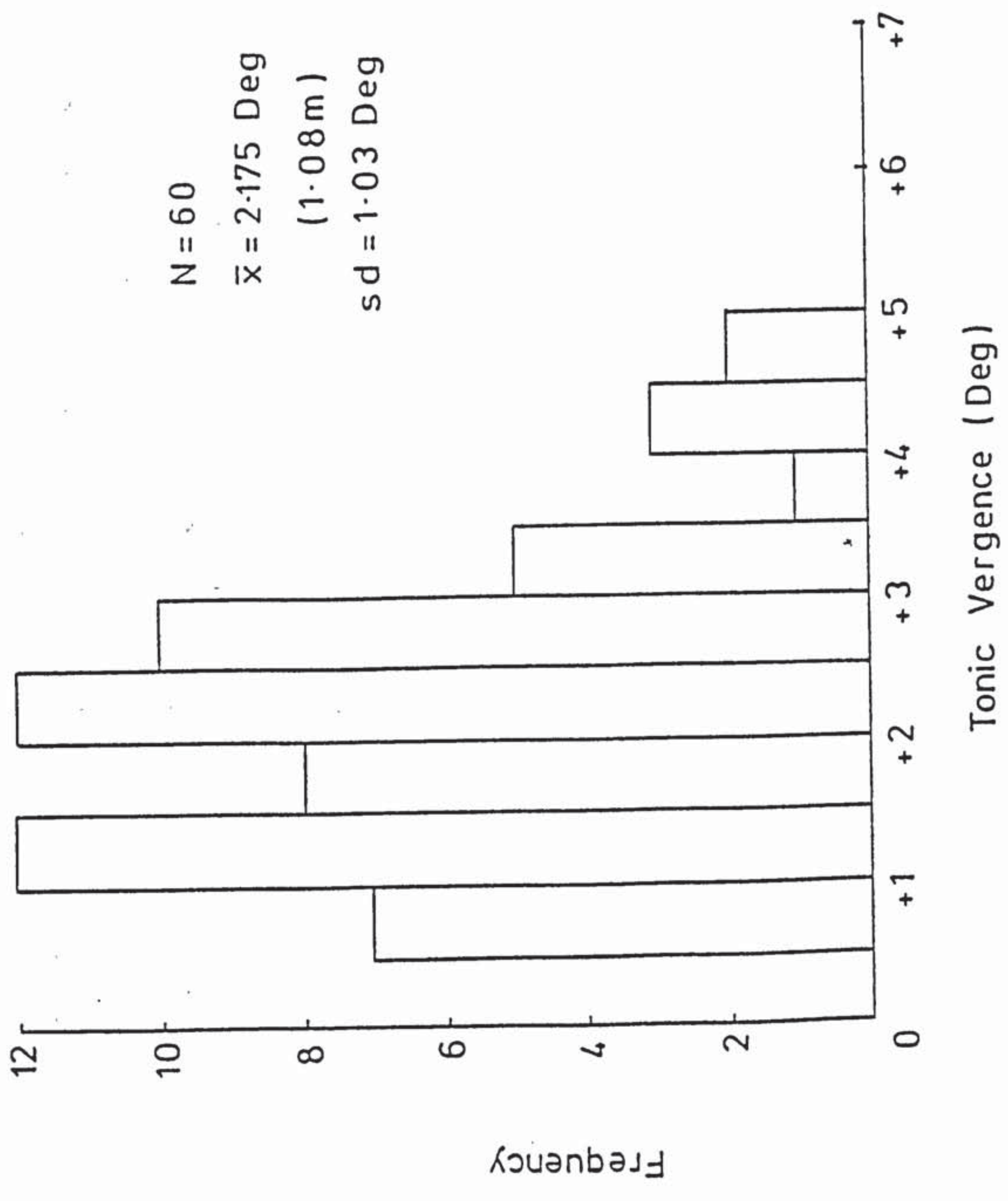

Figure 4.2 - Illustrates the frequency distribution of TV measurements from an N=60 group of observers. A positive abcissa value indicates degrees of convergence.

The most comprehensive study of tonic vergence to date is that of Owens and Leibowitz (1980), in which the mean TV was found to be 3.22 deg or 1116cm (for N=60). It is evident that the mean TV values compare well when expressed as a function of the distance (from the observer) that the visual axes horizontally intersect at a midline, whereas there would appear to be some difference between the mean results when expressed in terms of ocular rotation in degrees. This discrepancy between the two studies is due to a difference in the definition of the vergence angle: the present study considers the vergence angle to be the angle of rotation of each eye from the primary position (see sub-section 3.2B iii), the Owens and Leibowitz study however, considers it to be the angle described between the the visual axes at intersection along the midline, i.e. twice the vergence angle of the present study.

There are a number of methodological differences between the Owens and Leibowitz study and the present study. In the former study, the observers were not refracted and were only required to were their "normal" correction if necessary in order to attain a level of acuity of "20/35"; in the present study, all observers were required to wear their accurate, infinity-balanced and -centred, refractive correction, as ascertained immediately prior to the commencement of TV measurement. In the former study, the dichoptic stimuli of the vergence apparatus were viewed by the observers at a constant distance of 1m, regardless of the dark focus position found. It is considered that this procedure might induce errors in the perception of the alignment of the blurred dichoptic stimuli, if sufficient difference existed between the stimuli position and the resting focus[1]. In the measurement of

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[1] The author has observed that differences of only 0.75D between TA and the position of the vergence unit will cause the dichoptic stimuli to appear blurred, therefore increasing the liklihood of an erroneous result.

TV, the present study employed a strategy whereby the vergence unit was placed at an equivalent dioptric position to that of the TA position for each observer; in this way, the dichoptic lines were viewed in optimal focus, thereby assisting the perception of apparent alignment. This strategy would also have the effect of minimizing the interaction between accommodation and vergence measurements.

A further difference between the two studies concerns the calculation of the TV value. The Owens and Leibowitz study calculated their TV values for a mean inter-pupillary distance (IPD) of 65mm, in an attempt to "standardize" the results in order that TV could be described in terms of degrees and metres on the same axis (see Fig. 2.2). It is evident from Appendix XV that the IPD's encountered in the present study ranged from 58 to 72mm, with a mean of 64.58mm. In the present study the calculation of TV takes each individual IPD into account.

4.4 - TONIC PUPIL.

It is known that the accommodative response is influenced by pupil size and the associated effect on the depth of field (Ripps et al., 1962a; Hennessy et al., 1976). It is also acknowledged that pupil activity is involved with both accommodation and vergence within a synkinesis in the response to near vision (Duke-Elder, 1973; Burian and Von Noorden, 1974; and Davson, 1980). Measurement of pupil size under the stimulus-free conditions of total darkness (described in this thesis as Tonic Pupil or TP) for the N=60 database will be of interest with regard to this synkinesis. The measurement of TP will be of further interest (as normative data) for chapter 6 and its concern with the autonomic characteristics of the control of accommodation.

4.4A - The measurement of Tonic Pupil for an N=60 observer-group.

Pupil size was recorded under conditions of total darkness from the same N=60 database group employed in the previous TA and TV studies, using the technique of infra-red photography. Details of the technique and procedure employed in the present study have been provided in sub-sections 3.3Aii and iii respectively. The timing and methodological control of pupil measurement has been described in section 3.4. Horizontal pupil diameter was measured from slide-projection of the photographic film negative (as outlined in sub-section 3.3B).

4.4B - Results and discussion of TP measurements.

As would be expected under conditions of reduced illumination, the pupil was found to be dilated: the mean horizontal pupil diameter in total darkness was found to be 7.02mm, and ranged from 5.20 to 8.25mm, with a standard deviation of 0.56mm. The results have been incorporated within Appendix XV and are illustrated as a frequency distribution in Figure 4.3.

With regard to the acknowledged synkinesis between pupil activity, accommodation and vergence under "normal" visual conditions, it can be shown that the size of the pupil is unrelated to the state of accommodation under the astimulus conditions of total darkness (for TA t Rx, $r = -0.07$, $p = 0.6$; for TA ≠ Rx, $r = 0.04$, $p = 0.77$). Pupil size is similarly unrelated to the state of vergence for the same astimulus conditions (for TV-deg, $r = 0.001$, $p = 0.99$). It would appear therefore, that for pupil at least, the synkinesis has been broken.

There was no significance in the relationship between Rx and TP ($r = -0.06$, $p = 0.66$).

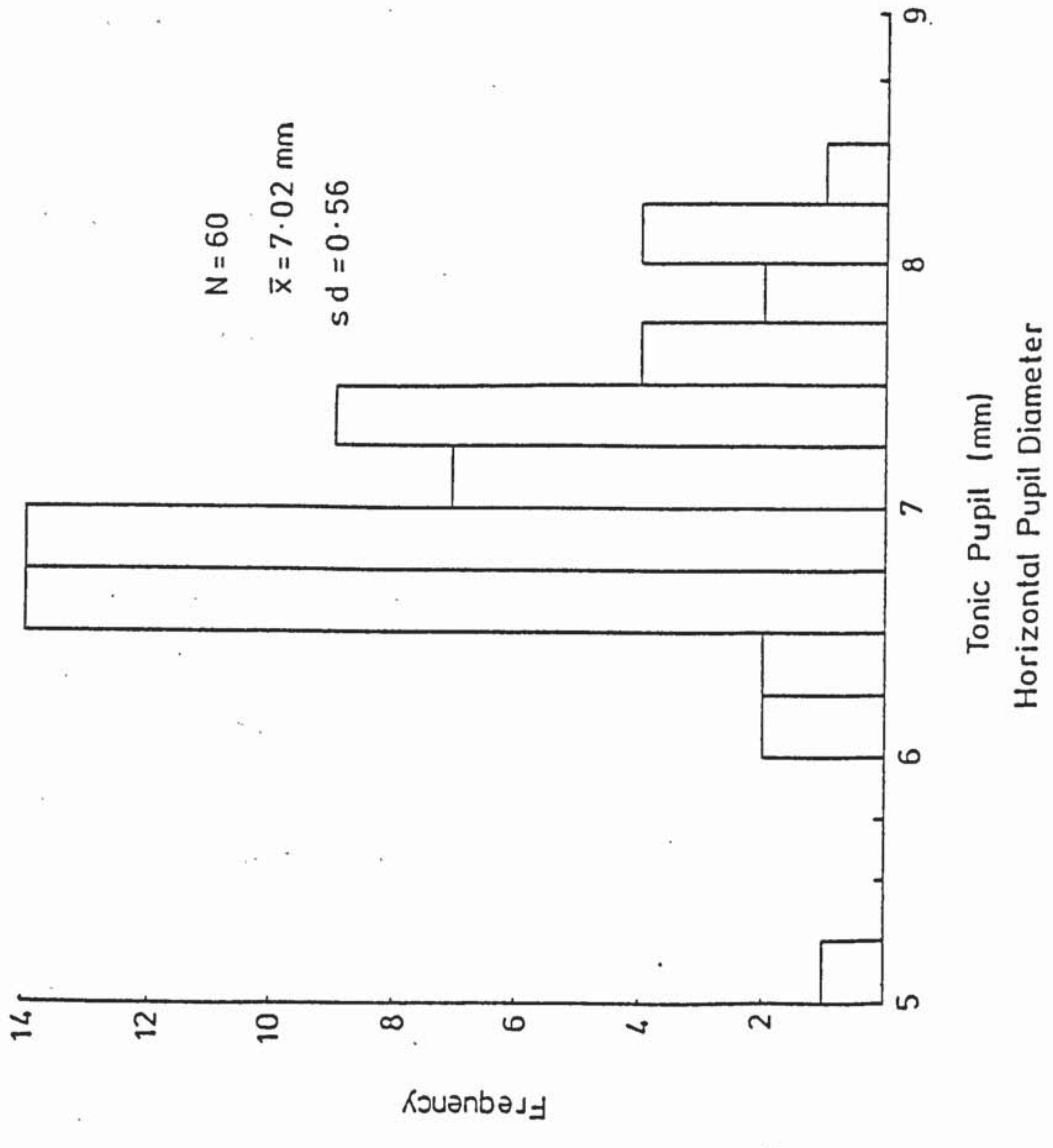

Figure 4.3 - Illustrating the frequency distribution of Tonic Pupil measures from an N=60 observer-group.

4.5 - THE OCULOMOTOR PROFILE OF THE N=60 OBSERVER GROUP.

4.5A-The determination of the oculomotor profile.

Immediately prior to the determination of TA and TV, each observer was refracted and had details recorded of the various aspects of the oculomotor balance measured with Rx in place and employing standard optometric techniques (each technique employed has been previously described by Hogan and Linfield, 1983). Dissociated heterophoria measurements were taken from each observer at stimulus distances of 6m and 33cm, using the techniques of Maddox rod and Maddox wing respectively. Measures of accommodative-vergence / accommodation (AC/A) ratio were also taken from each observer using the Maddox Wing and the "Gradient technique". The amplitude of accommodation (AA) was measured using a R.A.F. near point rule and the result recorded as the mean of three estimations. The near point of convergence (NPC) was measured as the closest distance that a 10 x 0.5mm vertical black line (drawn on white card) could be brought towards the observer, whilst maintaining single binocular vision.

4.5B - Results and discussion of the oculomotor profile.

The results of the determination of the oculomotor profile of the N=60 database have been incorporated into the Table contained in Appendix XV. The mean estimate of heterophoria at 6m was found to be almost orthophoric at 0.01_{Δ} of exophoria (XOP) and ranged from 5_{Δ} of esophoria (SOP) to 16_{Δ} of XOP, with a standard deviation of 2.72. The mean heterophoria at 33cm was found to be 1.96_{Δ} of XOP, with the results ranging from 5_{Δ} of SOP to 12_{Δ} of XOP, with a slightly larger standard deviation of 3.35. The mean AC/A ratio was found to be 2.73_{Δ}/D within a range from 0.33 to

6.33Δ/D and standard deviation of 1.28. The mean estimate of the NPC was found to be 6.72cm within a range from 2.5 to 12cm and a standard deviation of 1.75cm. The final parameter of the oculomotor profile was the A of A; this gave a mean of 8.69D within a range from 5 to 12D and a standard deviation of 1.56D.

There was a weak correlation between the level of heterophoria at 6m and that at 33cm ($r=0.49$, although the regression was significant at the 0.1% level. As expected, there was no significance in the relationship between the 6m heterophoria measurements and the AC/A ratio ($r=-0.09$, $p=0.51$), although the relationship found between the 33cm heterophoria measurements and the AC/A ratio ($r=-0.31$, $p<0.05$) did indicate a trend for those observers with low AC/A ratios to have the larger amounts of XOP at 33cm. The level of heterophoria at 33cm was also weakly correlated to the NPC ($r=0.32$) with the regression significant at the 1% level.

4.6 - THE RELATIONSHIP BETWEEN TA AND TV AND THE OCULOMOTOR PROFILE

The measurements of TA, TV and TP have, up until this stage of the thesis, been discussed as relatively separate entities. It will be interesting to ascertain whether or not the relationship that is known to exist between accommodation and vergence under conditions of a spatially dynamic visual environment is maintained under the astimulus conditions of total darkness. It will be of further interest to investigate how TA and TV inter-relate with other parameters concerned with the maintenance of the oculomotor balance under normal visual conditions.

4.6A - The relationship between TA and TV.

In 1962, Fincham used Purkinje image and corneal reflex infra-red photography to measure the accommodation and vergence responses of 9 subjects whilst attempting to "look into the distance" under conditions of darkness. His results indicated that while both accommodation and vergence in darkness assumed intermediate positions (with means of 137.9cm and 197.2cm, respectively), the level of accommodation attained for each observer did not correspond to the concurrent level of vergence. Owens and Leibowitz (1980) measured the "dark focus" and "dark vergence" of 60 observers using the techniques of laser optometery and vernier-alignment respectively and found that accommodation and vergence attained intermediate positions of 1.32D (75cm) and 3.22 deg (or 116cm) respectively - the frequency distributions of their results have been provided in Fig. 2.2. They found that accommodation and vergence were weakly correlated under darkroom conditions ($r=0.32$, $p < 0.05$, $N=60$) and presented their data in the form of a scatter diagram; this has been reproduced in Fig 4.4.

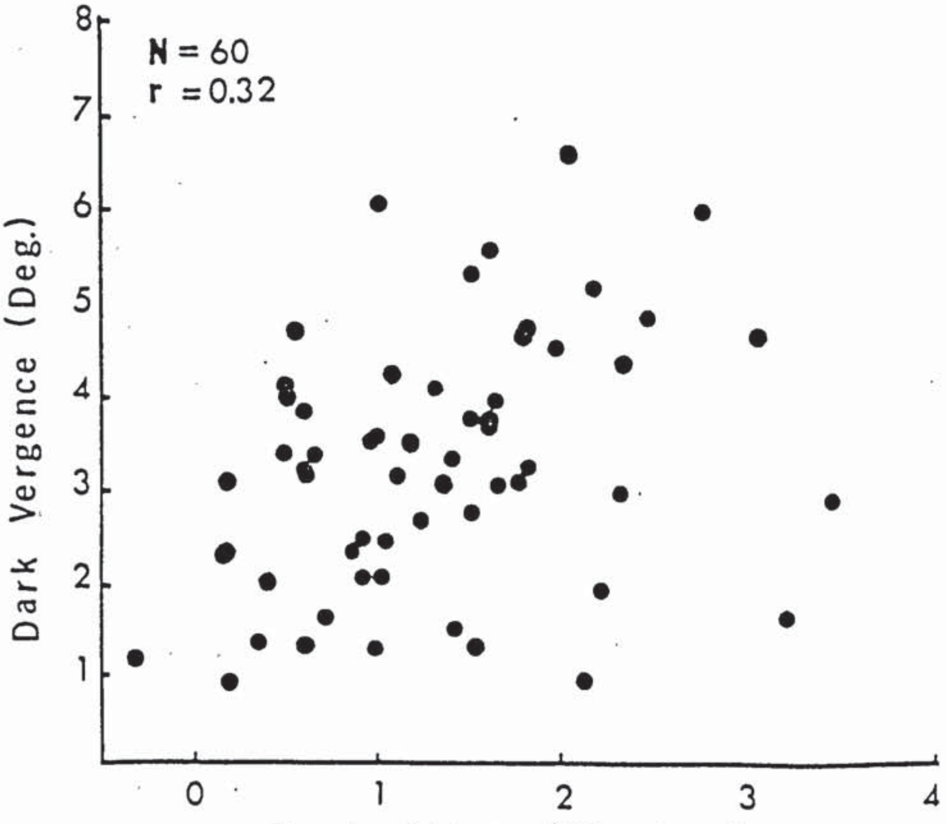

Figure 4.4 - Scattergram illustrating the relationship between accommodation and vergence under conditions of darkness (after Owens and Leibowitz, 1980). A positive ordinate value indicates convergence, whilst a positive abcissa value indicates an increase in dioptric power of the eye.

Aslin and Dobson (1983) measured accommodation and vergence under conditions of darkness, in 12 infants (ages ranging from 3 to 12 months) using the techniques of isotropic photorefraction (Atkinson et al., 1981) and fundal-reflex photography, respectively. Their results indicate that, for the majority of their infants, the accommodative and vergence systems became uncoupled in the dark.

It is with some interest therefore, that analysis of the results of the present study indicates the existence of a significant relationship between TA and TV for the individual observers within the N=60 database ($r=0.80$, $p<0.001$). Figure 4.5 presents a scattergram of these results, illustrating the positive correlation found between the resting states of accommodation and vergence under conditions of total darkness.

It is evident that there is relatively less spread of the data points in this latter diagram than in that of Owens and Leibowitz fig 4.4. It is interesting to note however, that the relationship between TA and TV (in the present study) appears to weaken at the higher resting levels. This can in fact be tested; for the 43 observers with TA values <2.00D, a similar correlation may be demonstrated to that of the N=60 group as a whole (for the N=43 group, $r=0.80$, $p<0.001$), whilst the relationship weakens for the 17 observers with TA values greater than 2.00D ($r=0.43$, $p=0.08$).

Why should the present study discover a significant correlation between TA and TV, whilst previous studies have, at best, only found a weak relationship? In an attempt to answer this question one must examine certain methodological shortcomings that exist in some of the previous studies.

It would appear from Fincham's (1962) study, that measures of the state of accommodation and vergence had been taken as soon as the fixation lights were extinguished, whilst his subjects were encouraged to "look into the distance". Due to the short-term variability of both accommodation and vergence, that is known to exist under conditions of total darkness (outlined in section 3.5D i), it is possible that Fincham had sampled the accommodative and vergence systems before they had fully assumed their respective rest positions: this may also account for the relatively low mean intermediate resting positions attained (0.73D or 137cm and 0.52 metre-angles or 197.2cm for accommodation and vergence, respectively).

The low accommodation value may also be due in part to the fact that measurements were taken from the observers whilst in the unrefracted state. It is also possible that the technique utilised by Fincham in the measurement of accommodation (i.e. third-Purkinje image photography), may not be as accurate as its theory suggests. Fincham readily acknowledges that the technique requires the careful selection of suitable observers for various reasons; e.g. variations in the definition of the image, variation in the angle-alpha and the variable effect of accommodation on the relative position of the image.

These factors led Fincham to state:

> "The accuracy of the determination of accommodation by the method of comparing the size of the images reflected by the front surface of the lens is obviously impaired in such cases".

It is perhaps a little unfair to compare the study of Aslin and Dobson (1983) to those studies involving adult observers, for the simple reason that the infant accommodative and vergence systems are are still relatively immature and are known to range within comparatively closer distances than their adult counterparts (for accommodation see the studies of Haynes et al., 1965; Banks, 1980; and for vergence see the studies of McKenzie and Day, 1972; Aslin and Jackson, 1979; 1981). The results of the Aslin and Dobson (1983) study confirm the findings of an earlier study by Aslin and Jackson (1981), in that infant TV measurements are much closer than adult TV measurements, although the TA measurements were comparable for the two populations. As with the Fincham (1962) study, Aslin and Dobson (1983) measured the resting positions of their infants while uncorrected for refractive error.

Several methodological and procedural shortcomings exist in the study of Owens and Leibowitz (1980): the lack of refractive control of the observers; the use of an inflexible (1m) "stimulus" distance for the dichoptic bars of the vergence apparatus; the "standardization" of vergence results for a IPD of 65mm; and the lack of a correction for induced prismatic effect on the perceived position of the dichoptic bars (due to distance centred spectacle correction).

A further difference between the two studies was the shutter duration used in the laser optometer. The Owens and Leibowitz study utilised a shutter duration of 500ms, whilst the present study used a shutter speed of 300ms (see section 3.5). It has been demonstrated (Hogan and Gilmartin, 1984b), that the variation in TA measurement is least with a shutter speed of 300ms. It is possible that a combination of these factors may account for the relatively increased spread of data points and the lower level of significance observed within the scattergram of the Owens and Leibowitz study (fig. 4.4), when compared to the results of the present study (fig. 4.5).

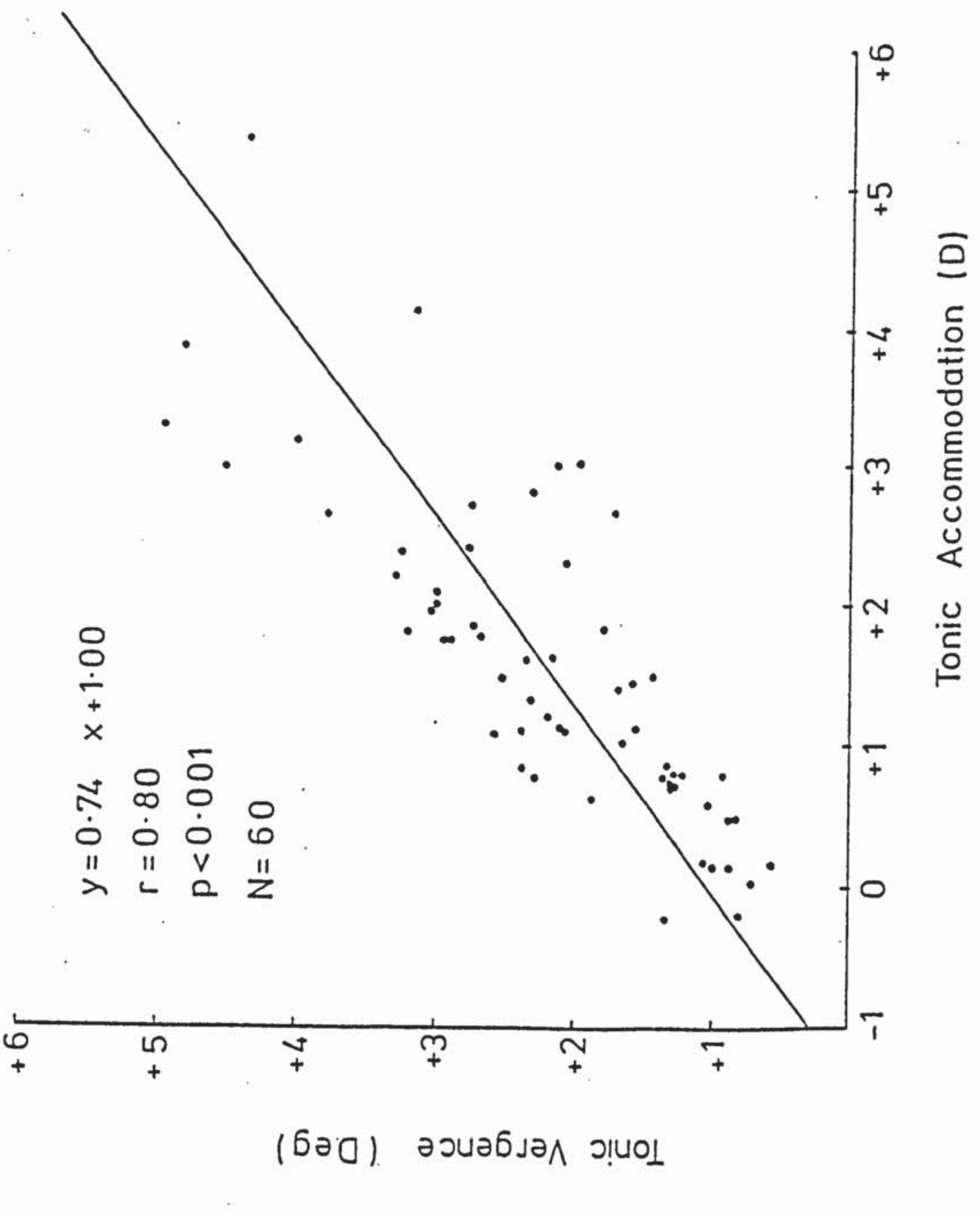

Figure 4.5 - A scatter diagram illustrating the relationship between TA(D) and TV(deg) for the N=60 group of observers. A positive ordinate value indicates convergence, whilst a positive abcissa value indicates an increase in ocular power.

4.6B- TA, TV and the oculomotor balance.

According to the Maddoxian concept of vergence eye movements (see section 2.3C) excessive "tonic convergence" produces latent overconvergence or esophoria, and that deficient "tonic convergence" produces latent underconvergence or exophoria. It would appear therefore, that some relationship between heterophoria and TV would be expected. Although few previous studies have attempted to assess the relationship between TA, TV and heterophoria, it has been possible to re-analyse some of the previous data. An analysis of the data from Table 1 of the Fincham (1962) study, reveals a strong relationship between distance (6m) heterophoria and dark convergence measures taken in metre-angles ($r=-0.85$, $p<0.001$). This data would suggest that esophoric observers demonstrate relatively high convergence in darkness. This led Fincham to state:

> "This persistence of the condition of vergence, although vision is not stimulated, is some indication that heterophoria is anatomical rather than functional in origin".

An analysis of the data from Table 2 of the Owens and Leibowitz (1976a) reveals a much weaker relationship than that found by Fincham between distance heterophoria and TV for 9 observers ($r=0.31$, $p=0.32$).

In a more recent study using a similar methodology to that of Owens and Leibowitz, 1976a), Francis and Owens (1983) reported that near heterophoria measures in 17 observers were more significantly correlated to TV ($r=0.62$, $p<0.01$) than were the distance heterophoria measurements ($r=0.40$, p = ns).

The results of the present study (N=60) would indicate that neither the distance nor the near heterophorias are as significantly correlated with TV as found in either of the previous studies. The near heterophoria measurements correlated very weakly with TV (r=0.19, p=0.15) as did the distance heterophorias (r=0.19, p=0.15). In view of the previous studies' success in finding a relationship between heterophoria and TV, the results of the present study are rather surprising. TA was not significantly correlated with either distance or near heterophoria.

4.6C - TA, TV and the AC/A ratio.

It is well accepted that accommodation and vergence exhibit a synergistic relationship under dynamic photopic visual conditions (e.g. Fincham and Walton, 1957). This relationship can be expressed as both, the accommodative-convergence / accommodation (or AC/A) ratio and the convergence-accommodation / convergence (or CA/C) ratio, with the the AC/A ratio applied more often.

A study by Hogan and Linfield (1983) measured the stimulus AC/A ratio of 10 Rx-corrected observers by the gradient technique using two different methods; namely, the "fixation disparity method" (see Martens and Ogle, 1959) and the Maddox wing method (see Duke-Elder, 1973). The results indicated that the fixation disparity method gave systematically higher mean values (4.35$_{\Delta}$/D) than the Maddox wing method (3.38$_{\Delta}$/D), although the accommodative distance was held constant for both methods (30cm). It was concluded that the difference in results was a function of the relative difference in the accommodative stimulus characteristics of the two methods chosen. Observations such as this, indicate the stimulus-dependency of the accommodative and/or vergence system(s), and therefore of the AC/A ratio.

Bohman and Saladin (1980) monitored the accommodation and vergence of the eyes of eight observers, whilst viewing a Snellen chart (contrast 73%) under 5 different light levels, ranging from 4.03×10^{-2} to 2.26×10^{2} cd/m^{2}. Unfortunately, Bohman and Saladin only provide the results of two observers "as being representative of the entire group" of eight. They were unable to detect any systematic trend between the level of accommodation, vergence and AC/A ratio. In their discussion Bohman and Saladin state:

> "Some patients showed significant amounts of night myopia but seemingly unrelated convergence. Others showed an almost linear relation between night myopia and convergence paralleling the AC/A line".

Their results show a clear trend for the development of "night myopia" as the luminance level reduced, whereas they report an inconsistent effect on vergence and it would appear from the limited data available that most observers gave divergent responses. This latter observation would suggest that Bohman and Saladin were measuring dissociated heterophoric recovery eye movements and not "dark vergence" (eye position was recorded by a Biometrics eye movement monitor, on removal of an occluder). It has been shown in numerous studies (e.g. Ivanoff and Bourdy, 1954, Francis and Owens, 1983) that vergence eye movements become progressively less accurate with both increasing retinal eccentricity and luminance. It is possible therefore, that Bohman and Saladin were indeed measuring heterophoria and not TV. The important point however, is that the Bohman and Saladin study indicates that the accommodative and vergence systems dissociate from the normal synergy found in the AC/A ratio.

The results of the present study indicate insignificant relationships between the AC/A ratio and TA and TV ($r=-0.11$, $p=0.61$ and $r=-0.10$, $p=0.56$ respectively). In an attempt to relate the TA and TV measurements to the AC/A ratio in a more uniform manner, the TV (deg) results were converted to prism dioptres and then divided by the TA (D) results. The resultant factor was not significantly correlated to AC/A ($r = -0.15$, $p =$ ns).

These latter observations would suggest that the observed relationship between TA and TV reflects the tonic levels of the accommodative and vergence systems in the absence of visual stimulation, and thus bears little resemblance to highly stimulus-dependent AC/A ratio. If the significant relationship, observed in the present study (Fig. 4.5), had originated from the same innervational interaction as that found in the AC/A ratio, it would not have been inappropriate to expect a higher significance in the relationships between TA, TV and the AC/A ratio. It is interesting to postulate that the relationship between TA and TV reflects a "tonic AC/A ratio", i.e. the ratio between tonic levels of accommodation and vergence in the absence of adequate visual stimulation: with TA compared to TV, a mean result of 1.3_Δ/D is obtained.

Further research is required to investigate the relationship between this tonic AC/A ratio and the interaction between accommodation and vergence under more normal visual conditions.

4.6D - The relationship between TA, TV and the near points of accommodation and convergence.

The study of Maddock et al. (1981) measured the "resting point of accommodation" and the amplitude (or near point) of accommodation (AA) in 40 observers provided with their refractive corrections. They found a mean resting point of 1.43D (including a chromatic aberration correction factor), s.d.=1.03D, whilst the mean near point gave a result of 10.21D, s.d.=2.10D. A correlation between these parameters was found not to be statistically significant (r=0.08). A study by Smith (1983) measured the "dark field" of accommodation and the AA from 13 observers (without refractive correction). He found the mean "dark field" to be 1.52D (s.d.=0.68) and the mean AA to be 6.98D (s.d.=2.67). Correlation between these accommodative parameters was found to be insignificant (r=0.24, p=0.48).

The mean TA (at 632.8nm) of the present study (N=60) was found to be 1.58D (s.d.=1.11D), while the mean AA was found to be 8.69D (s.d.=1.56). Correlation between the factors was found to be insignificant (r=-0.08, p=0.55). These results would indicate that TA is unrelated to AA.

It is interesting to note that Smith's mean AA is somewhat lower than either the Maddock or the present study. The ages of the subjects used in the Smith study ranged from 23 to 43 years, whilst in the Maddock study "all but one of the subjects were below the age of 25" and in the present study, the ages ranged from 18 to 36 witha mean of 21.6 (s.d. 3.02) years (with only four observers above 25 years). No significance was found in the relationship between TA and age (r=0.03, p=0.79); the age of the N=60 database was found to be weakly correlated with the amplitude of accommodation (r=-0.25, p<0.05). There was no significance in the relationship between between TV and the amplitude of accommodation (r=-0.11, p=0.61).

There is no mention in the previous literature of a relationship between TV, TA and the near point of convergence (NPC). The analysis of the results of the present study is unable to detect significance in the relationships between NPC and both TV (r=-0.05, p=0.72) or TA (r=0.03, p=0.79).

4.6E - Review of the relationships between TA, TV and the oculomotor balance.

The mean lateral distance heterophoria at a 6m distance was found to be orthophoric (N=60), whilst the mean near lateral heterophoria gave a result of almost 2Δ of exophoria. The mean AC/A ratio was found to be 2.73Δ/D, while the near points of accommodation and convergence (NPC) were found to be 8.69D and 6.72cm, respectively. The near heterophoria was found to be significantly related to both, the distance heterophoria and the AC/A ratio. The AC/A ratio was also significantly related to the NPC, but not to the amplitude of accommodation. None of the remaining combinations yielded significant relationships.

In accordance with the previous literature, the results of the present study have demonstrated that the accommodative and vergence systems assume intermediate resting positions under the astimulus conditions of total darkness: the mean TA (at 632.8nm) was found to be 1.58D (which corresponds to a distance of 63cm), whereas the mean TV was 2.18 deg (or 108cm), whilst the mean horizontal pupil diameter was 7.02mm. The relative resting positions of TA and TV are illustrated within figure 4.6.

A significant relationship was demonstrated between TA and TV. Previous studies on adults had found correlations ranging from "no-significance" to "significant only at the 5% level". It was concluded that the improved methodology of the present study had reduced the variation of certain factors that had previously masked this relationship.

The results of the present study do not support the Maddoxian concept of heterophoria[1] in that little significance was found in the relationships between TV and either of the distance and near heterophorias. A similar result was found for these relationships with TA. No significance was found between the combinations of relationships between TA, TV, NPC and the amplitude of accommodation.

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[1] That esophoria results from excessive tonic convergence and exophoria from deficient tonic convergence.

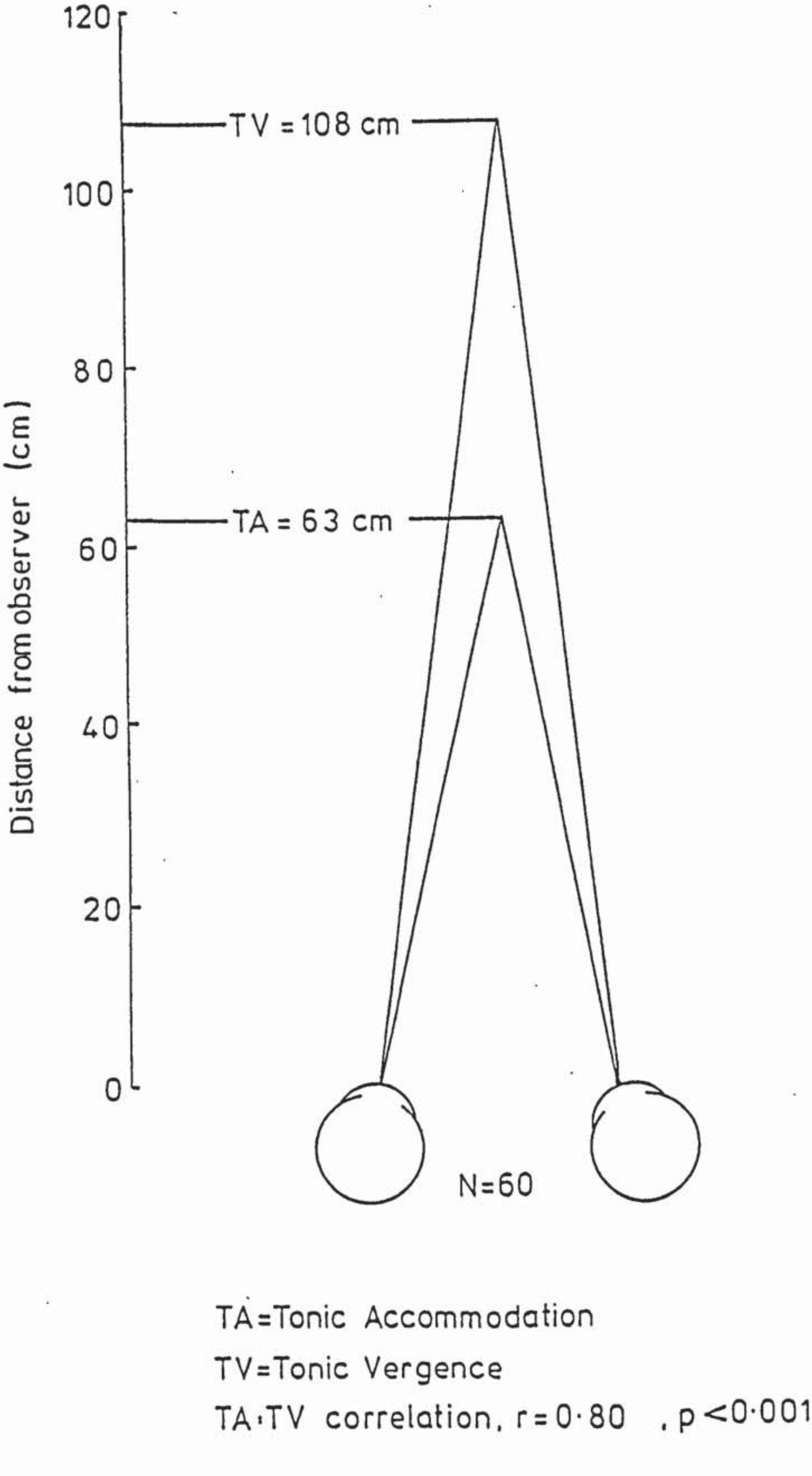

Figure 4.6 - Diagram illustrating the intermediate nature of the tonic resting positions of the accommodative and vergence systems of an N=60 group of observers.

There was little significance in the relationships between the AC/A ratio and either TA or TV, which would indicate that the two different resting positions for the accommodative and the vergence systems are independent of the sensory and motor innervations that occur for the interaction of accommodation with vergence under normal visual environments. This leaves a major question unanswered, "why then are the individual positions attained by the accommodative and vergence systems of the N=60 database (represented by TA and TV) so significantly correlated ?"

It is important to remember that the AC/A ratio is a measure of the level of convergence induced by the action of an accommodative response to a given stimulus[1] and, as outlined earlier (in section 4.6C), the absolute value of the AC/A ratio can also be demonstrated to be stimulus dependent[2]. TA and TV are, however, measures of the accommodative and vergence systems, in the absence of such stimulus dependent characteristics and are therefore, measures of the state of accommodation and vergence whilst in the absence of the dynamic and interactive innervation responsible for the level of induced accommodative convergence. It may be considered unlikely therefore, that the stimulus-free measures of TA, TV and their relationship TVA, would be significantly related to the AC/A ratio.

This does not explain however, why TA and TV are found to be significantly related. It is possible to hypothesize that an individual's TA and TV positions are the result of an innervational

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[1] the stimulus-dependency characteristics of the accommodative response has been outlined on p.2 of the general introduction.

[2] i.e. the amount of induced convergence is dependent upon the level of accommodation, which is in turn dependent upon the stimulus characteristics of the task.

or muscular tonus, induced in the ciliary and extra-ocular muscles by an "averaging process" of all the prior focussing and vergence responses over some previous period of time. The individual's AC/A ratio will have had much influence on the relative extent of the interaction between these focussing and vergence responses. The relationship between TA and TV may therefore reflect a tonic element of this interaction (the "tonic AC/A ratio), without actually being significantly correlated to the AC/A ratio as measured under normal visual stimulus conditions.

Current control-theory modelling of the interaction between accommodation and vergence has provided much information concerning the responses of these systems to their relative stimuli (for a review, see Semmlow and Hung, 1983). The "Interactive dual-feedback" model of Hung and Semmlow (1980) - see fig. 4.7 - is typical of this application of control-theory modelling; in that the tonic innervation to the ciliary muscle and extraocular muscles is the final neural input to these systems and as such is all that remains in the absence of a stimulus to the accommodative and vergence systems.

Although this model has been subjected to rigorous evaluation using computer simulation, it is limited in that it is concerned only with the short-term static responses. Adaptive processes such as those found in accommodation and vergence (as described by Ebenholtz, 1983; and Schor, 1980) have not yet been incorporated. It is possible that the dynamic interaction of A-C and C-A may influence the level of tonic innervation to the ciliary muscle and extraocular muscles during normal visual conditions and is therefore, reflected in the relationship TVA as a "tonic AC/A ratio", although there is no concurrent A-C or C-A innervation during its measurement.

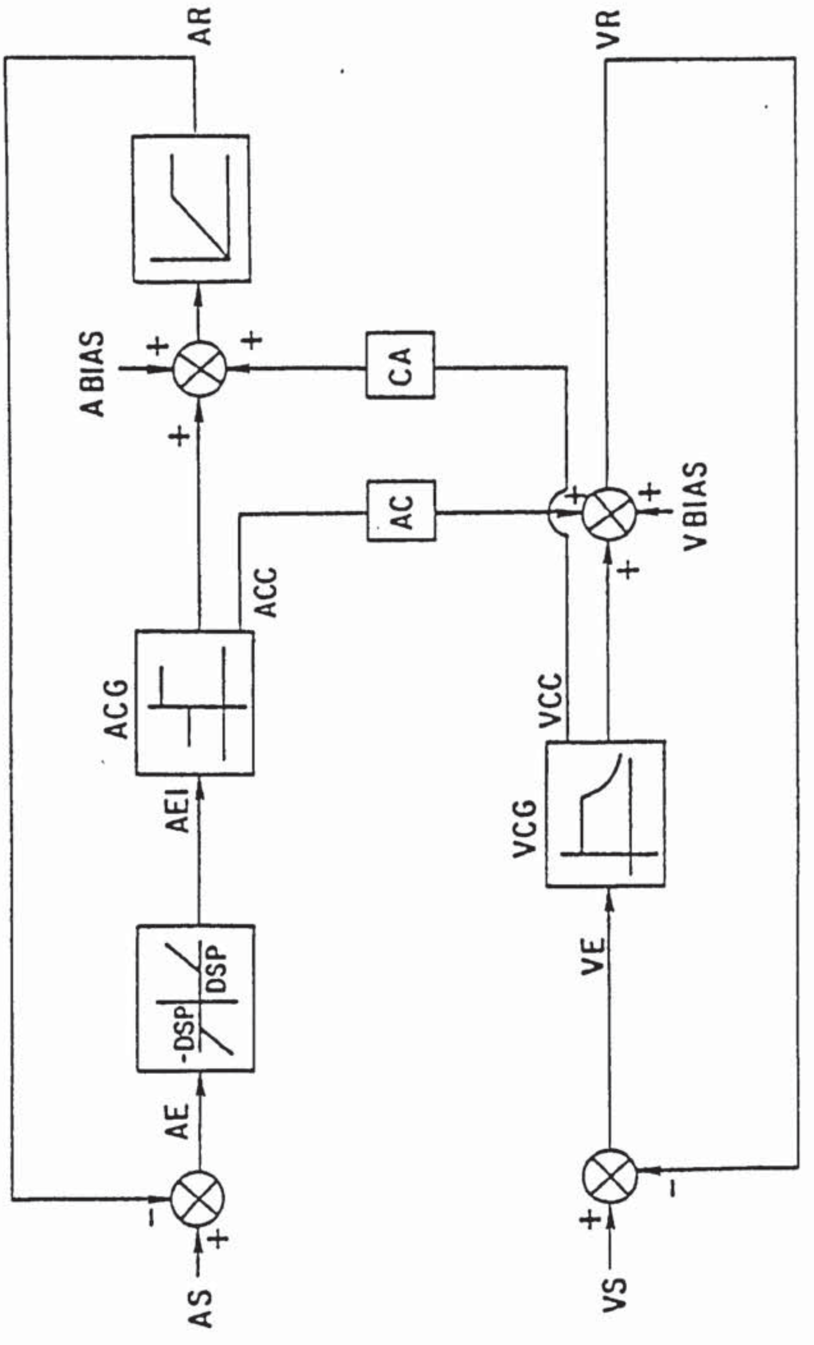

Figure 4.7 - Overall block diagram of the interactive dual feedback model of the accommodation and vergence systems: adapted from Hung and Semmlow (1980). AS = accommodative stimulus, AE = accommodative error, DSP = dead space operator (depth of focus), ACG = accommodative controller gain, A BIAS = accommodative bias (tonic accommodation), AR = accommodative response, AC = accommodative convergence: VS = vergence stimulus, VE = vergence error, VCG = vergence controller gain, CA = convergence accommodation, V BIAS = vergence bias (tonic vergence), VR = vergence response.

This above hypothesis would suggest that an individual principally engaged in near work (e.g. a VDU worker) should have closer tonic rest positions for TA and TV than an individual principally engaged in relatively more distant work (e.g. lorry-driver). Whilst there has been a relative paucity of evidence to support a long-term occupational or environmental effect on TA or TV there is however, evidence to suggest a short-term bias or hysteresis of TA and TV following relatively brief participation in far and near tasks (see the studies of Owens and Leibowitz, 1980; Ebenholtz, 1983; and Hogan and Gilmartin, 1985b; and indeed, chapter 7 of this thesis). The results of these studies would suggest that the tonic resting positions are influenced by prior activity. Whilst the "long-term" effects of prolonged near or far visual tasks on the accommodative and vergence systems are outside the scope of this thesis, it is possible to speculate that the "short-term" tonal effects on TA and TV may, in part, be responsible for such phenomena as "VDU-myopia" and prism-adaptation.

It is interesting to note the observation made earlier (in section 3.6E iv of the menstruation study), that although the levels of TA and TV of three female observers were found to fluctuate over the 28-day cycle, at no point did the difference between the levels reach statistical significance. This would indicate that the effects of the menstrual cycle on TA were, in some way, linked to the effects on TV.

It is evident, however, from the large standard deviations and ranges found for TA and TV by the previous and the present studies, that other factors must influence the state of accommodation and vergence under the astimulus conditions of total darkness. This is particularly so of accommodation; e.g. general autonomic arousal (for a review, see section 1.4E) and its basis in the concept of a dual-innervation by both the parasympathetic (PNS) and the sympathetic nervous systems (SNS) to the ciliary muscle (for a review see sections 1.4A, 1.4B, 1.4C and Chapter 6). The wide distribution in TA results has been demonstrated to be a function of variation in activity of the PNS, rather than the SNS (see section 6.4).

4.7 - THE RELATIONSHIP BETWEEN TA AND AMETROPIA.

4.7A - Introduction.

Recent research (reviewed in sections 1.4G to 1.4I) has demonstrated that, under conditions of reduced accommodative stimulation, the focus of the average refractively-corrected human eye is biased towards a mean intermediate myopic position of 1.5D (corresponding to a distance of approximately 67cm). While it has been shown that this resting state for an individual observer is relatively stable (see section 3.5D), there is considerable variation in the distribution between observers, even for the same age group (see table 1.2). It has been shown that the level of TA reduces with increasing age (Yamazaki, 1977; Simonelli, 1979; 1980b; 1983); an observation presumably due to the mechanical limitations imparted upon the accommodative mechanism by the process of presbyopia (Fisher, 1969a; 1969b; 1971; 1973; 1977). The wide variation within the distribution of TA thus decreases with age and approaches that of the far point (Marmolin and Rendahl, 1975; Yamazaki, 1977; Simonelli, 1979; 1980b; 1983), at a somewhat lower rate than that of the amplitude of accommodation (Hamasaki et al., 1956). Therefore, although we have seen (in section 4.6D) that the level of TA is unrelated to the near point of accommodation, it is clearly dependent upon the full range of accommodation; one extreme of which is the far point, whilst the other is the near point.

It is largely accepted that the overall amplitude of accommodation is fairly constant for any particular age group (Duane, 1909; 1912; 1922; Hamasaki et al., 1956; Wold, 1967; Litsinger, 1981), thus one would not expect this factor to account for the observed variation in the distribution of TA for a group of observers of the same age; in fact, several studies (Maddock et al., 1981; Smith, 1983; and the present - see section 4.5D), have demonstrated the lack of significance in the correlation between TA and the amplitude of accommodation. Is it possible then, that the other extreme of the accommodative range, namely the far point (with its relatively wide variation across all age groups) is, in some way, responsible for the distribution of TA and therefore, for the level of TA itself ?

Two possible relationships between TA and refraction may be discussed: the first possibility is that of a relationship between refractive error and the level of TA measured in the uncorrected refractive state; the second is the relationship between refractive error and the level of TA attained in the corrected refractive state. If the example is taken, of a 3.00D myope with an intermediate resting position of 1.5D, it would be expected that, without his distance refractive correction, the TA measurement would have increased myopically to 4.5D. If however, the example is taken of the 3.00D hyperope, also with a dark-focus of 1.5D, it would be found that the dark-focus value, when measured without his correction in place, would have reduced to 1.5D of hypermetropia. It is apparent therefore, that the resultant measurement of dark-focus would be expected to be dependent upon both the nature and accuracy of the refractive correction.

Several studies have confirmed the existence of this first possibility of a significant relationship between Rx and uncorrected TA: Yamazaki (1977) - using infra-red optometry on 108 ametropic eyes; Braddick et al. (1981) - using photorefraction on 46 eyes; Simonelli (1979; 1980b; 1983) - using polarized vernier optometry on 301 adults; and Mohindra (1977a; 1977b) using near-retinoscopy on 27 adults; have all indicated that not only is the resting state highly correlated to the far point of the uncorrected eye, but that uncorrected myopes have a significantly closer TA than emmetropes and hyperopes, respectively. A study by Smith (1983), somewhat anomalously however, found a negative correlation ($r=-0.49$, $p=0.10$) between the far point and the resting position of his 13 refractively uncorrected subjects. His results would suggest that hyperopes have the more myopic TA positions.

It would thus appear that for the uncorrected eye, there is generally a significant linear and positive relationship between the resting state of accommodation and the far point, such that the myopic eye has a more myopic resting position than the emmetropic, and in turn, hypermetropic eye.

The earlier discussion cited examples of myopic and hyperopic eyes having the same level of TA. This was in an attempt to illustrate the first of the possibilities of relationships between Rx and TA, in that one could predict a strong relationship between Rx and TA measured in the uncorrected state. What of the second possibility, that relationship between Rx and TA, as measured in the corrected state ?

Several studies have investigated this latter aspect. In an early study by Carreras (1951), the effects were measured of a reduction in illumination upon the monocular refractive correction required to enable his 21 subjects to just perceive the 3 min of arc gap in the Landolt 'C'. Carreras was unable to detect a significant difference between the night myopias of his 7 corrected myopes (with Rx from -4.00 to -21.00D), 10 emmetropes (of less than ± 2.00D) and 4 corrected hypermetropes (from +2.00 to +5.00D). The mean night myopias were found to be: for the myopic group, 1.60D ± 0.22D; for the emmetropic group, 1.73D ± 0.16D; and for the hyperopic group, 1.60D ± 0.27D. A later study by Irving (1957) measured the refractive changes of 50 corrected subjects under low-luminance conditions (0.02 cd/m^2) using a Ruka Variator (Thorner and Spanuth, 1932), and found a trend towards greater night myopia with increasing hypermetropia ($r=-0.61$).

More recently, Ramsdale (1978) used laser optometry to measure the resting points of 6 myopic eyes (Rx from -4.00 to -8.00D), 10 emmetropic eyes (of < ± 2.00D) and 6 hypermetropic eyes (from +2.00 to +7.00D). The mean resting points were found to be: for the myopic group, 1.25D ± 0.28D; for the emmetropic group, 2.15D ± 0.89D; and for the hyperopic group, 2.13D ± 1.38D. She was unable to report statistically significant differences between the mean resting points of the various refractive groups for this and a subsequent study (Ramsdale, 1982).

Maddock et al. (1981) reported the results of two independent studies (one from UWIST, Cardiff and the other from Davis, California) using laser-optometry to investigate the relationship between refractive error and TA measured with Rx in place. The "Cardiff" study found that the relationship between refractive status and the resting point of accommodation was not statistically significant, although they added that this was probably due to the small sample sizes used in this study. The tendency was for the mean resting point to be greatest (1.29D ± 1.25D[1]) for the 5 corrected hypermetropes (Rx from +2 to +4D)

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[1] Figures taken from the review by Charman (1982).

and lowest (0.73D ± 0.56D) for the 9 corrected myopes (Rx from -7D to -2D), and intermediate (0.96D ± 0.52D) for the 9 emmetropes (Rx between ± 2D). The "Davis" study found a significantly lower resting point (0.94D ± 0.46D) for their 10 high myopes (greater than -3.00D) than in the 20 emmetropes ($t=2.28$, $df=27$, $p<0.03$). No other between-group differences in resting point were found to be significantly different.

Simonelli (1979; 1980b; and 1983) used a polarised vernier optometer (Simonelli, 1980a) to measure the "relative dark focus positions" of accommodation under total darkness of 301 observers. He found a low correlation ($r=0.15$, $p=0.008$) between the far and resting points, indicating that that "there is a very small but reliable tendency" for the resting point to be larger for the most myopic eyes and smaller for the most hypermetropic eyes.

The study of Heron et al. (1981), using laser-optometry, were unable to report a significant relationship between Rx and TA ($r=0.007$), although they added that their sample size did not have a normal distribution of refractive error.

It would appear therefore, that the relationship between the far point and the accommodative resting state, measured with distance refraction corrected, is neither definite nor highly significant. It will be interesting to investigate the significance of the relationships between Rx and both corrected and uncorrected TA, for the N=60 database.

4.7B - The measurement of Rx for an N=60 data group of observers.

The refraction of each individual observer was measured immediately prior to the TA measures, using standard optometric techniques: the objective technique of esoscopic streak retinoscopy (at 2/3m) and the subjective technique of cross-cylinder (at 6m).

Each monocular refraction was binoculary balanced for infinity, using the Humphriss and duochrome techniques. All measurements were taken by the same refractionist, who also used the same equipment for each case. The Snellen chart utilised had a contrast of 90% and the room luminance was 45cd/m^2.

TA measurements were taken from the left eye of each observer under the two refractive conditions, with and without the distance refractive correction.

4.7C-The relationship between Rx and TA- results.

The refractive results for each observer are recorded in Appendix XV, as are the TA results (at 632.8nm) for the two refractive conditions. Although the full astigmatic refraction was measured and worn by the individual observer for the "with Rx" condition, the Rx results in Appendix XV represent the "best-sphere" computation from the sphero-cylindrical refraction[1]. The highest level of astigmatism encountered was 1.50D in observer BG.

It will be apparent from Appendix XV that the mean best sphere Rx for the N=60 group was 0.79D of myopia: this is not typical of the population as a whole but is probably typical for the population that exist within a university environment, from which most of the previous investigations have taken their samples. In fact, a recent study by Septon (1984) found an even greater level of myopia (best-sphere = -2.21D) amongst 447 2nd-year optometry students with refractions ranging from -11.00 to +5.50D. In the present study, the most myopic "best-sphere" refraction was found to be -6.25D, whilst the most hyperopic refraction was found to be +5.75D. It is evident therefore, that the refractions of the

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[1] i.e. the spherical component plus half the cylindrical component.

N=60 database encompass a range of 12 dioptres.

The mean value for TA (at 632.8nm), measured with Rx in place (TA+Rx), was found to be 1.58 of resting myopia; the results encompassed a range of 5.45D (from 5.27D of resting myopia to -0.18D of resting hyperopia). The mean value for TA, when measured without the refractive correction (TA-Rx), was found to be 2.13D of resting myopia; the results encompassed a range of 12.58D (from 8.58D of resting myopia to 4.00D of resting hyperopia).

The relationship between Rx and TA+Rx was found to be statistically insignificant (r=0.18, p=0.16) and is illustrated by the scattergram of fig. 4.8.

It is evident from the slope of the line of regression that, not only is the relationship between Rx and TA c Rx weak (p=0.16), but that the trend (r=0.18) is for myopes to have the higher tonic resting positions.

The relationship between Rx and "TA s Rx" was however, found to be much more significant (r=0.84, p<0.001) and can be appreciated by reference to the scattergram of fig. 4.9.

It is evident from fig. 4.9 that the level of TA is significantly dependent upon the uncorrected refractive state of ametropia of the observer, and that in all cases the level of TA observed represented an increase in ocular power from the far point.

There was no demonstrable significance in the relationships between Rx and TV (r=-0.05, p=0.72).

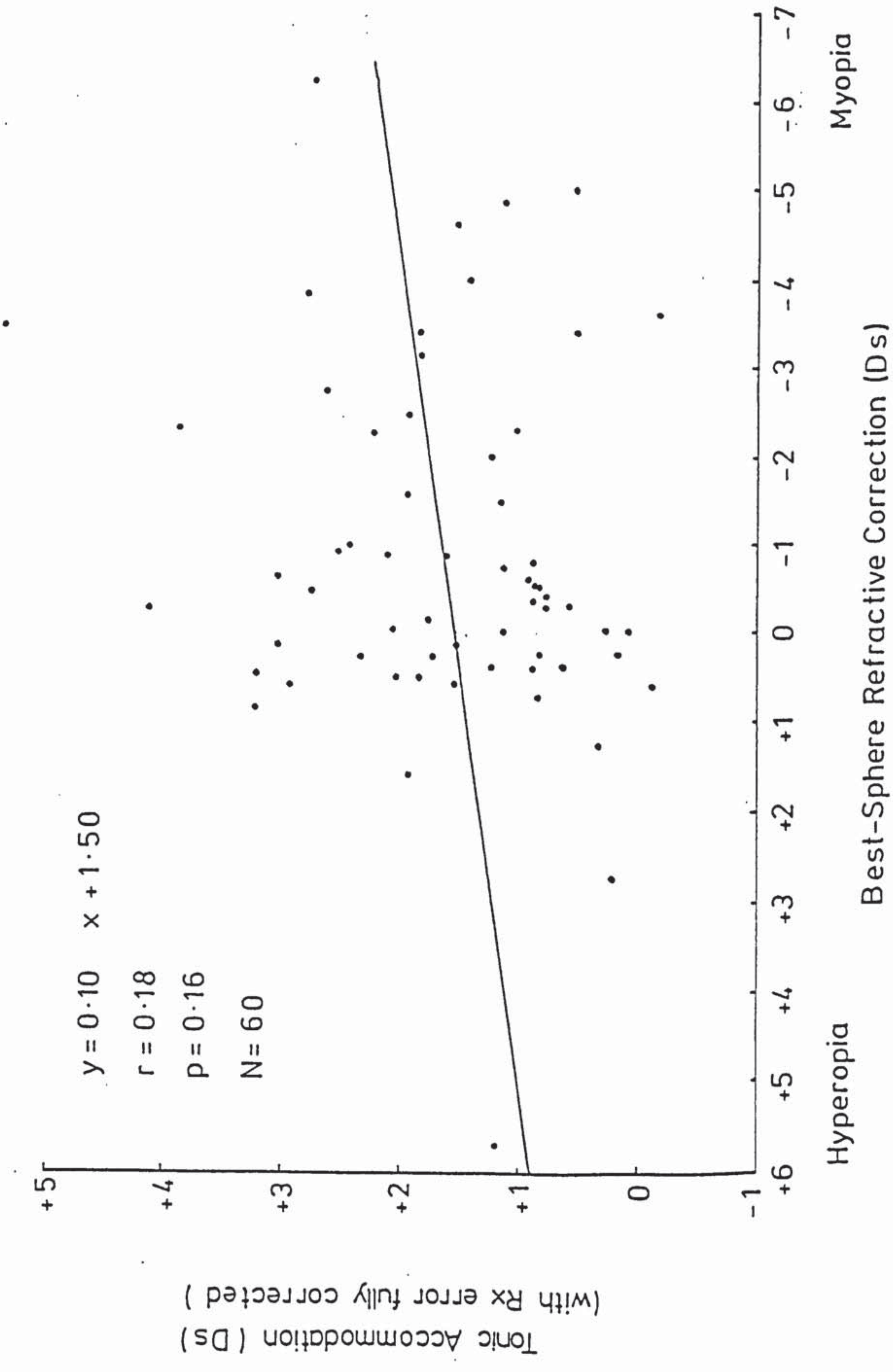

Figure 4.8 - A scatter diagram representing the weak relationship between refractive error (Rx) and TA of the N=60 database, measured with Rx in place.

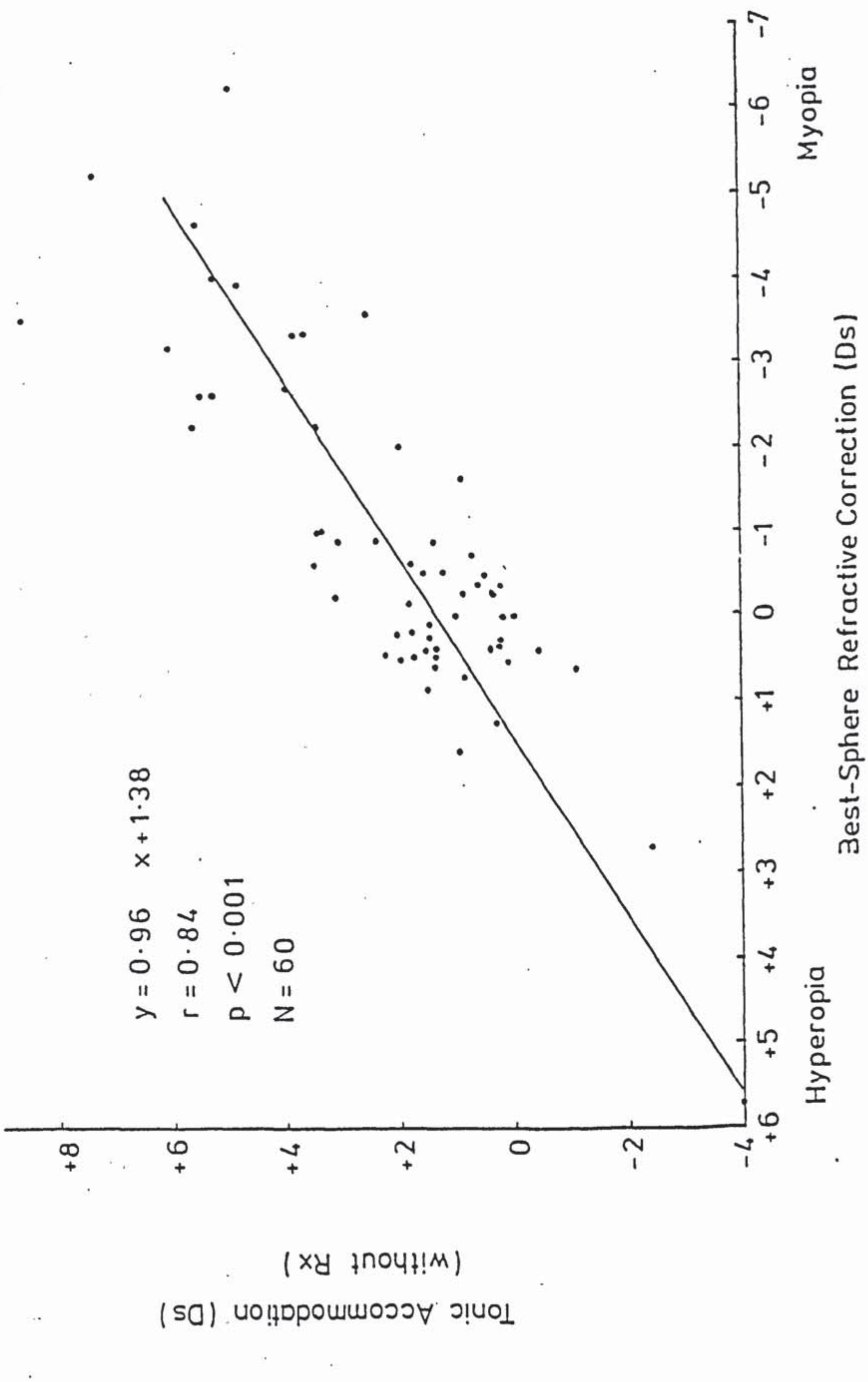

Figure 4.9 - A scatter diagram representing the significant relationship between refractive error (Rx) and TA of the N=60 database, as measured without Rx worn.

4.7D - Discussion on the relationship between refractive error and TA.

The results of the present study support the observations of Yamazaki (1977), Mohindra (1977a), Simonelli (1980a) and Braddick et al. (1981), in that the resting state of accommodation (measured without refractive correction) is significantly correlated to the far point of the uncorrected eye. The techniques of near retinoscopy and photo-refraction have been suggested as suitable alternatives to standard refractive techniques by Mohindra and Braddick et al. respectively: it is evident, however, that a correction factor to account for "tonus" would need to be applied in order that a recognisable refraction result be attained. The results of the present study (and fig. 4.9) would further suggest that an individual's best-sphere refraction can be predicted from his TA result. This can be explained with reference to the theoretical discussion of section 4.7A. The observed values for refraction of the N=60 database cover a range of 12.00D and it is interesting therefore, to note that the observed values for TA cover a similar range of 12.6D.

The results of the present study do not support the observations of certain previous investigations (notably Irving, 1957; and the two studies included in the report of Maddock et al., 1981) of the relationship between Rx and TA+Rx. The present study supports the observations of Simonelli (1979; 1980b; and 1983) in that the relationship between Rx and TA+Rx supports a weak tendency for myopes to have higher TA values than emmetropes and, in turn hyperopes. The study of Carreras (1951) found myopes and hyperopes to have the same levels of night myopia, with emmetropes having an insignificantly higher level. Ramsdale (1978) found the emmetropes and hyperopes to have similar levels of resting points, whilst the myopic group had a lower level, although this was subsequently found to be non-significant. An important limitation of the previous studies (with the exception of Simonelli's) is that they suffer from low numbers of observers in each refractive group.

The data of the present N=60 study can similarly be divided into the various refractive groups. Due to the low number of hyperopes (above +2.00D) encountered in the present study, the refractive groups within the N=60 database have been divided on the following basis: the myopic group consisted of 30 observers with an Rx greater than -0.25D; the emmetropic group consisted of 13 observers with an Rx <= ± 0.25; whilst the hyperopic group consisted of 17 observers with an Rx greater than +0.25D. The mean TA+Rx for these groups were found to be as follows: 1.66D for the 30 myopes; 1.39D for the 13 emmetropes; and 1.59D for the 17 hyperopes. The mean TA values can be compared to those of other studies by reference to fig. 4.10.

It is clear from fig. 4.10 that there is little evidence to suggest a systematic effect of refractive status upon the level of TA as measured with the refractive error corrected. Within these five studies presented there are however, three different measurement techniques, large differences in refractive limits and large differences in the sizes of the groups. These factors alone may account for the inconsistency in observations.

Ramsdale (1978; 1979; 1982) found a trend for myopes to show lower accommodative responses than emmetropes and, in turn, hyperopes for the same accommodative stimulus. She proposed that this variation in accommodative response may be observed from the stimulus-response characteristics of the above three refractive groups, in both their corrected and uncorrected state.

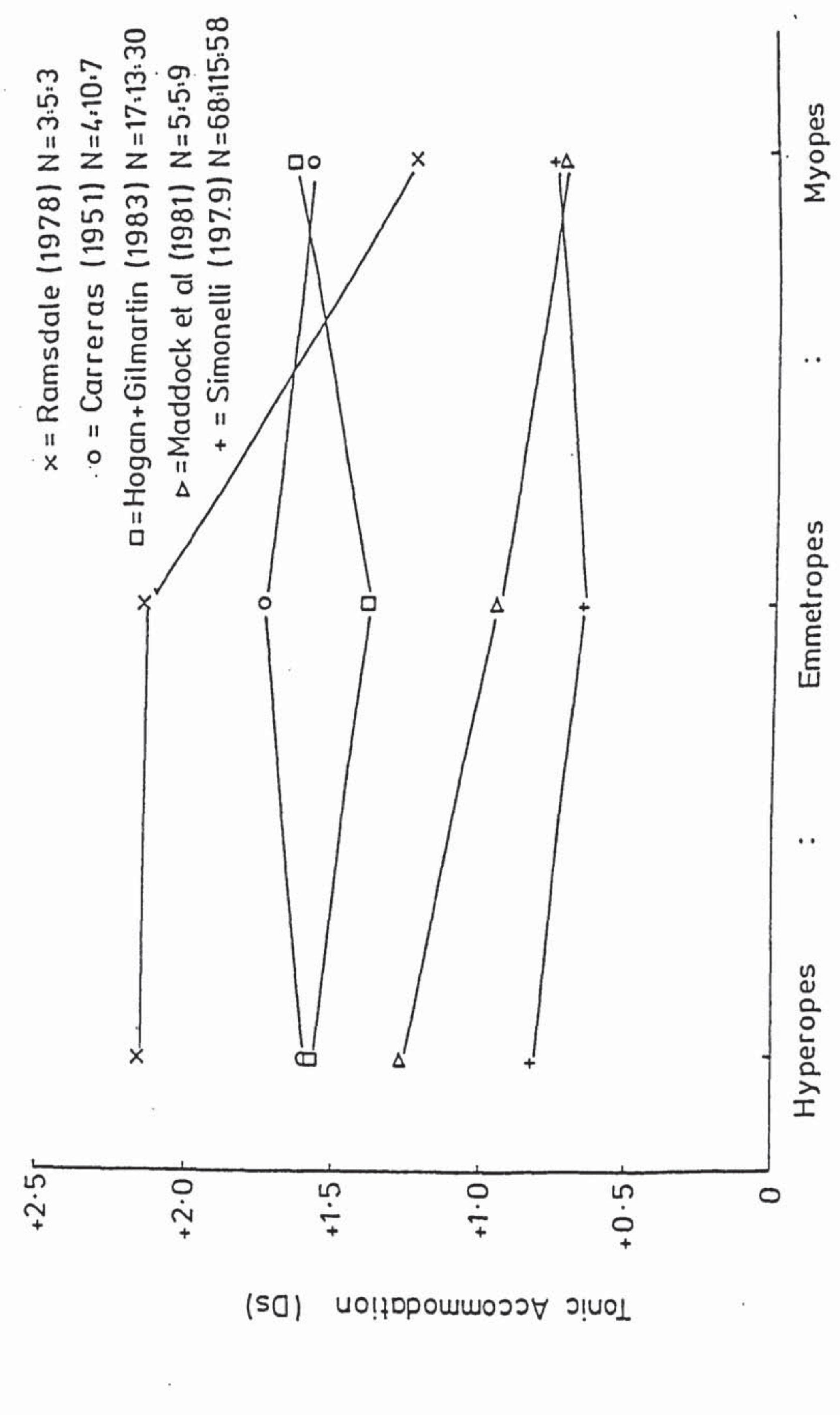

Figure 4.10 - A comparison of the mean TA results found by 5 different studies for the three refractive groups myopia, emmetropia and hyperopia. It is important to note that the limits of each refractive group differ.

When Ramsdale (1982) employed the same selection criteria as she had used in her earlier study (Ramsdale, 1978 - see above), the order and magnitude of "cross-over" points of the stimulus-response curves for the various refractive groups were as follows: 1.65D for myopes; 1.80D for emmetropes; and 3.25D for hypermetropes. If she then re-defined the limits of her refractive groups with emmetropes as less than ± 0.50D and myopes and hypermetropes as everything either side of this, respectively, the cross-over points then became: 1.92D for myopes; 1.35D for emmetropes; and 1.10D for hypermetropes. The magnitude and order of the cross-over points was found to completely reverse. These results demonstrate that a change in the criterion for a refractive group has a significant bearing upon the mean accommodative response for that group. In an attempt to avoid this problem the results of the present study have been analysed as a continuum, rather than discrete refractive groups.

Although, the observers in Ramsdale's studies wore accurate infinity-balanced corrections, it was acknowledged that the prior refractive habits of the subjects may have influenced their responses: it is a clinical observation that low myopes may use their spectacles for distance vision only, often resorting to unaided vision for close work. Such a situation will clearly influence their "normal" near vision responses. The converse situation may be found for hyperopes. It is possible that the strength of the relationship between the accommodative and vergence systems may depend upon the length of time that a particular refractive condition has been imposed. It is interesting therefore, to note that the Davis study of the report by Maddock et al. (1981) found a significant negative correlation between the number of years since the initial diagnosis of myopia (and presumably onset of correction) and both amplitude of far accommodation (the interval between the resting position and far point) and the resting position (r=-.58, p<0.01 and r=-0.53, p<0.02, respectively).

It has been reported that the normal physiological tone of the ciliary muscle in hyperopes is greater than in myopes (Duke-Elder, 1970, p.258-259). This observation would seem to be at odds with the interpretation of results of certain epidemiological studies (e.g. Richler and Bear, 1980; Angle and Wissmann, 1980; and Kinney et al., 1980) and those studies which have attempted to modify the progression of myopia using procedures designed to reduce the accommodative response to a near task (e.g. Stuart-Black Kelly et al., 1975 - with the use of cycloplegics; and Greenspan, 1981 - with the use of positive lenses). These studies have suggested that near work leads to a relative pseudomyopia due to the inability of the cilary muscle to relax fully on changing from near to distance, and would suggest that the tonus of the cilary muscle would be dependent upon the level of near work conducted. This would in turn, be expected to be dependent upon the refractive condition of the observer and whether they wore their correction or not. With relevance to this aspect, further studies are required to investigate the effect on TA (and TV) of such aspects as: the provision of a neo-myope with his/her first and subsequent refractive correction; also the provision of the first and subsequent reading corrections to the presbyope.

In his much-cited monograph, Van Alphen (1961) proposed that three factors, "S", "P" and "R", contributed significantly to the development of emmetropia. Factor "S" (relevant to to axial length and corneal curvature), predicts that larger eyes would have flatter corneae (independent of refraction). Factor "P" (relevant to axial length, anterior chamber depth and crystalline lens power) predicts that larger eyes would have deeper anterior chambers and flatter lenses. It is presumed (Gilmartin, 1986), that the leptokurtosis of the distribution of refractive error implies that the factors "S" and "P" contribute successfully to the process of emmetropization. Van Alphen, however, implicated the anomalous operation of his third variable, factor "R" (relevent to the resistance offered to the IOP by the ciliary muscle - choroid layer), as the causal element in the development of ametropia. He speculated that the resistance to stretch offered by the ciliary-choroid capsule emanated directly from the tone of the ciliary muscle. The subsequent proposals made by Van Alphen, concerning the development of ametropia have been reviewed by McBrien and Barnes (1984).

Van Alphen's emmetropization model also predicts that individual's with high levels of tonic accommodation would be hyperopic, whereas myopes would exhibit low levels of tonic accommodation: supporting the studies of Maddock et al., 1980, etc). Van Alphen's proposal, that ametropia is due to an inadequate response of the eye's stretch mechanism to the intraocular pressure and that the basis of this stretch mechanism is the degree of ciliary tone, led him to the interesting postulate that ametropia may be controlled by pharmacological agents.

Section 1.4 was concerned with a discussion on the concept of an autonomic innervation to the cilary muscle. The evidence discussed therein has led to the consideration (see the reviews of Toates, 1972; Charman, 1982) that the intermediate resting position for accommodation represents an equilibrium between resting levels of parasympathetic and sympathetic innervation, as found under those conditions in which the stimulus to accommodation is absent.

By adhering to Toates's (1970) model of the accommodation system, Charman (1982) acknowledges the "growing acceptance" that "increased sympathetic activity is responsible for adjusting the ocular focus for distance vision, while parasympathetic activity is required for near vision". Charman hypothesised that, in myopia the sympathetic system was weak (or the parasympathetic system strong) and unable to reduce the lens power sufficiently for distance viewing, and that if this myopic eye was then refractively corrected (taking its far point relatively outwards), its resting state would lie at a lower dioptric value than that of an emmetropic eye having a "normal" innervational balance. He reasons that therefore, a relatively strong sympathetic branch (or weak parasympathetic branch) might result in hyperopia and, in the corrected eye, to a relatively higher dioptric value for the resting state. He cites the studies of Irving (1957) and Maddock et al. (1981) as supporting his hypothesis.

Garner (1983) however, offers the suggestion that the converse situation might be more likely, i.e. that the myopic eye is associated with a "strong sympathetic, weak parasympathetic combination". He suggests that the growing eye with a tendency towards myopia would be countered by increased sympathetic innervation, in an attempt to see at distance; the increased sympathetic level would be reflected in the ciliary tonus, theoretically producing a reduced "tonus position".

Both of the reviews (Charman, 1982; Garner, 1983) have been based upon the general proposition that, of the two branches of the autonomic nervous system thought to innervate the cilary muscle, sympathetic activity is responsible for distance viewing, whilst parasympathetic activity is responsible for near viewing. It is evident from studies of the reaction time to accommodative stimuli (such as those of Campbell and Westheimer, 1960; O'Neill and Stark, 1968; Shirachi et al., 1978; and Tucker and Charman, 1979) that such a proposition would require the facility for sympathetic mediated 'negative' accommodation to be as rapid and extensive as the facility for parasympathetic mediated 'positive' accommodation. As discussed in section 1.4B, the work of Tornqvist (1967) has demonstrated that stimulation of the cervical sympathetic nerve to the ciliary muscle, produces a maximal effect in monkeys after 10 to 40sec, much too slow to provide an effective temporal response to the rapidly changing stimulus conditions of a normal visual environment. Furthermore, one year earlier Tornqvist (1966) had reported that the stimulation of of the pre-ganglionic cervical sympathetic nerves of monkeys produced a negative accommodation response provided the ciliary muscle was initially in a state of pharmacologically induced contraction.

It would appear therefore, that the sympathetic system is too slow to provide an adequate negative accommodation response and is maximally effective against a background of parasympathetic activity. An aspect pertaining to the proposals of both Charman (1982) and Garner (1983) however, should be considered; namely the effect of an autonomic imbalance on ciliary muscle tonus. In this respect the recent study by Ebenholtz (1983) is of particular interest. It was shown that following a sustained 8-min fixation period at both the near and the far points, the TA of 12 emmetropes either increased by 0.34D or decreased by 0.21D, respectively. No significant shifts in the TA position occurred when fixation was placed at the observer's previously determined TA position.

It is understandable that some degree of smooth muscle tone is retained after a sustained period of fixation, and that this accommodative hysteresis effect will become evident in the subsequent short-term measures of TA. Ebenholtz's results suggest a non-linearity of hysteresis effect following far and near point fixation. This non-linearity may be the result of an enhanced inhibitory sympathetic input associated with the high level of concurrent parasympathetic activity during near point fixation. The results of Ebenholtz's study suggest an alternative role for the sympathetic input to the ciliary muscle. It is proposed that the role of the sympathetic nervous system in normal visual environments is to attenuate the accommodative hysteresis effects that follow prolonged close tasks. Studies to investigate the autonomic characteristics of the ciliary muscle and its sympathetic innervation will be carried out in Chapter 7.

In summary therefore, the results of this study are unable to support the theoretical proposal that corrected hyperopic observers have relatively higher tonic resting positions than myopes. . It is possible that the lack of support for the proposal by empirical observation is caused by the apparent plasticity or adaptiveness of the accommodative system. Whether the hysteresis effects represent a temporary autonomic imbalance in innervation to the ciliary muscle or are some form of attempt to reduce further "strain" on the ciliary muscle by the adaptation of the basic refraction, is at this stage mere speculation: it is to be noted that Ebenholtz observed hysteresis effects ocurring for distance as well as near viewing. It is also possible that this tonal basis for refractive error is linked-up with the process of 'emmetropization': such a possibility requires further investigation.

CHAPTER 5

THE RELATIONSHIP BETWEEN TONIC VERGENCE AND THE EFFECT OF OCULOMOTOR STRESS ON THE OCULOMOTOR BALANCE.

5.1 - Introduction.

It was suggested in the general introduction (p.9) that measures of tonic vergence (TV) might be utilised in the investigation and subsequent explanation of the previously observed effects of ethanol on heterophoria and other aspects of binocular vision (Hogan and Linfield, 1983). The effects of ethanol on the oculomotor balance are well documented and have been considered typical of other agents (e.g. barbiturates, marihuana and nitrous oxide) that have been shown to produce similar signs of stress of the oculomotor system. There are similarities to the effects on the vergence system when under conditions of reduced visual stimuli and during the early development of binocular vision. Traditional vergence theory has not however, lent itself to an adequate explanation of these observations.

The traditional concepts of the accommodative system are currently undergoing review: e.g. an intermediate resting position of tonic accommodation (TA); a dual-innervation to the ciliary muscle; and dependency of the accommodative response on the various characteristics of the stimulus. With the exception of the concept of dual innervation[1], the application of parallel developments to the vergence system may provide a more satisfactory explanation of the previously mentioned effects of oculomotor stress.

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[1] See sub-section 2.1B ii for the pharmacological aspects of vergence innervation.

5.1A - The Maddoxian concept of "tonic convergence".

Maddox (1893) is widely credited as being the first to formalize a classificational model of vergence eye movements, which has subsequently formed the basis of many subsequent clinical models (e.g. Morgan, 1968; Alpern, 1969a). As previously outlined within section 2.2B, Maddox proposed that convergence could be divided into four components: i) tonic; ii) accommodative; iii) convergence due to a "knowledge of nearness", now referred to as proximal convergence; and iv) "reflex", now known as fusional or disparity convergence (see Stark et al., 1980). Considerations of the three latter types of vergence have been outlined within sections 2.2C i, 2.2C ii and 2.2C iii, respectively.

Maddox maintained that tonic convergence was responsible for bringing the eyes from some indeterminable position of anatomical rest (which he believed to be a position of divergence) to a position of physiological rest. He observed that the eyes of refractively-corrected alert subjects did not usually diverge when viewing a distant object with one eye occluded but rather maintained a parallel or slightly convergent posture. He concluded that this was the result of tonic convergence due to both muscular tone and the involuntary action of convergence innervation.

Maddox considered the former aspect of tonic convergence was the tonus exhibited by living, physiologically active, striated muscle whereas the latter aspect he described as a "persistent activity of the converging innervation" related to the midbrain control of the vergence mechanism. This persistent activity was believed to be affected by conditions such as fatigue, sleep and death or by external agents such as alcohol and anaesthetics. Maddox observed that the level of muscular tone and convergent innervation could influence the magnitude of tonic convergence and observed it to vary amongst individuals. He claimed that excessive tonic convergence produced latent over-convergence (esophoria), whereas a deficiency in tonic convergence produced latent under-convergence (exophoria).

In addition, he assumed that in order to maintain single binocular vision, compensation must be provided by reflex (fusional or disparity) convergence. He considered this compensation to be stressful and as such, potentially fatiguing, leading to headaches and other asthenopic symptoms. He also observed the level of tonic convergence to be modified by the alteration of requirements for "reflex" convergence in the interests of single binocular vision. Whilst experimenting on himself, Maddox found that adaptation to base-out prisms increased his latent convergence at distance, whereas adaptation to plus lenses reduced his latent divergence for near; he attributed both changes to an induced increase in the tonic level of convergence, in an attempt to reduce the load on reflex convergence.

In summary therefore, Maddox concluded that vergence eye movements could be analysed in terms of four integrated components: tonic convergence moving the eyes from the anatomical to the physiological position of rest; accommodative convergence related to the accommodative effort required; proximal or voluntary convergence related to a "knowledge of nearness" and finally; reflex convergence compensating for any deficit in tonic convergence. Furthermore, Maddox considered that the vergence response resulted from the additive combination of the four components of convergence, operating in direct opposition to an inherent divergent bias of the eyes.

5.1B - Evidence for an intermediate resting position of tonic vergence (TV).

An area of some debate, concerning Maddox's unidirectional model, has been the assumption that divergence results from the release of passive elastic forces, pulling the eyes towards the anatomical resting position upon the relaxation of convergence, rather than an active process (for a discussion of the anatomical position of rest see section2.3B). This assumption has since been refuted by electromyographical studies of human extraocular muscle, demonstrating activity in the lateral recti during both divergence and steady fixation (Bjork, 1952; Adler, 1953; Breinin and Moldaver, 1955; Breinin, 1957a+b; Miller, 1959; Breinin, 1959; Keller and Robinson, 1972; Keller, 1973). In order that disparity vergence is able to operate for an outward change in task position, an efficient and active divergence mechanism is essential.

A further area of some debate concerns the position of physiological rest. Maddox considered the eyes to maintain a parallel or slightly convergent posture when at rest. There is however, much documented evidence in support of a more convergent or intermediate physiological resting position. The experimental evidence for a convergent tonus position is provided by studies of:

A) The effects of oculomotor stress (see section 2.3C ii), as induced by: i) ethanol (for a review see Table 2.2); ii) marijuana (Adams, 1977); iii) barbiturates (Westheimer, 1963); iv) nitrous oxide (Amos, 1976); v) anoxia (Wilmer and Berens, 1918; Adler, 1945).

B) The effects of a reduction in the quality of the stimulus to the vergence system (see section 2.3C i), such as: i) reduced illumination (see Table 5.1); ii) total darkness (see Table 5.1); iii) peripheral vergence stimuli (for a review see section

2.3C iii).

C) The effects of immature visual development (for a review see section 2.3C iv and Table 5.1).

TABLE 5.1 - Results of previous literature of the effect of reduced illumination, darkness and immature visual development on vergence.

AUTHORS	N	METHODS	RESULTS
Ivanoff & Bourdy (1954)	9	nonius alignment	1) distance eso-disparity 2) near exo-disparity 3) mean vergence position 56cm
Fincham (1962)	10	I/R photography	1) mean vergence position 197cm 2) loss of A-C synkinesis
Levy (1969)	16	phi-phenomenon	1) mean vergence 39cm or 9.6°
Owens & Leibowitz (1976a)	12	nonius alignment	1) mean vergence position 170cm or 2.96°
Bohman & Saladin (1980)	8	eye movement monitor	1) variable A-C relationship between
Owens & Leibowitz (1980)	60	nonius alignment	1) mean vergence 116cm or 3.22° 2) loss of A-C synkinesis
Aslin & Jackson (1981)	18	I/R photography	1) mean vergence position 31cm for 1 to 5 month old infants 2) corresponds to the distance of the most accurate vergence response
Aslin et al. (1982)	24	I/R photography	1) mean vergence position <100cm for 3 to 36 month old infants 2) loss of A-C synkinesis
Aslin & Dobson (1983)	12	I/R photography	1) mean vergence position 102cm for 3 to 12 month old infants 2) only minimal A-C correlation
Hogan & Gilmartin (1984a) and section 4.2	60	nonius alignment	1) mean TV position 108cm or 2.18° 2) TA correlated to TV ($r=0.8$, $p<0.001$)

Such evidence has shown that the functional range of vergence is found to reduce whenever visual performance is affected by the above factors. In the absence of visual stimuli or under conditions where demands on the accommodative response are minimised, the human accommodative system is known to rest at a position of intermediate bias (of around 76cm - see Owens and Leibowitz, 1980 and Table 2.1). The various conditions under which this phenomenon has been observed have provided such descriptive titles as; e.g. night myopia, dark focus, empty-field myopia, wide-field myopia, instrument myopia and small pupil myopia. Leibowitz and Owens (1975a) have demonstrated a significant relationship between the various "anomalous myopias", and conclude that they all have a common causal origin within the biasing of the accommodative system towards its intermediate tonic resting position.

It has been shown that ethanol induces a progressive esophoria and exophoria at distance and near respectively (see Table 2.2). It may be hypothesised that such observations are due to the progressive biasing of the vergence response towards an intermediate TV position. In order that such a hypothesis be tested however, measurements of both heterophoria and TV will need to be taken from the same set of observers whilst under the influence of ethanol. If this hypothesis is correct, it would be expected that whilst ethanol was able to induce the heterophoric changes it would not affect TV, as measured in total darkness.

The present study was designed to test the above hypothesis, by taking measurements of heterophoria, tonic vergence, tonic accommodation and other oculomotor parameters, immediately before and 1 hour after a moderate dose of ethanol.

5.1C - Ethanol and the neurophysiology of the vergence system.

The neurophysiology of the vergence system has previously been outlined within section 2.1C. It is known that ethanol is not a stimulant but a central nervous system depressant: the apparent stimulation arises from the unrestrained activity of various parts of the brain. Electrophysiological studies suggest that ethanol exerts its first depressant action upon the integrating function of the reticular activation system (Caspers, 1958; Himwich and Callison, 1972; Perrine, 1974). There is evidence to show that the anatomical areas surrounding the abducens nucleus (including portions of the medullary and pontine reticular formation, the rostral vestibular nucleus complex, and the prepositus hypoglossi nucleus) contain the cell units involved in the generation of tonic eye position signals required by the motor-neurons during fixation (Keller, 1974; Henn and Cohen, 1976; Luschei and Fuchs, 1972). Mays (1983) suggests that tonic convergence and divergence cells, lateral to the oculomotor complex in the paramedian pontine reticular formation, could provide the signals required by the medial and lateral recti motorneurons for convergence and divergence, repectively. Thus ethanol may disrupt the coordination of the motor control cell complexes within this region, leaving the steady tonic signals to remain.

The metabolism of ethanol has been discussed in an earlier study (Hogan and Linfield, 1983).

5.2- EXPERIMENTAL DESIGN.

5.2A - Subjects.

Ten male student observers with ages ranging from 20 to 26 years (mean age 22 years) and body-weights ranging from 140 lb to 210 lb (mean weight 168.8 lb), provided the data for the present study. During the course of a full refractive examination, each observer was screened for any defects of pathology or binocular vision; no abnormalities were detected and all observers were required to wear appropriate infinity-balanced refractive correction for all measurements during the subsequent investigation. All subjects reported "average" drinking habits and had been instructed to abstain from any alcohol for 24hrs prior to the experimental session (held at 2.00p.m.). All subjects had eaten similar light lunches one hour prior to the session.

5.2B - Apparatus.

The time sequencing, monitoring and data collection (relating to measurements of tonic vergence and tonic accommodation), were controlled by the programming of an Apple II plus computer, in conjunction with a CIL PC1 6000 interface unit (as outlined within section 3.4A).

TA was measured in total darkness using the He-Ne Badal-laser optometer previously described in section 3.1C i. A laser-speckle presentation time of 300ms was used, thus taking into account the latency of accommodation of around 360ms (see Table 3.1), the shorter response times associated with repetitive stimuli (Stark et al., 1965), and the increased variance in accommodation measurements for greater exposure times (see the results of section 3.5). TV was measured in total darkness using the vernier alignment device (VAD) described in section 3.2B i.

Measures of heterophoria (at 6 m and 33 cm), AC/A ratio, lateral fusional ability, near points of convergence and accommodation were measured using standard optometric apparatus.

5.2C - Procedure.

Measurements of TA and TV were taken after an initial period in total darkness of between 5 and 10 minutes. The techniques and psychophysical procedure utilised have been fully described in section 3.1C ii and 3.2B ii, respectively.

The other parameters of heterophoria (at 6 m and 33 cm), AC/A ratio, lateral fusional ability and near points of convergence and accommodation were then measured under more normal consulting room conditions, at 45 cd/m^2.

Each subject was then allowed 5 min to imbibe 35.16 g of ethanol in the form of four 1/6 gill measures of vodka (strength, 65.5° or 37.4% absolute ethanol), diluted to taste with a small amount of orange or lime juice. For the next hour the subject was accompanied for a walk around the campus. The whole experiment was then repeated one hour later and the results recorded.

5.3 - Results and analysis.

The pre- and post-ethanol data are presented in Table 5.2. One hour after taking ethanol, all subjects demonstrated a statistically significant increase in esophoria at 6m (t=6.33, $p<0.001$, df 9), with a mean increase of 1.4_Δ. The mean increase in exophoria at 33 cm of 1.4_Δ was also significant (t=4.12, $p<0.01$, df 9). The post-ethanolic AC/A ratios were found to have reduced significantly from the pre-ethanolic AC/A ratios, from 2.53 to 1.73_Δ/D by an average of 0.8_Δ/D (t=7.87, $p<0.001$, df 9). The divergent lateral fusional reserves reduced on average by 3.3_Δ (t=6.66, $p<0.001$, df 9)[1], whereas there was little significance in the 1_Δ mean increase in convergent fusional ability (t=0.88, p=0.60, df 9). The near point of convergence was found to recede significantly by a mean of 2 cm (t=4.30, $p<0.01$, df 9), whilst the amplitude of accommodation was unaffected by ethanol; the mean increase being a mere 0.05 D (t=0.79, p=0,26, df 9).

The effects of ethanol on both TV and TA were found to be insignificant. There was a mean reduction in TV of 0.03 deg, which was clearly insignificant (t=0.91, p=0.61, df 9) and the mean increase of 0.006D in TA also had little significance (t=0.14, p=0.89, df 9).

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1. The clinical significance of such a reduction in divergent fusional ability is enhanced by the fact that five of the ten subjects required base out prism to correct an ethanolic induced eso-fixation disparity.

		Subject										
Parameter		K.E.	I.J.	M.R.	I.L.	J.R.	M.P.	A.S.	G.V.	M.M.	M.W.	Mean
Heterophoria (Δ)	6 m pre	0.5 XOP	1.0 SOP	0.5 SOP	ORTHO	ORTHO	0.5 SOP	ORTHO	1.0 SOP	1.0 SOP	2.0 SOP	0.55 SOP
	6 m post	1.0 SOP	4.0 SOP	2.0 SOP	0.5 SOP	1.0 SOP	2.0 SOP	2.0 SOP	2.0 SOP	2.0 SOP	3.0 SOP	1.95 SOP
	33 cm pre	2.0 XOP	ORTHO	2.0 SOP	ORTHO	2.0 XOP	6.0 XOP	2.0 XOP	1.0 SOP	1.0 XOP	ORTHO	1.00 XOP
	33 cm post	2.0 XOP	ORTHO	1.0 SOP	3.0 XOP	4.0 XOP	7.0 XOP	3.0 XOP	2.0 XOP	2.0 XOP	2.0 XOP	2.40 XOP
AC/A ratio	Pre	2.33	2.00	2.67	3.00	2.67	2.00	2.33	2.67	2.67	3.00	2.53
	Post	1.00	1.67	2.00	2.33	2.00	1.33	1.33	2.00	1.33	2.33	1.73
Lateral fusional ability (Δ)	Base-in pre	4	4	1	5	5	4	5	3	5	3	3.90
	Base-in post*	−1	−1	−1	−1	2	2	3	−1	3	1	0.60
	Base-out pre	8	10	6	16	8	7	18	10	7	11	10.1
	Base-out post	14	10	6	18	6	6	14	16	12	9	11.1
Near point of convergence (cm)	Pre	10	5.5	9	8	8.5	6	5	6	6.5	5.5	7.0
	Post	12.5	7	10	9	13	10.5	7	8	7	6	9.0
Amplitude of accommodation (D)	Pre	9.5	11.5	6	8.5	9.5	9.5	8	9	8.5	12.5	9.25
	Post	8.5	11.0	7	9.0	9.0	9.5	8	9.5	8.5	13.0	9.30
Tonic accommodation (D)	Pre	2.46	0.69	2.02	0.30	1.30	2.80	1.95	1.01	1.84	0.19	1.46
	Post	2.60	0.73	1.94	0.11	1.41	2.94	2.13	0.93	1.61	0.24	1.46
Tonic vergence (°)	Pre	3.21	2.87	1.76	1.17	2.16	3.64	3.06	2.00	2.42	1.34	2.36
	Post	3.10	3.08	1.63	1.08	2.16	3.52	2.95	1.94	2.53	1.31	2.33
Spherical Rx (D)		−0.25	−1.50	−1.12	−0.37	+0.50	+0.50	+0.12	−0.25	+0.37	−0.37	−0.24

*The minus sign indicates the level of base-out required to correct an induced eso-fixation disparity.

TABLE 5.2 - The effect of ethanol on the oculomotor balance and tonic resting states of accommodation and vergence.

The correlation between the ethanol-induced change in heterophoria at 6 m and the post-ethanol TV values can be illustrated in Figure 5.1: the relationship was found to be significant at the 5% level ($r=0.64$, $p<0.05$). A stronger relationship ($r=-0.74$, $p=0.01$) can be demonstrated between the ethanol-induced change in heterophoria at 33 cm and the post-ethanol TV values, this is illustrated in Figure 5.2. The changes in heterophoria at 6 m and 33 cm were significantly negatively correlated ($r=-0.74$, $p=0.14$). A significant relationship can be demonstrated between TV and both the pre- and post-ethanolic AC/A ratio values ($r=0.92$, $p<0.001$ and $r=0.90$, $p<0.001$, respectively). The relationship between TA and AC/A ratio was found to be insignificant for the pre-ethanol measures ($r=0.58$, $p=0.08$), yet much stronger for the post-ethanol measures ($r=0.81$, $p<0.01$).

The total ethanol-induced change in both distance and near heterophoria may be illustrated as a function of post-ethanol tonic vergence by plotting the mean of the total heterophoria change at distance and near against the level of TV for each individual (see Figure 5.3). Consequently, the mean total change is found to be significantly related to the level of TV ($r=0.75$, $p=0.02$), such that the line of regression between the mean total change and tonic vergence intersects the abcissa at a TV of 2.23deg.

A correlation ($r=0.76$, $p=0.01$, df 9) can be demonstrated between the pre-ethanolic values of TV (mean 2.36deg) and TA (mean 1.458 D, at 632.8 nm), and would support the relationship between TV and TA observed within the N=60 study of section 4.5A. As found in section 4.6C, the correlation between TA and distance refraction was not significant ($r=0.39$, $p=0.27$, df 9).

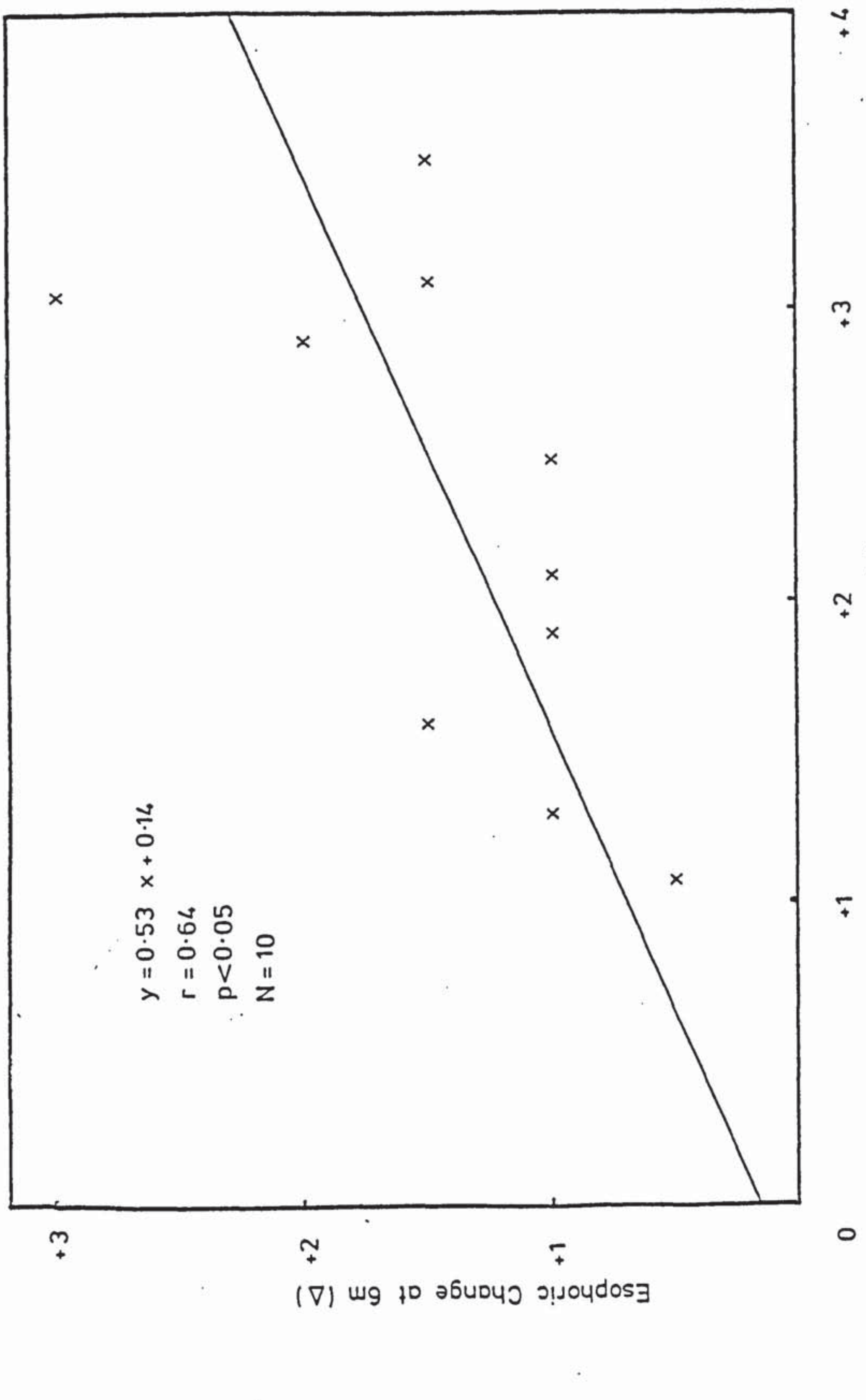

Figure 5.1 - Diagram illustrating the relationship between the ethanol-induced esophoric change in the distance heterophoria and TV. The change in heterophoria is proportional to the magnitude of TV.

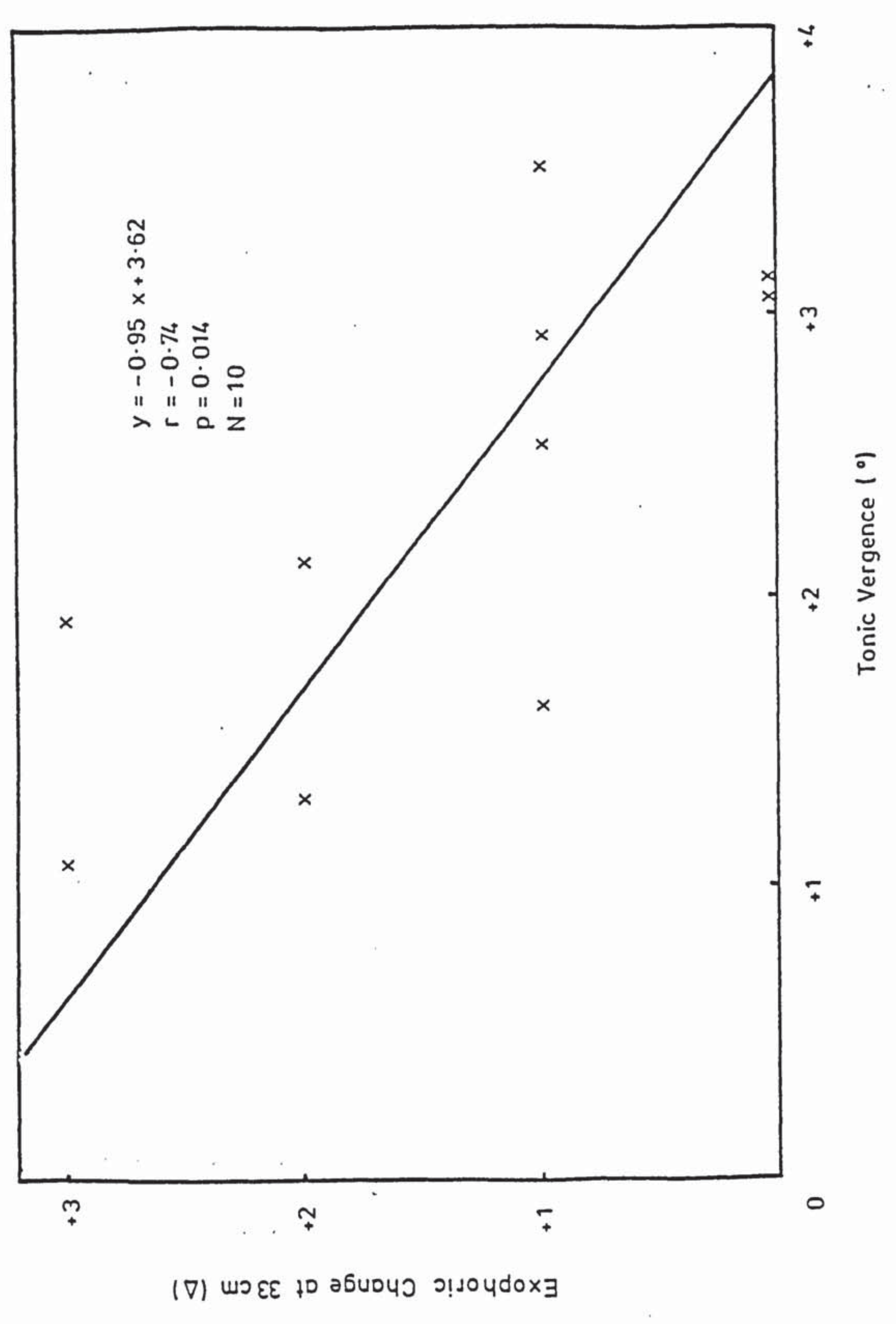

Figure 5.2 - Diagram illustrating the relationship between TV and the ethanol-induced exophoric change in the near heterophoria. The change in the near heterophoria is proportional to the magnitude of TV.

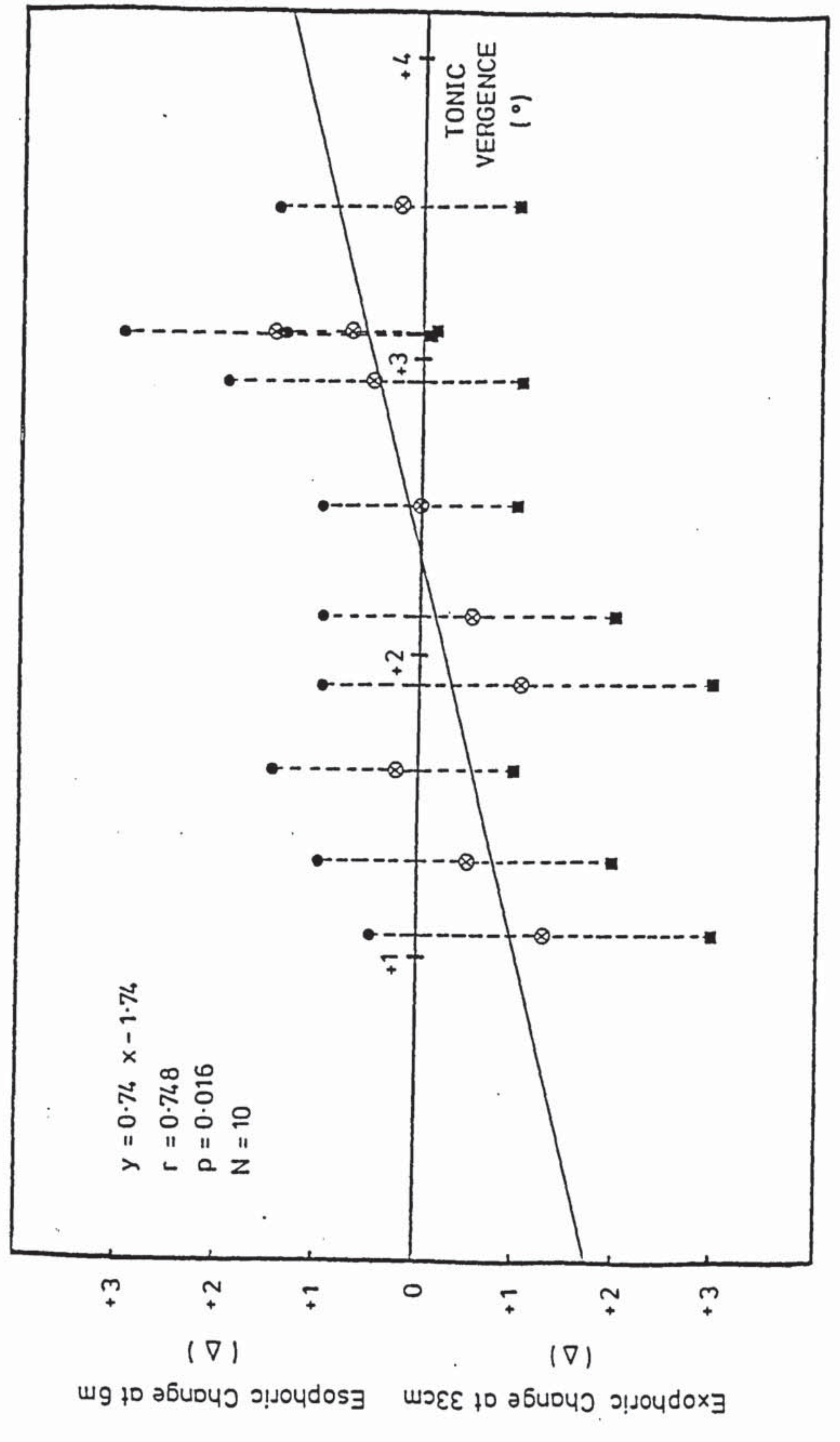

Figure 5.3 - Diagram illustrating the mean ethanol-induced change in heterophoria as a function of the level of post-ethanol TV. The regression line of the mean change intersects the abscissa at 2.23deg of TV (the mean TV for the study was 2.33deg). The change in distance heterophoria is given by—●—; the change in near heterophoria is given by-·■·-; and the midpoint of the total change is given by -⊗- .

5.4 - Discussion.

The results of table 5.2, of the the effects of ethanol on heterophoria, AC/A ratio, lateral fusional ability and the near points of convergence and accommodation, concur with and augment the results of previous investigations (listed in Table 2.2).

It is evident from Fig. 5.1 that the greatest esophoric change is induced in the distance heterophorias of those subjects with the largest (i.e. nearest) TV values, whereas there is less effect on the distance heterophorias of subjects with lower (i.e. distant) TV's. Similarly, Fig. 5.2 illustrates a greater exophoric change in the near heterophoria of those subjects with the least TV and a smaller change in the near heterophoria of those subjects with larger TV's. It may be concluded therefore, that, whilst the increase in esophoria at distance is directly proportional to the magnitude of TV, the increase in exophoria at near is inversely proportional to the magnitude of TV. Figure 5.3 provides further evidence to support this relationship; the regression line of the mean total heterophoric change as a function of post-ethanol TV demonstrates a significant trend towards the TV position. It is of interest to note that the regression line of this function intersects the abcissa at 2.23deg, a vergence value that is remarkably close to the mean post-ethanol tonic vergence value of the study (i.e. 2.33deg). In the larger N=60 study (of section 4.2) a mean tonic vergence of 2.18deg was found.

The effect of ethanol on the AC/A ratio is of interest: Cohen and Alpern (1969) investigated this aspect and stated that:

> "....while ethanol is associated with an unequivocal decrease in AC/A, it is also associated with a systematic increase in tonic convergence. Indeed, the increase in tonic convergence goes hand in hand with (though recovery occurs sooner than) the decrease in AC/A; the correlation coefficient between them was very high (r=-0.62, N=45) and significantly different from zero."

It is evident from their discussion that Cohen and Alpern had some difficulty reconciling their observations with the traditional (Maddoxian) theories on vergence:

> "If the usual way of interpreting vergences according to the classical categories of Maddox has any validity (and we know of nothing more meaningful to replace it), it is difficult to understand how a single depressing action of the drug produces both effects."

The important difference between Cohen and Alpern's understanding of the effects of ethanol and that of the present study is the adherence by Cohen and Alpern to the Maddoxian concept of the physiological position of rest. As it is now largely accepted that the resting position of the vergence system is at some individually determined intermediate position, the reduction in AC/A ratio can be explained as a systematic biasing of vergence towards this intermediate resting position. It is evident from the results of the present study that neither TA nor the amplitude of accommodation were affected by the ethanol and therefore, the effects on the AC/A cannot arise from accommodation. Furthermore, both pre- and post-ethanolic measures of the AC/A ratio were highly correlated with TV. The reduction in the AC/A ratio may therefore, be explained by interpretation of the hypothesis proposed earlier in the introduction (section 5.1B).

The differences in level of convergence between measures of Maddoxian tonic convergence and measures applying the current concepts of TV are essentially due to differences in the conditions of measurement. Maddoxian tonic convergence is based on measures of lateral heterophoria whilst monocularly viewing a bright distance fixation stimulus (Hebbard, 1952) and assumes that during distance fixation accommodation is relaxed and thus, provides little if any accommodative vergence input. In contrast, TV is measured in the absence of visual stimuli. Furthermore, there is a growing body of evidence to suggest that during fixation of a distance stimulus the accommodative system is not relaxed.

It is now generally accepted that the resting or tonic position of accommodation is not at infinity but at a distance of about arm's length and that "negative accommodation" would be necessary to view a distance fixation target, beyond the tonic accommodation position. It is known that accommodation and convergence are linked via the AC/A ratio and it could be hypothesised that negative accommodation would induce "accommodative divergence". Thus distance heterophoric estimates of tonic convergence may well indeed be relatively more divergent. In total darkness, with the accommodative system at its own position of rest, accommodative interference would be at a minimum. Therefore, the results obtained using the technique adopted in the present study, represent a more valid measurement of tonic vergence.

The evidence concerning a relationship between tonic vergence and tonic accommodation would seem to be equivocal (for a review see section 4.5A). However in the present study, simultaneous measures of tonic levels of vergence and accommodation were found to correlate at the 1% level. The results of the larger, N=60 study (section 4.5A) demonstrated a relationship significant at the 0.001% level. The implications of this relationship have been discussed in section 4.5E.

Thus it can be seen that under certain conditions where there is a reduction in stimulus quality (such as total darkness), both the vergence and accommodative systems return passively and independently, to their own stable, tonic resting positions. It is proposed that these positions of tonicity represent the "bias levels", induced by an averaging of all the innervation to the respective system, over a period of time, thus becoming the central reference positions for future vergence and accommodative response. This may provide explanations for both the long term stability (Mershon and Amerson, 1980; Owens and Higgins, 1983; and the observations of section 3.5D) and the short term hysteresis and plasticity of the tonic positions (Owens and Leibowitz, 1980; Ebenholtz, 1983; and Chapter 7 of this thesis).

In summary therefore, two major reviews (Toates, 1974; Owens and Leibowitz, 1983) have discussed the intermediate biasing of vergence under the various causal conditions and have acknowledged the lack of correlating evidence. The results of the present study have demonstrated that oculomotor stress, as induced by a moderate dose of ethanol, was found to have no effect on tonic vergence or accommodation, whilst producing the well documented changes in heterophoria, AC/A ratio, fusional ability and the near point of convergence (see also Hogan and Gilmartin, 1985a). It is concluded from this study that the heterophoric changes induced by ethanol are biased towards the tonic vergence resting position, thus providing affirmative evidence for the hypothesis introduced by Hogan and Linfield (1983).

CHAPTER 6

THE RELATIONSHIP BETWEEN TONIC ACCOMMODATION AND CILIARY MUSCLE INNERVATION

6.1 - INTRODUCTION

The traditional theory of accommodation (Helmholtz, 1909; Duke-Elder, 1970) maintains that the accommodative system of an emmetropic eye would be at rest when focussed for infinity, and would require stimulation of the parasympathetic nervous system (PSNS), to produce an increase in the refractive power of the eye; thus enabling the eye to focus for a near object or conversely, an inhibition of the PSNS, to produce a relaxation of accommodation for a relatively far object[1]. Although many investigators over the last 150 years have proposed that a supplementary innervation by the sympathetic nervous system (SNS) to the ciliary muscle should be considered, its existence was neither required nor sought by exponents of the traditional theory and thus, has been largely unrecognized for many years. There is much anatomical, clinical and pharmacological evidence however (see sections 1.4A to 1.4E), to suggest that the sympathetic innervation to the ciliary muscle may, indeed, play a significant role in the determination of ocular focus (see section 1.4F).

Toates (1972) reviewed the evidence for a dual innervation to the ciliary muscle, and applied it to a theoretical model (Toates, 1970). He proposed that the control of ocular focus could

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[1] An historical review of the accommodative system has been provided in section 1.2, whilst outlines of the relevant anatomy and neurology may be found in sections, 1.1A to 1.1C, and 1.3A to 1.3E.

be acheived by modification of the innervational balance between the inputs of the PSNS and the SNS to the ciliary muscle about a rest position of about 1.0 - 1.5D.

Dual-innervation of the cilary muscle has also been put forward as an explanation for a group of phenomena known collectively as the "anomalous myopias": i.e., those myopias associated with low-luminance viewing conditions (see section 1.4Gi); empty-field or "Ganzfeld" viewing (see section 1.4Gii); and the use of optical instruments or viewing through small pupil apertures (see section 1.4Giii). All these visual conditions produce a myopic state due to the accommodative system adopting an intermediate (or tonic) resting position when the stimulus to accommodate is degraded by: a reduction in luminance; a lack of target detail; or when the quality of the retinal image is not dependent on the extent of accommodative effort (see section 1.4I).

It is apparent from both the literature and the studies reported in the earlier chapters of this thesis, that measures of an individual's tonic resting accommodative state may be utilised as a metric of the accommodative system, whilst free from the constraints of stimulus-dependency. The accommodative stimulus-free nature of tonic accommodation (TA) readily lends itself in its application to the investigation of the pharmacology and innervation of the cilary muscle.

The anatomical, pharmacological and clinical evidence for a sympathetic input to the ciliary muscle has previously been outlined in sections 1.4A, 1.4B and 1.4C. Much of this evidence would suggest, however, that the sympathetic input to the ciliary muscle is likely to play a more limited role in the neural control of accommodation, than that envisaged by Toates: i.e., the effects of sympathetic stimulation have been shown to be too small, too slow and too dependent on the level of concurrent background parasympathetic activity, to provide an effective negative accommodation function.

The present series of studies have been designed to determine whether the level of tonic accommodation is a consequence of a steady-state equilibrium between parasympathetic and sympathetic innervation of the ciliary muscle. The relative importance of the PSNS and SNS in both resting and dynamic accommodation will be discussed.

The first study investigates the effects of a non-selective beta-adrenoceptor antagonist (Timolol Maleate, 0.5%) on tonic accommodation, tonic vergence and pupil diameter under darkroom conditions; whereas, the second study considers the effects of a non-selective beta-adrenoceptor agonist (Isoprenaline Sulphate, 3%) on TA and pupil diameter. The results give a clear indication that an input by the SNS to the ciliary muscle, plays a significant role in determining the TA position, and that this sympathetic input is mediated by inhibitory beta-adrenoceptors.

It has previously been demonstrated that TA varies significantly among individuals; typical values would be, mean = 1.5D with standard deviation = 0.7D (see Table 1.2 together with section 4.2B). The third study considers the effect of a muscarinic receptor antagonist (Tropicamide, 0.5%) on the distribution of TA. The results are compared to the effects on the distribution of TA of the two beta-adrenergic agents used in the earlier studies. It is shown that the distribution of TA is due to variation in parasympathetic innervation to the ciliary muscle, rather than to variation in sympathetic input.

The results of previous studies (outlined in sections 1.4B and 1.4C), would suggest that the temporal response characteristics of a sympathetic input to the ciliary muscle, would be too slow to provide an effective negative accommodative facility, to cope with the rapid and sophisticated demands of normal dynamic visual tasks. It is proposed that the parasympathetic input to the ciliary muscle is solely responsible for these demands, but that the SNS may have a role in the adaptation of the accommodative system to sustained visual tasks involving high levels of cognitive demand (e.g. prolonged interaction with a visual display unit).

6.2 - THE EFFECT OF A NON-SELECTIVE BETA-ADRENOCEPTOR ANTAGONIST ON TONIC ACCOMMODATION AND VERGENCE.

6.2A - Introduction.

Of the studies reviewed earlier (see section 1.4C), relatively few have employed autonomic effector drugs in an investigation of a dual-innervation of the ciliary muscle as it relates to Toates model (1970) of the accommodative system. There are several reports of investigations into the vascular effects of alpha-adrenoceptor effecter drugs on the accommodative function (e.g. Fleming, 1957; Biggs et al., 1959; Hurwitz et al., 1972b), and a recent study (Garner, et al., 1983) has even considered the effects of the alpha-adrenoceptor agonist Phenylephrine HCL on the resting point of accommodation. It was concluded from this latter study that, although the drug produced an effect on the near point of accommodation, it had no significant effect on the resting point.

Tornqvist (1967) considered the induced negative accommodation effects of sympathetic stimulation to be independent of vascular changes (as measured by ciliary body volume changes) and to be due instead to a modification of inhibitory beta-adrenoceptor activity. The pharmacological studies of Kern (1970) and Van Alphen (1976) support Tornqvist's findings, in that they provide further evidence of the beta-inhibitory nature of the sympathetic receptors. It may be deduced, therefore, that sympathetic stimulation produces negative accommodation, whilst parasympathetic stimulation induces positive accommodation.

The tonic resting state of accommodation (TA) may be considered a consequence of an equilibrium in the basal neural activity between the levels of sympathetic and parasympathetic innervation. A reduction in sympathetic activity would be expected to induce a positive or myopic shift in TA, whilst an increase in sympathetic innervation should produce a negative or hyperopic shift. A suitable mode of sympathetic blockade is afforded by the use of the nonselective beta-adrenoceptor-antagonist, Timolol Maleate: a drug widely utilised as a topically-applied ocular hypotensive agent in the management of open-angle glaucoma (Zimmerman and Boger, 1979).

The interaction between accommodation, vergence and pupil size under normal visual conditions is well documented (e.g., Alpern, et al., 1961; Davson, 1980). There is less agreement, however, concerning the state of this relationship in the absence of visual stimulation (for a review, see section 4.6). The present study includes concurrent measures of tonic vergence (TV) and tonic pupil (TP) in order to examine their synkinetic relationships with any Timolol-induced changes in TA. Whilst the evidence for a sympathetic involvement in vergence movements is inconclusive (see section 2.1Bii), there is stronger evidence implicating the SNS in pupil responses (see Lowenstein and Loewenfeld, 1969). The studies of Kern (1970) and Van Alphen (1976) have demonstrated the presence of alpha- and beta-receptors on the sphincter pupillae, in approximately equal amounts. If these beta receptors are also inhibitory in nature, then blockade might be expected to induce a contraction in pupil size. Measurement of Timolol-induced changes in the intraocular pressure (IOP), before and after application of the drug, should provide the study with a convenient check that the Timolol has indeed reached the ciliary body and also, to check for any potential correlation with the effects on TA.

6.2B - Methodology, design and materials.

Ten observers were used in the study; eight males and two females, with ages ranging from 19 to 37 (mean = 23.2) years. All observers were provided with an optimum, infinity-balanced and -centred refractive correction, giving distance visual acuities of at least 6/6, in each eye. Observers with a history of a cardiac or asthmatic condition were not permitted to take part in the study.

Two drops of the topical anaesthetic, Benoxinate (0.4%)[1] were instilled into the lower fornix of each eye over a period of 20s: this was used to maximize the transmission of subsequent drugs through the cornea; to inhibit reflex lacrimation and to produce topical anaesthesia for subsequent measures of intra-ocular pressure (IOP) by applanation tonometry (see later). A double-blind protocol was employed between Timolol Maleate (0.5%)[2] and a control of normal saline[1]: a separation period of at least 2 days (mean = 4.5 days) was allowed. After instillation of the Benoxinate, each observer was given two topical instillations (separated by a period of 10mins) of either Timolol or Saline (depending on the protocol). Each instillation was made using a precision micro-pipette set to deliver 25 microlitres of drug (therefore total drug delivered per eye = 50 microlitres).

Measurements of TA and TV were taken in the dark, prior to

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1. Smith and Nephew UK, single-dose applicators
2. Merck Sharp and Dohme UK, multi-dose applicators.

drug instillation and then at various periods during the 40min post-drug experimental period. TA was measured using laser optometry at a wavelength of 632.8nm (see sections 3.1Cii and 3.1Ci), whilst measures of TV were obtained using the vernier alignment device (see section 3.2Bi), according to the procedure described in section 3.2Bii. Horizontal pupil size in total darkness (TP) was measured, both before and 40min after drug instillation, using an infra-red photographic technique and procedure previously described in sections 3.3Aii and 3.3Aiii. All measures of TA, TV and TP were under the control of an Apple IIe microcomputer (see sections 3.4Ai and 3.4Aii).

The use of Benoxinate facilitated the measurement of IOP, before and 40mins after the instillation of the investigative drug, using a Perkins hand-held applanation tonometer (for a description of the procedure see Perkins, 1965; Dunn and Brubaker, 1974).

Pre- and 40min post-drug measures of refractive error (Rx) and amplitude of accommodation (AA) were taken using standard optometric procedures (previously described in sections 4.7B and 4.5A, respectively). Measurements were also made of the distance and near heterophorias (using the procedures of Maddox 'rod' and 'wing'), and the AC/A ratio (using a 'gradient' procedure): these procedures have been described by Hogan and Linfield (1983). It was necessary for these measurements to be carried out as a separate procedure on a subsequent occasion to that of the main study, due to the effect of possible corneal trauma (from the applanation tonometry) on the accuracy of the refractive results, and also because of the possibility that the procedures utilised in the measurement of AA and AC/A ratio might have influenced any subsequent measures of TA and TV (see chapter 7). Although a double-blind procedure was not employed in the refractive and oculomotor balance tests, the use of Timolol Maleate and Benoxinate was exactly as that employed in the main study.

6.2C - Results of the effects of Timolol on TA and TV.

The mean pre-drug values for TA (at 632.8nm) for the N=10 observer group during the Timolol and Saline-control studies, were 1.31D and 1.29 respectively; whilst, for TV the mean pre-drug values of the Timolol and Saline studies were 2.12 and 1.97 deg; for TP the pre-drug values were 7.13 and 7.04mm respectively: the data from which all these mean values have been calculated may be found in the tables of Appendix XVII. These mean values for TA, TV and TP are similar to those of earlier studies of this thesis (see particularly sections 4.2B, 4.3B and 4.4B, respectively). The product-moment correlations between the Timolol and Saline-control pre-drug measures of TA, TV and TP were high, thus indicating a significant level of repeatability: i.e., for TA, $r = 0.97$, $p < 0.001$; for TV, $r = 0.94$, $p < 0.001$; and for TP, $r = 0.95$, $p < 0.001$.

It had been planned that the post-drug measurements of TA and TV were to be taken at intervals of 5min after the second drug instillation. Most observers were, however, unable to provide reliable subjective data for the first 10 - 15mins and furthermore, individual observers differed in their ability to provide end-points exactly "on cue", nevertheless, measurements were taken as close as possible to each 5min interval. Tables XVII.1 to 4 of Appendix XVII give the value and time taken of all measurement points of TA and TV. Each observer thus provided 5 measurements of TA and TV over the post-drug period. Table 6.1 (below) indicates the mean and standard deviations of these measurements and the overall mean sampling times. It will be appreciated that the mean sampling times are reasonably close to the planned sampling times of 20, 25, 30, 35 and 40 mins (see the last column of Table 6.1).

Table 6.1 - The means and standard deviations (sd) of the pre- and 5 post-drug readings of TA and TV for the N=10 observer group. The maximum drug effect is indicated at the foot of each column. The right-most column provides the overall mean sampling times of both drug and both measurement conditions.

	TONIC ACCOMMODATION (D)				TONIC VERGENCE (deg)				
	SALINE		TIMOLOL		SALINE		TIMOLOL		MEAN
READING	mean	sd	mean	sd	mean	sd	mean	sd	SAMPLE TIME
pre-drug	1.29	0.61	1.31	0.57	1.97	0.80	2.12	0.75	0.00
1	1.32	0.69	1.58	0.70	1.94	0.81	2.11	0.73	18.03
2	1.32	0.70	1.79	0.75	1.96	0.83	2.15	0.73	24.85
3	1.29	0.64	1.91	0.76	2.02	0.83	2.13	0.74	29.70
4	1.27	0.62	2.06	0.84	2.00	0.83	2.12	0.75	35.50
5	1.27	0.67	2.13	0.80	2.00	0.81	2.11	0.74	40.90
MEAN MAXIMUM EFFECT	+0.03D		+0.82D		+0.03deg		+0.03deg		

It will be evident from Table 6.1 that, whilst there is no appreciable effect of Timolol on TV or of Saline on measurements of TA or TV over the 40min post-drug period, Timolol has induced a mean myopic shift in TA of +0.82D. A three-way analysis of variance (3-way ANOVA) of the TA data (from appendix tables XVII.1 and XVII.2) demonstrates high levels of significance for drug effect (F = 501.19, p < 0.001, df 1, 45), for the time course (F = 28.96, p < 0.001, df 5, 45), and for subject (F = 362.91, p < 0.001, df 9, 45). The second order interactions of drug/time and drug/subject are also significant (F = 34.91, p < 0.001, df 5, 45 and F = 16.31, p < 0.001, df 9, 45 respectively). A visual comparison of the effects of Timolol and Saline on TA may be made from Figure 6.1.

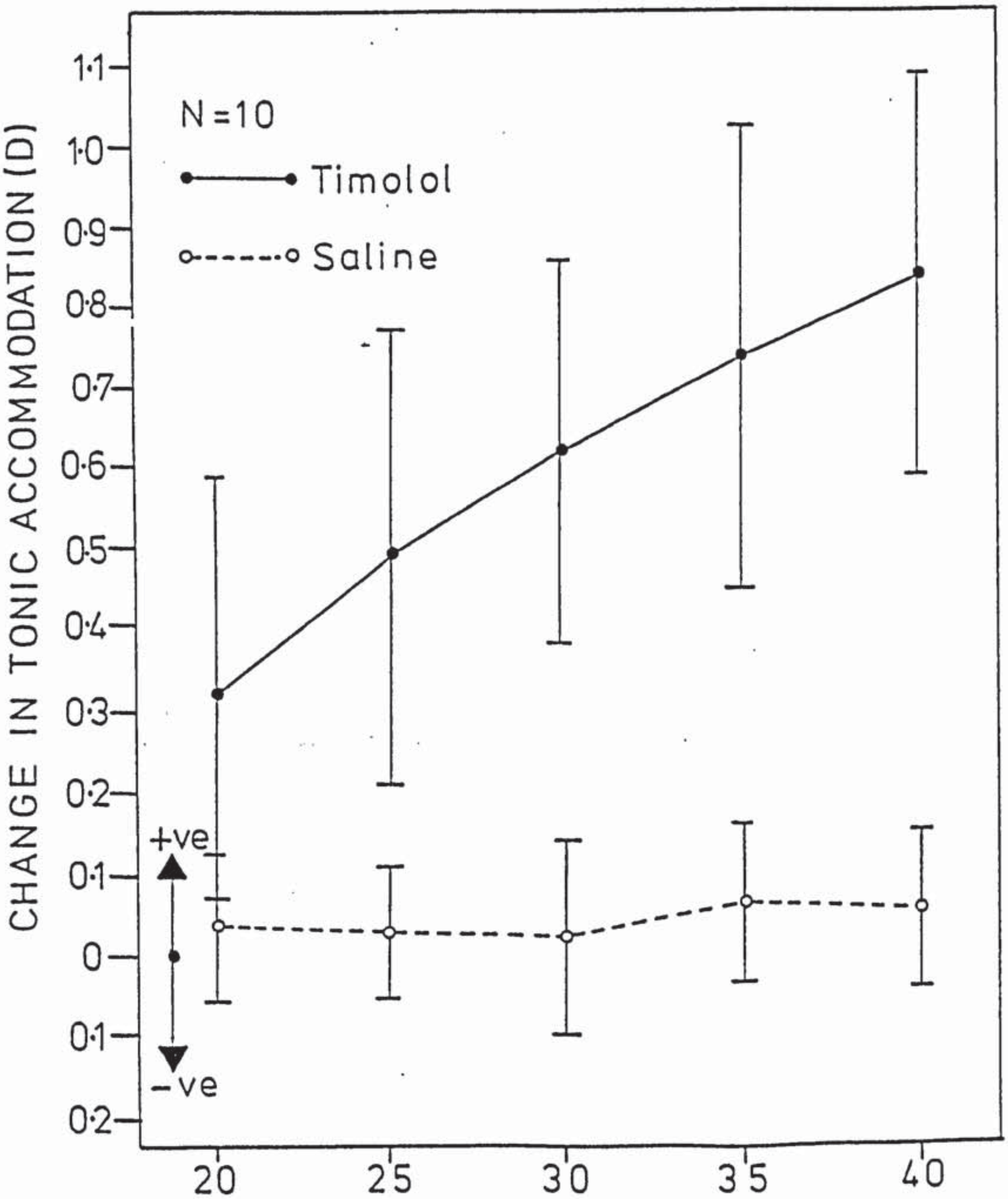

Figure 6.1 - The effect on TA over a 40 min period, of 50 microlitres of Timolol Maleate (0.5%) and a Saline control. The error bars represent ± 1 sd.

A 2-way ANOVA of the TV data from Tables XVII.3 and XVII.4 shows no significance in the effect of drug (F = 0.30, p = 0.59, df 1, 36) or time (F = 0.001, p = 0.97, df 1, 36).

Timolol induced a mean reduction in tonic pupil (TP) size from 7.13mm to 6.97mm. A 2-way ANOVA of the TP data for the 0min and 40min instillations (see Table XVII.5) demonstrates, however, that the 0.16mm reduction is not statistically significant (see Table Table 6.2).

Table 6.2 - Mean levels of tonic pupil (mm) before and at 40min after, 50 microlitres of Timolol (0.5%) and Saline. A 2-way ANOVA indicates the effects to be non-significant.

TONIC PUPIL

	SALINE		TIMOLOL	
	0 min	40 min	0 min	40 min
MEAN	7.04	7.07	7.13	6.97
SD	0.41	0.39	0.35	0.42

ANOVA DETAILS	DRUG EFFECT	F = 0.001	p = 0.97	df 1, 36
	TIME EFFECT	F = 0.27	p = 0.61	df 1, 36

Table 6.3 - Mean levels of IOP (mmHg) for the R and L eyes of 10 observers, immediately before and at 40min after, 50-microlitres of Timolol and Saline. A 3-way ANOVA indicates a significant timolol-induced reduction in IOP.

INTRA-OCULAR PRESSURE

	SALINE				TIMOLOL			
	0 min		40 min		0 min		40 min	
	R	L	R	L	R	L	R	L
MEAN	14.2	14.3	14.2	14.3	14.7	14.7	12.0	12.2
SD	1.40	1.49	1.03	1.49	1.06	1.06	1.33	1.03

3-WAY ANOVA DETAILS	DRUG EFFECT	F = 9.19	p = 0.004	df 1, 72
	TIME EFFECT	F = 21.50	p < 0.001	df 1, 72
	D/T EFFECT	F = 21.50	p < 0.001	df 1, 72
	R/L EFFECT	F = 0.13	p = 0.72	df 1, 72

With regard to the ocular hypotensive effects of Timolol, a reduction was found in the mean IOP of the right (R) and left (L) eyes of the 10 observers; from 14.7mm (R + L), to R = 12.0mm and L = 12.2mm, over 40mins. A 3-way ANOVA on the data from Table XVII.6 demonstrates the mean-IOP reduction to be statistically significant for drug effect, time-course and the drug/time interaction (see Table 6.3). No significant difference was detected between the effect on the R and L eyes.

It will be apparent from Table 6.4, that Timolol induced a 0.1D myopic shift in the mean distance best-sphere Rx. The results of a 1-way ANOVA on the data for 0min and 40min (see Table XVII.7) are, however, found to be insignificant: there were no reports from the 10 observers of blurred or fluctuating vision. The effects of Timolol on the 0min and 40min amplitude of accommodation data of Table XVII.7 are also found to be non-significant (see Table 6.4). There was no significant difference between the refractive data of the left and right eyes, it is for simplicity, therefore, that the left-eye data alone is supplied.

Table 6.4 - Mean levels of L-eye best-sphere distance Rx (D) and L-eye amplitude of accommodation (D), immediately before and at 40min after, 50-microlitres of Timolol. A 1-way ANOVA indicates the effects to be non-significant.

	MEAN-SPHERE DISTANCE Rx		AMPLITUDE OF ACCOMMODATION	
	0 min	40 min	0 min	40 min
MEAN	-0.84	-0.94	+7.58	+7.58
SD	2.22	2.19	1.57	1.70
F	0.01	df 1, 18	0.00	df 1, 18
p	0.92		0.99	

Table 6.5 - Mean levels of heterophoria (at 6m and 33cm) and AC/A ratio immediately before and at 40min after 50-microlitres of Timolol. A 1-way ANOVA indicates the effects to be non-significant.

	HETEROPHORIA at 6m		HETEROPHORIA at 33cm		AC/A RATIO	
	TIMOLOL		TIMOLOL		TIMOLOL	
	0 min	40 min	0 min	40 min	0 min	40 min
MEAN	0.25 Sop	0.35 Sop	2.2 Xop	1.5 Xop	2.15	2.33
SD	0.86	1.00	3.20	3.20	0.73	0.70
F	0.06	df 1, 18	0.07	df 1, 18	0.27	df 1, 18
p	0.81		0.78		0.61	

Further use of the 1-way ANOVA technique demonstrates the effects of Timolol on the oculomotor balance measures of heterophoria and AC/A ratio (see the data of Table XVII.7) to be statistically non-significant (see Table 6.5).

Little significance was found between the timolol-induced change in TA and the change in IOP after 40mins ($r = 0.37$, $p = 0.30$). Significance was found, however, in the correlation between the change in TA and the initial TA value ($r = 0.79$, $p = 0.007$). The relationship between the change in TA and the pre-drug TA is illustrated in Figure 6.2.

The timolol-induced change in TA is found to be significantly correlated to the change in Rx, after a similar period of time ($r = 0.76$, $p = 0.01$). This relationship is illustrated in Figure 6.3.

Extended and separate experimental sessions were performed on two further subjects in order to determine the duration of the observed Timolol-induced changes in TA. In agreement with the earlier results, Timolol produced maximum respective changes in TA of 0.57D and 0.64D. These values were found to revert back to the pre-drug TA levels in both observers after a period of 3hrs.

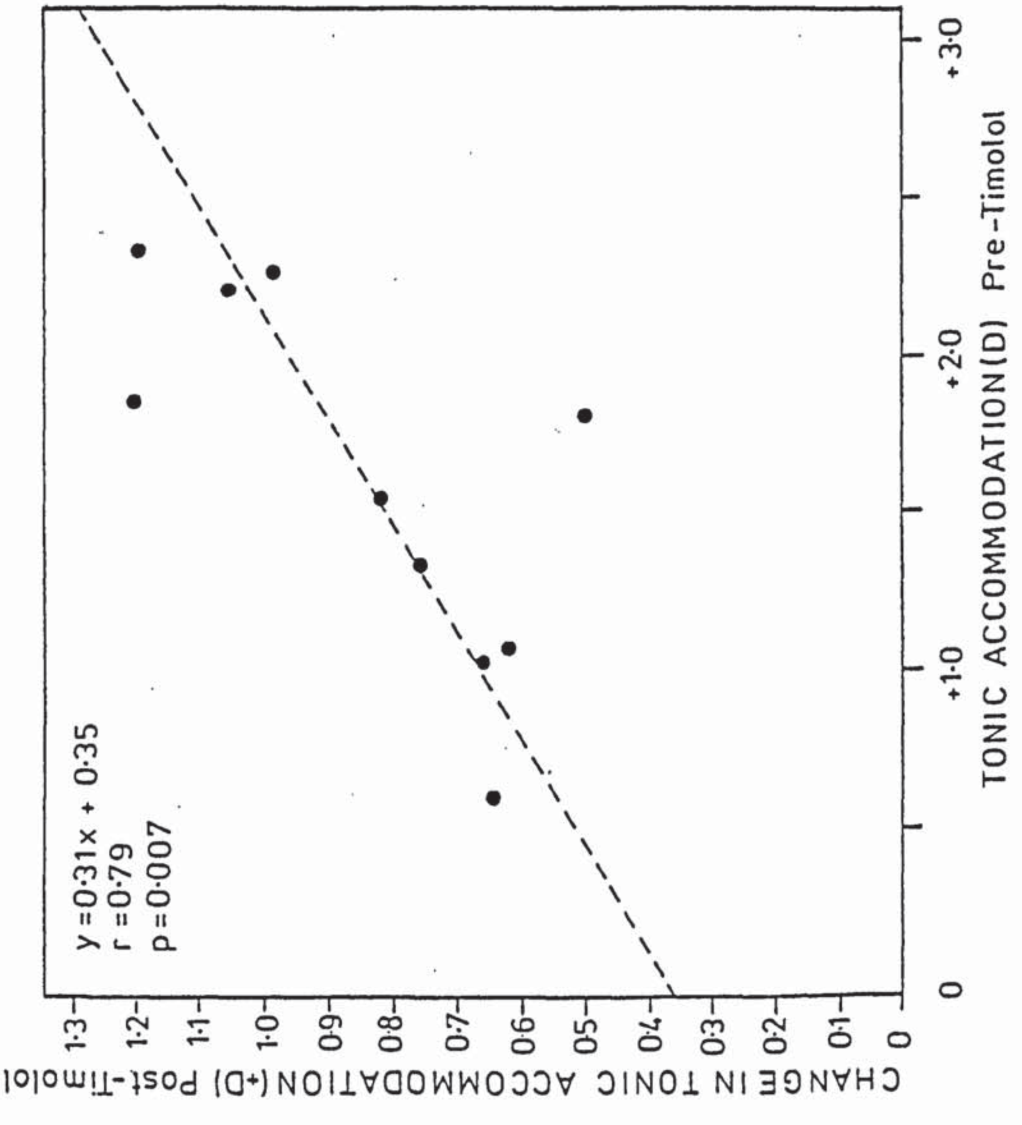

Figure 6.2 - The relationship between the pre-drug TA level and the change induced in TA 40min after the instillation of 50-microlitres of Timolol Maleate (0.5%).

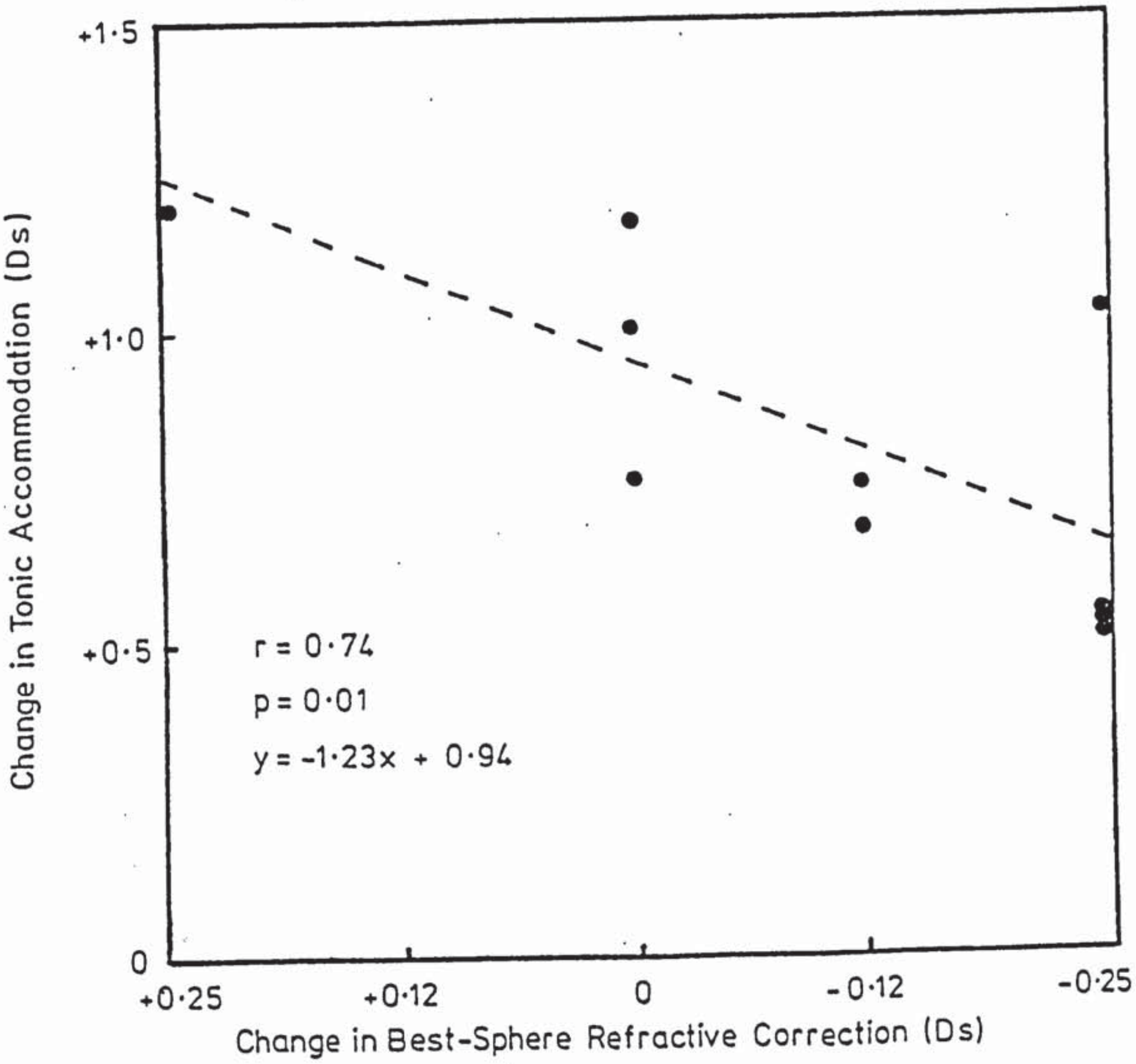

Figure 6.3 - The relationship between the Timolol-induced changes in TA and Rx.

6.2D - TIMOLOL AND TA - DISCUSSION.

The significant effects of Timolol on the accommodative resting position offer clear support for the earlier reports of a sympathetic innervation to the ciliary muscle, mediated by inhibitory beta-receptors (Tornqvist, 1966, 1967; Kern, 1970; Van Alphen, 1976). Furthermore, the observed +0.82D Timolol-induced mean myopic shift in tonic accommodation indicates that this sympathetic innervation must play a significant role in the determination of TA.

It is interesting to note, however, that the Timolol-induced changes in TA are demonstrable in the absence of any concurrent effects on the standard refractive and oculomotor measures. This suggests that the SNS does not directly contribute to the neural control of the accommodative response under normal visual environments. The earlier cited work on monkeys by Tornqvist (1966; 1967) supports this suggestion; he found that stimulation of the cervical sympathetic nerve produced a slowly developing decrease in accommodation with a maximal effect after a period of 10 - 40sec. This is evidently too slow to provide an effective temporal response to the changing stimulus conditions of a dynamic visual environment. Conversely, he found that stimulation of the parasympathetic oculomotor nerve induced a maximal myopic effect after a period of only 1 - 2sec. If these observations were applied to the Toates (1970) model, cited earlier, one would expect to find significantly different accommodative latencies for near and far stimuli. It is interesting to note, therefore, that the mean "positive" and "negative" accommodative reaction times under normal visual conditions are remarkably similar (at 379 ± 70msec and 376 ± 47msec, respectively - see Table 3.1 of chapter 3). It would seem unlikely, therefore that the sympathetic innervation to the ciliary muscle had made a significant contribution to the ciliary muscle movements during negative accommodation.

Tornqvist (1967) also noted that the inhibitory effects from sympathetic stimulation varied, according to the level of concurrent background parasympathetic activity. He found that, in the non-accommodating monkey (i.e., under anaesthesia), stimulation of the sympathetic nerve (at a constant rate of 5 stimuli/sec), produced an average hyperopia of 0.6D, however, when the parasympathetic level of activity was increased to give equivalent accommodation responses of 1.8, 3.1 and 7.1D, there was a proportionate increase in the inhibitory effect up to a maximum hyperopic shift of 1.5D (which was maintained even for higher levels of oculomotor stimulation).

Hurwitz et al. (1972a) investigated the effects of monkey ciliary muscle beta-receptor stimulation and blockade (using subconjunctival injections of the beta-adrenoceptor agonist and antagonist, Isoproterenol and Propranolol, respectively), while inducing monocular positive accommodation via electrical stimulation of the mid-brain. It was considered that inhibition of the PSNS had greater significance than beta-receptor stimulation as an antagonist to positive accommodation. Furthermore, it was noted that the inhibitory effects of beta-receptor stimulation were only significant when the mid-brain stimulation produced accommodative levels greater than 2-4D. This concurs with Tornqvist's observation that the level of sympathetic inhibition increases with increases in concurrent levels of parasympathetic activity, and would suggest that Tornqvist's monkey's "non-accommodating" state was in fact equivalent to that of a significant level of accommodation[1].

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[1] The work of Westheimer and Blair (1973) demonstrates that Tornqvist's (1967) anaesthesised monkeys would have an intermediate accommodative resting state of 2.5 - 3.0D, whilst un-anaesthesised monkeys had levels of resting accommodation analagous humans.

The nerve stimulation experiments indicate, therefore, that the effects of sympathetic input to the monkey ciliary muscle are relatively small, slow and directly related to the level of concurrent background parasympathetic activity. These indications allow one to speculate whether the function of the SNS in human accommodation is more relevant to those tasks requiring a sustained effort of accommodation rather than to those tasks requiring a rapid change in accommodative response.

In this respect, the recent study of Ebenholtz (1983) is of particular interest. His results suggest that task-induced positive and negative shifts in TA are determined by the relationship between the task position and initial pre-task TA. It was shown that after an 8min fixation period the TA levels of 12 emmetropic observers either increased by 0.34D or decreased by 0.21D, depending upon whether the point of fixation had been at the near point or the far point of accommodation, respectively. No significant shifts in the level of TA occurred following fixation at the observer's pre-task TA position. Ebenholtz described the task-induced shifts in TA as "accommodative hysteresis". It is understandable that some degree of smooth muscle tone would be retained following a sustained period of effort and that this "hysteresis" would, in the case of the ciliary muscle, be evident in subsequent measures of TA.

Ebenholtz noted, however, a non-linearity in the degree of accommodative hysteresis that followed fixation at the near and far point. The far point target was, on average, 0.98D beyond the mean pre-task TA level and produced a -0.21D mean hyperopic shift in TA. The near point target was, on average, 5.12D closer than the pre-task TA position, yet only induced a mean myopic shift of +0.34D. Whilst not identifying the PSNS or the SNS specifically, Ebenholtz suggested that this non-linearity could be attributed to "separate systems governing accommodative increase and relaxation respectively".

It is possible that the non-linearity in hysteresis may be accounted for by an increase in sympathetic inhibitory input, induced by the high level of parasympathetic activity associated with sustained near point fixation. When present, this inhibitory input may account for the differences in recovery times found by Ebenholtz in the hysteresis effects due to far point fixation (mean = 14.4min) and to near point fixation (mean = 123.1min). Tornqvist (1967) had earlier noted the slow response and recovery times for sympathetic inhibitory effects. Thus, the accommodative hysteresis effects described by Ebenholtz may result from imbalances in ciliary body autonomic tone induced by the prior fixation conditions.

It is postulated (in the next chapter) that the sympathetic inhibitory input to the ciliary muscle may provide a mechanism whereby accommodative responses to sustained stimuli situated at the extremes of the accommodative range, are biased towards the observer's tonic resting position. In this context, the major role of the sympathetic system, under normal visual conditions, may be to attenuate the hysteresis effects that are found to follow prolonged near visual tasks. Furthermore, this bias could account for the well established non-linearity of the accommodation stimulus-response graph (see Toates, 1972), and explain the matching of stimulus and response that occurs at the mean TA position (Johnson, 1976).

Timolol induced a significant mean reduction in IOP of 2.6mmHg over the 40min period. Previous investigations have suggested that this ocular hypotensive effect is probably due to beta-2 adrenoceptor blockade (Trope and Clarke, 1982). It has been suggested that "tonic" activity is supplied to the inflow mechanism by these receptors and that blockade would result in a reduction in aqueous production (Coakes, 1980; Thomas and Epstein, 1981). Trope and Clarke (1982) found a mixed receptor population for the "iris-ciliary body diaphragm" for Beta-1 to Beta-2 in the order of 10-25%:75-90%, and considered that the majority of Beta-1 receptors are situated in the muscle fibres and/or the large blood vessels of iris/ciliary body diaphragm.

A more recent study (Wax and Molinoff, 1984) has, however, reported that the beta receptors are present in human iris/ciliary body in the following proportion: ciliary processes - 30%; iris - 30%: ciliary muscle - 40%. Furthermore, it was reported that all of the receptors were of the beta-2 subtype. The present report suggests that the Timolol-induced changes in TA of the present study are most likely due to antagonism of Beta-2 receptor activity, although it is unable to demonstrate a significant correlation between the induced changes in TA and IOP ($r = 0.37$, $p = 0.30$): this would suggest that the Beta-receptors responsible for the changes in TA are anatomically independent to those Beta-receptors implicated in the reduction of IOP.

Although it is most attractive to seek a Beta-2 mediated inhibitory effect on the muscle fibres themselves, the possibility arises of the changes in TA being caused by a Beta-1 mediated inhibitory effect on the cilary body vascular network. The Timolol-induced beta-adrenergic receptor blockade may produce an accumulation of noradrenaline at the synaptic cleft. It is conceivable that this excess Noradrenaline may diffuse into the ciliary body, producing vasoconstriction of the ciliary-body blood vessels via its alpha-receptor activity. Whether the vasoconstriction is due to beta-inhibition or alpha-stimulation, cilary-body volume would be reduced, increasing the tension on the zonular fibres and flattening the anterior portion of the crystalline lens, with the subsequent production of a hyperopic (rather than a myopic) shift in the TA position. Consequently, the Timolol-induced myopic shift in TA may be an underestimate of the total effect. A recent study (Garner et al., 1983) has shown, however, that the alpha-receptor-agonist Phenylephrine has no effect on TA; thus any underestimate in TA would be of little significance to the present study.

The present study found a significant correlation between the Timolol-induced change in TA and the initial pre-Timolol TA level (see figure 6.2): the higher the initial pre-Timolol TA level, the greater was the effect of Timolol on TA. However, before one is able to interpret the significance of this correlation with regard to individual variations in TA, the extent of Timolol-induced beta-receptor-antagonism would have to be determined. If it were assumed that maximal receptor-blockade had been achieved, it could then be concluded that the distribution of TA values were, in part, a consequence of individual variations in ciliary muscle parasympathetic tone. At the very least, this is a further illustration of the inhibitory nature of the sympathetic input to the cilary muscle.

It has been proposed that individual variations in TA may, in part, be related to distance refractive error (see section 4.7): it is thought that corrected myopes possess the lowest TA values, whilst hyperopes have the highest with the emmetropes intermediate. The present study is, however, unable to support this proposal (albeit for a small sample-size) and is consistent with the earlier results of chapter 4, in that significant systematic trends are not found (r = -0.07, p = 0.84). Similarly, the Timolol-induced changes in TA for varying levels of corrected ametropia were inconclusive (r = -0.37, p = 0.30). The logical conclusion would be to assume that variations in the physiological tonus of the ciliary muscle are not associated with variations in refractive error.

It is interesting, therefore, to observe that, although the standard optometric and oculomotor balance measurents taken in this study were not significantly affected by Timolol, there is reasonable significance in the relationship between the change in TA after 40min and the change in the distance refraction, after the same period of time (r = 0.76, p = 0.01: see Figure 6.3). None of the other relationships reached levels of significance (i.e., change in TA with change in amplitude of accommodation).

This study has demonstrated that the sympathetic innervation to the cilary muscle plays a significant role in the determination of TA and, furthermore, that this innervation is mediated by inhibitory beta-adrenoceptors. The next study will confirm these results by investigating the effects, on the TA postion, of the beta-adrenoceptor agonist, Isoprenaline.

6.3 - THE EFFECT OF A NON-SELECTIVE BETA-ADRENOCEPTOR AGONIST ON TA AND TV.

6.3A - Introduction

In the previous study, topical instillations of the beta-adrenoceptor antagonist Timolol Maleate (0.5%) were utilised to demonstrate that sympathetic innervation plays a significant role in determining the position of TA. Timolol was found to induce a mean myopic shift in TA of +0.82D, consistent with the interpretation that the sympathetic innervation is mediated by inhibitory beta-adrenoceptors.

The present study is designed to test these findings, using the non-selective beta-adrenoceptor agonist Isoprenaline Sulphate (3%). In the context of Toates's (1970) model, the tonic position of accommodation may be considered a consequence of a tonal equilibrium between the sympathetic and parasympathetic innervation to the ciliary muscle: Isoprenaline will be expected to induce a hyperopic shift in TA; an effect contrasting with that observed in the Timolol study.

As in the Timolol study, measurements of tonic vergence and pupil diameter will be taken, together with measurements of intra-ocular pressure, distance refraction and the amplitude of accommodation.

Isoprenaline Sulphate is a potent adrenoceptor-agonist and, although the drug is to be topically instilled, the possibility exists of systemic absorption via the blood-vessels of the conjunctiva and nasal-mucosa. To monitor possible beta-adrenoceptor agonistic systemic effects, the heart-rate and blood pressure of all subjects will be assessed.

6.3B - Experimental design, materials and methods.

Ten observers were used, seven males and three females, with ages ranging from 19 to 37 (mean = 22.9) years. All observers were provided with an optimum refractive correction, giving distance visual acuities of at least 6/6 in each eye. Observers with a medical history of cardiac or asthmatic problems were not included.

Over a 20sec period two drops of Benoxinate (0.4%)[1] were instilled into the lower fornix of each eye: this was used to

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[1] Smith and Nephew UK, single-dose applicators.

maximize the transmission of subsequent drugs through the cornea; to inhibit reflex lacrimation and to produce topical anaesthesia for the subsequent measurement of IOP via applanation tonometry (see later). A double-blind protocol was employed between Isoprenaline Sulphate (3%) and a control solution[2]. Following the instillation of Benoxinate, each observer was given two topical instillations (separated by a period of 10mins) of either Isoprenaline or Control (depending on the double-blind protocol). A "wash-out" period of at least 2 days was allowed between each drug. Each instillation was made using a precision micro-pipette set to deliver 25 microlitres of drug (therefore total drug delivered per eye = 50 microlitres).

Measurements of TA and TV were taken in the dark, prior to drug instillation, and then at various intervals over the post-drug experimental period. TA was measured via laser optometry at a wavelength of 632.8nm (see sections 3.1Cii and 3.1Ci), whilst measures of TV were obtained using the vernier alignment device (section 3.2Bi), according to the procedure described in section 3.2Bii. The state of horizontal pupil size in total darkness (TP) was measured, both before and 35min after drug instillation, using infra-red photography (see sections 3.3Aii and 3.3Aiii). All measures of TA, TV and TP were under the control of an Apple IIe microcomputer (see sections 3.4Ai and 3.4Aii).

The use of Benoxinate (outlined above) facilitated the measurement of IOP, before and 40mins after the instillation of the investigative drug, using a Perkins hand-held applanation tonometer (for a description of the procedure see, Perkins, 1965; also, Dunn and Brubaker, 1974).

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[2] Details of the preparation of Isoprenaline and its control are provided in Appendix XVIII.

Resting heart-beat rate was measured before and 35min after drug instillation, via the application of fore-finger digital pressure to the venous-pulse at the observer's wrist, and calculated as the number of pulses/min. Measures of the systolic and diastolic blood pressure levels were taken, before and 35min after drug instillation, using a commercially available electronic unit[1].

Pre-drug and 40min post-drug measures of refractive error (Rx) and the amplitude of accommodation (AA) were taken using standard optometric procedures described in sections 4.7B and 4.5A, respectively.

6.3C - Results of the effects of Isoprenaline on TA, TV and TP.

The mean pre-drug TA values of the Isoprenaline and Control studies were 1.31D and 1.35D respectively; whilst, for TV the mean pre-drug values of the studies were 1.74 and 1.93deg; for TP the pre-drug values were 7.32 and 7.33mm respectively (the data from which all these mean values have been calculated may be found in Tables XIX.1 - XIX.5, of Appendix XIX). These mean values for TA, TV and TP are of the same order as those of earlier studies of this thesis (see particularly sections 4.2B, 4.3B and 4.4B, respectively). The product-moment correlations between the Isoprenaline and control pre-drug measures of TA, TV and TP were high, thus indicating a significant level of repeatability: i.e., for TA, $r = 0.98$, $p < 0.001$; for TV, $r = 0.79$, $p = 0.007$; and for TP, $r = 0.99$, $p < 0.001$.

From a short pilot study on two observers, it was found that the maximal effects of Isoprenaline on TA occured 20 - 25mins

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[1] "U-CHEK" II Electronic Blood Pressure Measurement Unit. Brethren Corporation, Tokyo, Japan.

after instillation. Sampling times were thus planned at intervals around this period. Tables XIX.1 - 4 of the appendix give the value and time taken of all measurement points of TA and TV. Each observer thus provided 6 measurements of TA and TV over the post-drug period. Table 6.6 (below) indicates the mean and standard deviations of these measurements and the overall mean sampling times.

Table 6.6 - The means and standard deviations (sd) of the pre- and 6 post-drug readings of TA and TV for the N=10 observer group. The maximum drug effect is indicated at the foot of each column of readings. The right-most column provides the overall mean sampling times of both drug and measurement conditions.

	TONIC ACCOMMODATION (D)				TONIC VERGENCE (deg)				
	ISOPRENALINE		CONTROL		ISOPRENALINE		CONTROL		MEAN
READING	mean	sd	mean	sd	mean	sd	mean	sd	SAMPLE TIME
pre-drug	1.31	0.95	1.35	1.03	1.74	0.82	1.93	1.01	0.00
1	1.24	1.00	1.36	1.00	1.63	0.74	1.86	0.95	15.98
2	1.05	0.97	1.38	1.03	1.58	0.77	1.89	0.97	18.73
3	0.89	1.03	1.38	1.07	1.49	0.70	1.92	0.97	21.40
4	0.76	0.99	1.36	1.06	1.48	0.62	1.88	0.96	24.75
5	0.79	1.01	1.36	1.03	1.46	0.59	1.89	0.99	28.65
6	0.96	0.99	1.33	1.01	1.46	0.60	1.89	1.00	32.35
MEAN MAXIMUM EFFECT	-0.55D		+0.03D		-0.28deg		-0.05deg		

It will be evident from Table 6.6 that whilst Isoprenaline has induced a maximal hyperopic shift in TA of -0.55D, the control has produced a myopic shift of only +0.03D. The maximum Isoprenaline-induced hyperopic shift in TA was detected at a mean of 24.9mins. A three-way analysis of variance (3-way ANOVA) of the TA data (from Tables XIX.1 and XIX.2) demonstrates high levels of significance for drug effect ($F = 392.81$, $p < 0.001$, df 1, 54), for the time effect ($F = 19.73$, $p < 0.001$, df6, 54), and for the differences between subjects ($F = 1215.96$, $p < 0.001$, df 9, 54).

The second-order interactions of drug/time and for drug/subject are also significant ($F = 20.37$, $p < 0.001$, df 6, 54 and $F = 21.02$, $p < 0.001$, df 9, 54, respectively). A visual comparison of the effects of Isoprenaline and its control solution on TA may be made from Figure 6.4.

A 2-way ANOVA of the TV data (of Tables XIX.3 and XIX.4) shows no significance in the effect of drug ($F = 0.02$, $p = 0.88$, df 1, 6) or time ($F = 1.26$, $p = 0.39$, df 6, 6).

Isoprenaline was found to produce no effect on the mean tonic pupil (TP) size - see Table 6.7 (data in Table XIX.5).

Table 6.7 - The effects on TP (mm) of 50 microlitres of Isoprenaline (3.0%) and Control . A 3-way ANOVA indicates the effects of drug and time to be non-significant.

TONIC PUPIL

	ISOPRENALINE		CONTROL	
	Pre	Post	Pre	Post
MEAN	7.32	7.32	7.32	7.33
SD	0.85	0.85	0.85	0.85

ANOVA DETAILS				
	DRUG EFFECT	F = 0.10	p = 0.75	df 1, 9
	TIME EFFECT	F = 0.01	p = 0.92	df 1, 9
	SUBJECT EFFECT	F = 545.73	p = <0.001	df 9, 9

Isoprenaline was found to induce a mean reduction in IOP of 0.85mmHg (see Table XIX.6). A 2-way ANOVA of the effects of Isoprenaline and its Control solution demonstrates this effect to be non-significant (see Table 6.8).

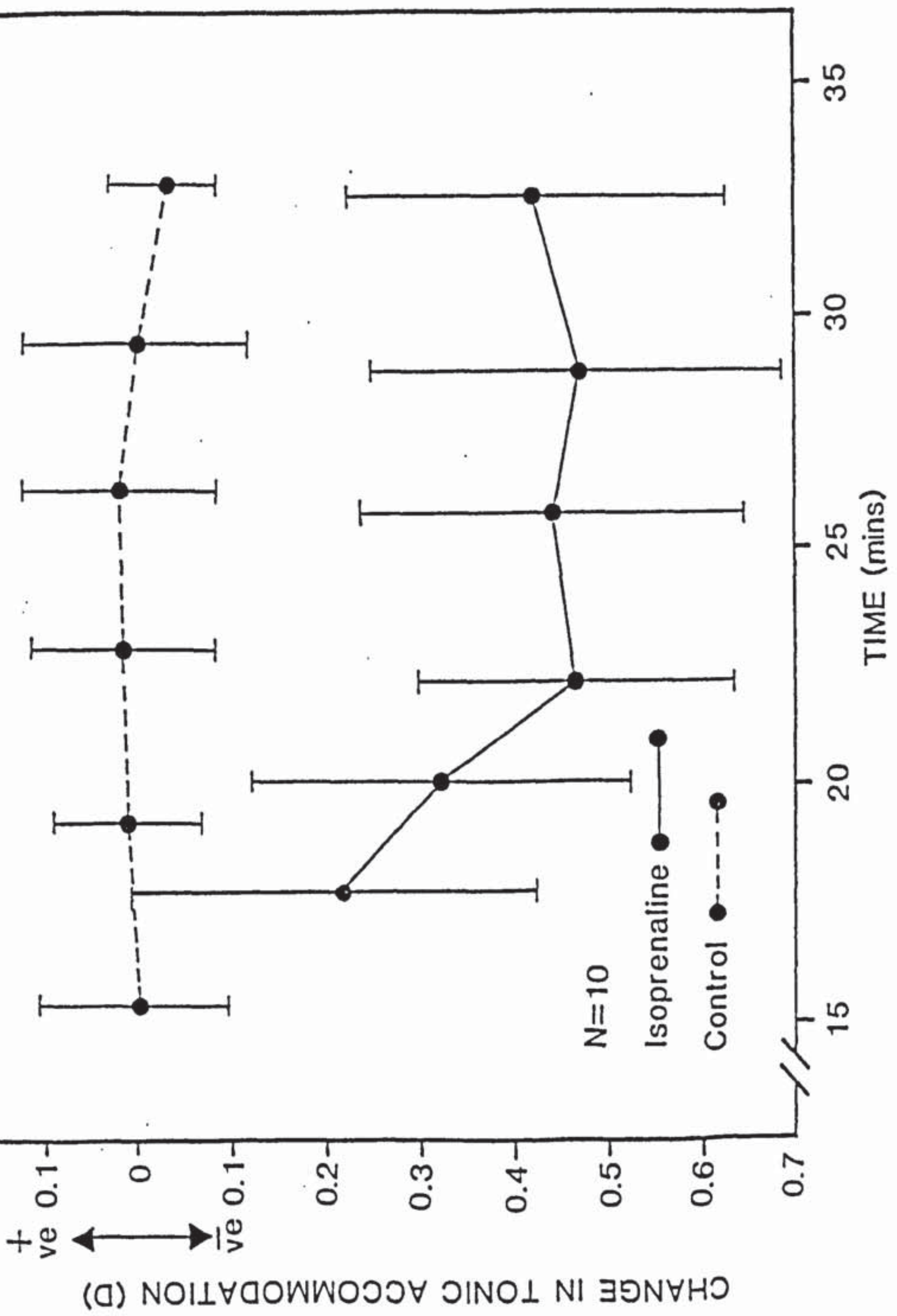

Figure 6.4 - The effect on TA of 50 microlitres of Isoprenaline (3%) and a Control, over a 35min period. The error bars represent ± 1 standard deviation.

Table 6.8 - The effect of Isoprenaline and a Control solution on mean levels of IOP (mmHg) for the left eyes of the 10 observers. A 2-way ANOVA indicates the results to be non-significant.

	INTRA-OCULAR PRESSURE			
	ISOPRENALINE		CONTROL	
	Pre	Post	Pre	Post
MEAN -	16.47	15.62	15.99	15.96
SD -	2.76	2.04	2.05	2.06

ANOVA DETAILS	DRUG EFFECT	F = 0.01	p = 0.94	df 1, 1
	TIME EFFECT	F = 0.38	p = 0.64	df 1, 1

Isoprenaline induced a mean myopic-shift in the best-sphere Rx: of +0.05D (see Table XIX.7): this effect can be demonstrated to be non-significant (see Table 6.9). It is interesting to note that Isoprenaline earlier been shown (in Table 6.6) to produce a significant -0.55D hyperopic shift in TA. As with the earlier Timolol study, there were no subjective reports of blurred or fluctuating vision. The effects of Isoprenaline on the pre- and post-drug amplitude of accommodation (see Table XIX.7) are similarly found to be non-significant (see also Table 6.9).

Table 6.9 - The effect of Isoprenaline on mean levels of left-eye best-sphere distance Rx (D) and L-eye AA (D). A 1-way ANOVA indicates the effects to be non-significant.

	MEAN-SPHERE DISTANCE Rx		AMPLITUDE OF ACCOMMODATION	
	ISOPRENALINE		ISOPRENALINE	
	Pre	Post	Pre	Post
MEAN	-1.75	-1.80	9.00	8.65
SD	2.55	2.64	2.30	2.30
F	1.85	df 1, 18	0.12	df 1, 18
p	0.97		0.74	

In an attempt to monitor the level of systemic absorption of Isoprenaline, measures had been taken of heart-rate and blood-pressure. The effects of the drug on the heart-rate were estimated by the measurement of the pulse (see Table XIX.8). The mean pre-drug pulse of 68 per min was found to be significantly increased to about 106 (see Table 6.10). Isoprenaline was also found to induce an increase in the mean systolic blood pressure-phase, yet a decrease in the mean diastolic phase of the heart (+13 and -7mmHg, respectively: see Table XIX.8). The effects of the drug were, however, found to be non-significant (see Table 6.10).

Table 6.10 - The effects of Isoprenaline and Control on measures of the heart-rate (as measured by the pulse) and peripheral blood-pressure. The results of ANOVA's are also included.

	PULSE (No. per min)				BLOOD PRESSURE (mmHg)			
	ISOPRENALINE		CONTROL		ISOPRENALINE		CONTROL	
O	Pre	Post	pre	Post	Pre	Post	Pre	Post
MEAN	68.3	106.5	68.0	67.6	132/76	145.5/69.5	128.5/72.5	129/72.5
SD	9.02	10.97	8.19	7.93	20.98/ 14.30	21.40/ 11.41	19.16/ 8.25	20.11/ 8.25

F (drug) = 46.33, $p < 0.001$

F (time) = 43.08, $p < 0.001$

df 1,1

F (drug) = 1.96, p = 0.40

F (phase) = 279.31, $p < 0.001$

F (time) = 0.26, p = 0.69, df 1,1

There is no significance in the relationship between the drug-induced change in TA and the initial TA level (r = -0.001, p = 0.98). Similarly, non of the remaining possible relationships reached levels of significance.

6.3D - Discussion - the effects of Isoprenaline on TA, TV and TP.

In the previous study, it was found that topical instillation of 50 microlitres of the beta-adrenoceptor antagonist, Timolol Maleate (0.5%), induced a significant myopic shift of +0.82D in the mean tonic resting states of accommodation (TA) of 10 observers, over a 40min period. It was concluded that sympathetic innervation to the ciliary muscle played a significant role in determining the TA position and, furthermore, that this sympathetic input was mediated by inhibitory beta receptors.

The present study was designed to provide a counter-check for these conclusions, by investigating the effects of a beta-adrenoceptor agonist, Isoprenaline Sulphate (3%). Indeed, the Isoprenaline results clearly demonstrate a significant hyperopic shift of -0.55D in the TA levels of a similar observer group, whilst under the same experimental conditions as those used in the Timolol study. The average maximum hyperopic shift with Isoprenaline was found to occur much faster (24.8min) and to be more transient (initial TA levels were resumed within 1hr) than was found for the average myopic shift with Timolol (i.e., 40.9min and 3hrs, respectively). It is probable that these observations are due in part to the relative difference in the potency and stability of the drugs selected: Timolol is a widely used and commercially available treatment for chronic open-angle glaucoma (its stability and efficacy has therefore been optimized), whilst the Isoprenaline had to be specially manufactured (see Appendix XVIII).

It should be noted that the observed sympathetically-induced effects on TA occur in the presence of a substantial resting parasympathetic tone (see next study). It will be evident therefore, that whilst the Timolol-induced myopic shift in TA is due to the effect of a relatively-unopposed parasympathetic tone, the induced-hyperopic effects of Isoprenaline on TA occur in spite of it.

The significance of any comment on the quantitative importance of the sympathetic innervation to the ciliary muscle is somewhat reduced, without knowledge of the extent to which all the adrenoceptors have been blocked by Timolol, or stimulated by Isoprenaline, in the concentrations used in these studies. It is interesting to note, however, the evident potency of Isoprenaline from the significant mean increase in heart-rate, as induced by the topical instillation of a mere 50 microlitres: as expected, measures of blood-pressure were not, however, significantly affected (via the effect on Beta-receptor activity in the peripheral skeletal vasculature).

It is evident that the results of the present study provide additional support for the conclusions of the Timolol investigation: i.e., that sympathetic innervation to the ciliary muscle, mediated by inhibitory beta-adrenoceptors, plays a significant role in determining the TA position. As found in the Timolol study, the induced-changes in TA are demonstrable in the absence of any significant concurrent effects on standard optometric refractive measures. This would support the previous study's proposal, that the SNS does not contribute significantly to the neural control of the accommodative responses to stimuli offered by the normal visual environment. It is speculated in Chapter 7, however, that a possible role for the SNS input to the ciliary muscle, may be to participate in an adapative mechanism, designed to attenuate the potentially harmful hysteretic effects of sustained visual tasks carried out at the extremes of the accommodative range.

In the previous study, Timolol induced a non-significant mean decrease in TP of 0.16mm. This would be consistent with the beta-receptor distribution across the iris-musclature (see Van Alphen, 1976; and Table 1.1). Blockade of the relatively small number of beta-adrenoceptors in the sphincter-pupillae by the Timolol, would have been expected to induce a slight decrease in pupil size as the basal activity of the parasympathetic innervation to the dilatator and the alpha-sympathetic innervation to the sphincter, would then be unopposed. The parasympathetic activity of the sphincter is undoubtedly the more dominant feature of the autonomic innervation to the iris: sympathetic activity, mediated by alpha-adrenoceptors, is principally found in the dilatator. It is perhaps not surprising, therefore, that stimulation (by Isoprenaline) of the relatively small number of beta receptors in the sphincter was not detectable as a significant change in TP, from the results of the present study.

6.4 - THE EFFECT OF A MUSCARINIC RECEPTOR ANTAGONIST ON TA AND TV.

6.4A - Introduction.

It is well established that the ciliary muscle has a predominantly parasympathetic input mediated by the action of acetylcholine on muscarinic receptors and that, in its excitatory phase, this interaction initiates positive accommodation. The earlier investigations of the present Chapter (sections 6.2 and 6.3) have provided additional support for a sympathetic involvement, via the adrenoceptor-blockade and -stimulation induced by topical instillations of the beta-antagonist and -agonist, Timolol Maleate and Isoprenaline Sulphate, respectively.

The stimulus-free accommodative parameter of TA was utilised to monitor the effect of these drugs: Timolol induced a +0.82D myopic shift in TA, whilst Isoprenaline was found to produce a -0.55D hyperopic shift in mean levels of TA from a group of 10 observers.

It has been shown that TA varies significantly among individuals: typical values have been shown to be; mean = 1.5D, standard deviation (s.d.) = 0.7D (see Table 1.2 and section 4.2B). It can be shown that the above induced shifts in TA were not, however, accompanied by significant changes in the s.d. of the TA distribution of the sample population used (see tables 6.1 and 6.6). Figure 6.5 illustrates the effect of Timolol Maleate (0.5%) on the distribution of TA, for an N=10 observer-group (data from Table XVII.1), whilst Figure 6.6 demonstrates the effect of Isoprenaline Sulphate (3%) on the distribution of TA of a similarly-sized group of observers. It will be apparent from these two figures that neither stimulation nor blockade of the sympathetic input to the ciliary muscle, has induced a significant variation in the pre- and post-drug distribution of TA. This would suggest that the variation of TA is due to inter-subject variations of parasympathetic input to the ciliary.

Consequently, the primary aim of the present study was to investigate the effects of parasympathetic receptor blockade on the sample distribution of TA (N=10), via topical instillation of the muscarinic receptor antagonist Tropicamide (0.5%). The effects of Tropicamide on measures of TV, TP, Rx and AA will also be taken.

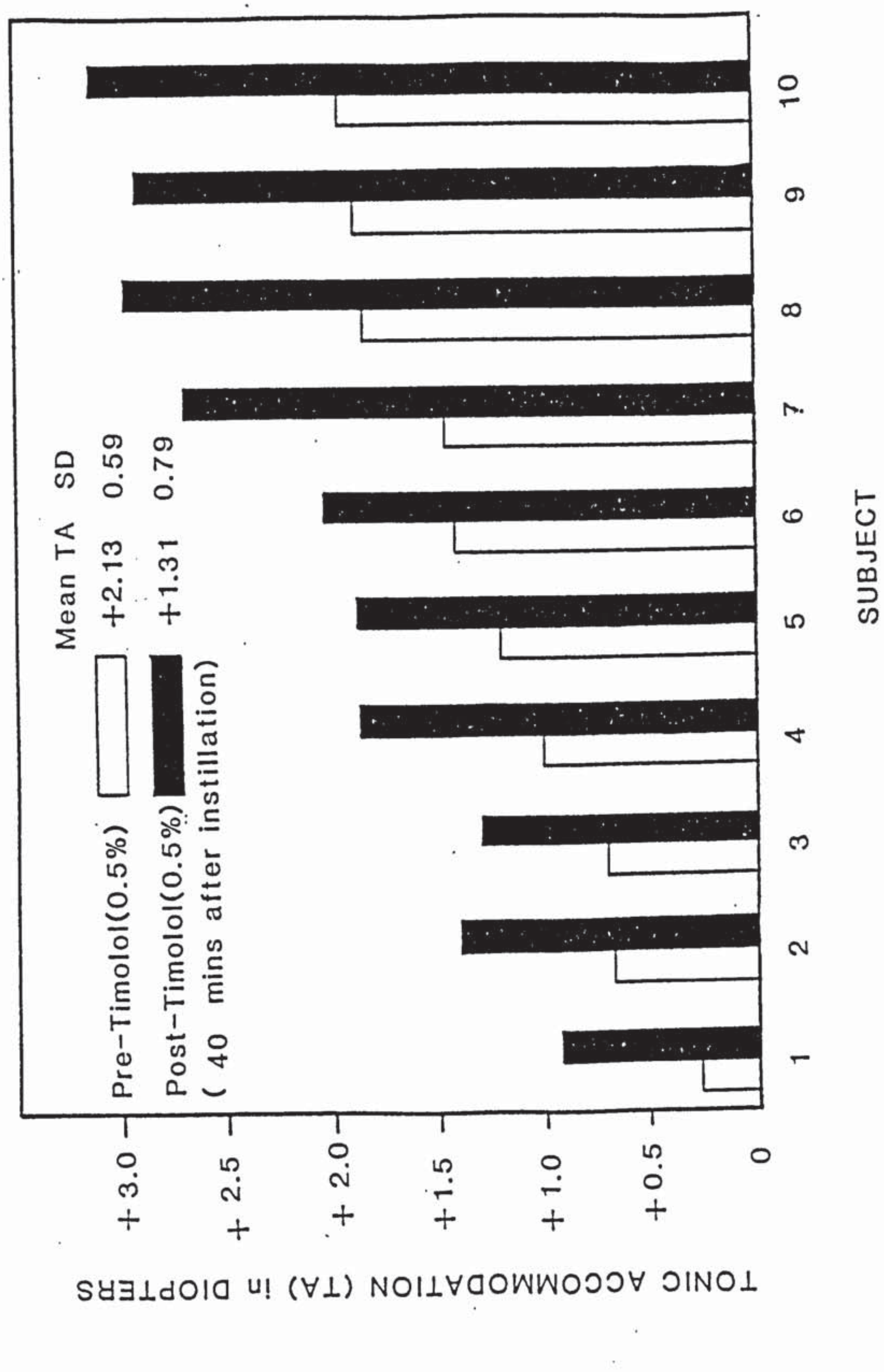

FIGURE 6.5 - The effect of Timolol Maleate (0.5%) on the distribution of TA. Each observer is arranged in a rank order based on the level of their pre-drug TA.

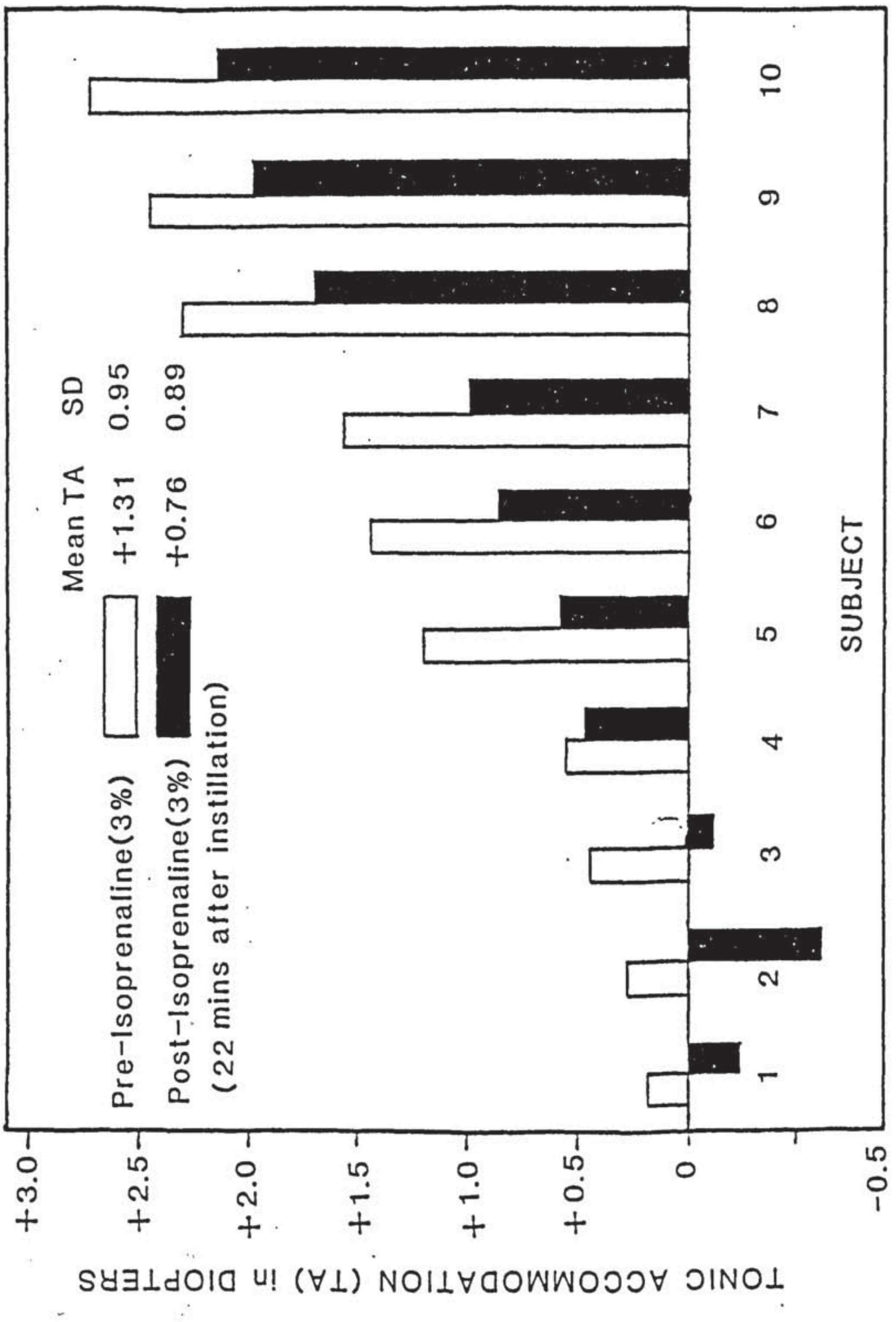

FIGURE 6.6 - The effect of Isoprenaline (3%) on the distribution of TA. Each observer is arranged in a rank order based on the level of their pre-drug TA.

6.4B – Methodology, design and materials.

Ten observers, 5 males and 5 females (ages ranging from 19 to 37, mean = 23.2 years) were provided with an accurate refractive correction, giving distance visual acuities of at least 6/6 in each eye.

Two drops of Benoxinate (0.4%)[1] were instilled into the lower fornix of each eye, over a period of 20sec: this was used to inhibit reflex lacrimation and to maximize the transmission of the subsequent drugs through the cornea. Following the application of Benoxinate and over a period of 10mins, each observer was given two topical instillations of either Tropicamide (0.5%)[1] or the control solution, Saline[1], as selected by the double-blind protocol. A "wash-out" period of at least 5 days was allowed between each drug, allowing for dissipation of the induced cycloplegic and mydriatic effects. Each instillation was made via a precision micro-pipette, set to deliver 25 microlitre of drug (therefore, total drug delivered each eye = 50 microlitres).

Measurements of TA and TV were taken in the dark prior to drug instillation, and then again at various intervals during the post-drug experimental period. TA was measured using He-Ne Badal-laser optometry at a wavelegnth of 632.8nm (see sections 3.1Ci and 3.1Ci), whilst measures of TV were obtained using the vernier alignment device (see section 3.2Biand 3.2Bii). TP was measured both before and after the post-drug period, using infra-red photography (see sections 3.3Aii and 3.3Aiii). All measures of TA, TV and TP were under the control of an Apple IIe mcrocomputer (see sections 3.4Ai and 3.4Aii). Pre- and post-drug

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[1] Smith and Nephew UK, single-dose applicators (Minims).

measures of Rx and AA were taken using standard optometric procedures (previously described in sections 4.7B and 4.5A, respectively.)

6.4C - Results of the effects of Tropicamide on the distribution of TA.

The mean pre-drug drug values for TA (measured at 632.8nm) for the N=10 observer group were found to be 0.93D and 0.95D for the Tropicamide and Saline control, respectively; whilst for TV the two mean pre-drug values were 1.61deg and 1.62deg, respectively; and for TP the mean pre-drug values were 7.28mm and 7.33mm (the data from which all these mean values have been calculated may be found in Tables XX.1 - XX.5 of Appendix XX). These mean values for TA, TV and TP are of the same order as those found in the earlier studies of this thesis (see particularly, sections 4.2B, 4.3B and 4.4B, respectively). The product-moment correlations between the Tropicamide and Saline control pre-drug measures of TA, TV and TP were high, indicating a significant level of repeatability: i.e., for TA, $r = 0.99$, $p = <0.001$; for TV, $r = 0.99$, $p < 0.001$; and for TP, $r = 0.80$, $p = 0.005$.

Measurements of TA and TV were made at 5 intervals during the 30min period following the instillation of the drug/control. Appendix tables XX.1 - 4 give the value and time taken of all the sampling points of TA and TV. Table 6.11 (below) indicates the mean and standard deviations of the measurements and the overall mean sampling times.

Table 6.11 - The means and standard deviations (sd) of the pre-drug, the 6 post-Tropicamide and control measures of TA and TV for the N=10 observer group. The maximum drug effect is shown at the foot of each column of readings. The right-most column provides the overall mean sampling times of both drug and both measurement conditions.

	TONIC ACCOMMODATION (D)				TONIC VERGENCE (deg)				
	TROPICAMIDE		SALINE		TROPICAMIDE		SALINE		
READING	mean	sd	mean	sd	mean	sd	mean	sd	MEAN SAMPLE TIME
pre-drug	0.93	0.87	0.95	0.81	1.61	0.64	1.62	0.64	0.00
1	0.04	0.45	0.94	0.80	1.57	0.67	1.57	0.67	15.68
2	-0.17	0.37	0.98	0.84	1.57	0.67	1.63	0.64	19.08
3	-0.27	0.17	0.93	0.81	1.57	0.64	1.61	0.68	22.13
4	-0.31	0.16	0.96	0.80	1.62	0.63	1.59	0.66	24.33
5	-0.35	0.14	0.95	0.81	1.62	0.65	1.60	0.67	26.75
MEAN MAXIMUM EFFECT	-1.28		+0.03		-0.04		-0.05		

It is evident from Table 6.11 that Tropicamide has induced a mean hyperopic shift of -1.28D from the initial mean level of TA, whilst the Saline control has produced a slight myopic shift of +0.03D: the maximum Tropicamide-induced shift in mean TA occured at 26.3min. A three-way analysis of variance (3-way ANOVA) of the TA data (from Tables XX.1 and XX.2) demonstrates high levels of significance for drug effect (F = 313.96, p < 0.001, df 1, 45), for the time effect (F = 12.77, p < 0.001, df 5, 45), and for the differences between subjects (F = 34.00, p < 0.001, df 9, 45). The second-order interactions of drug/time and for drug/subject are also significant (F = 12.77, p < 0.001, df 5, 45 and F = 12.50, p < 0.001, df 9, 45, respectively). A visual comparison of the effects of Tropicamide and the Saline control on TA may be made from Figure 6.7.

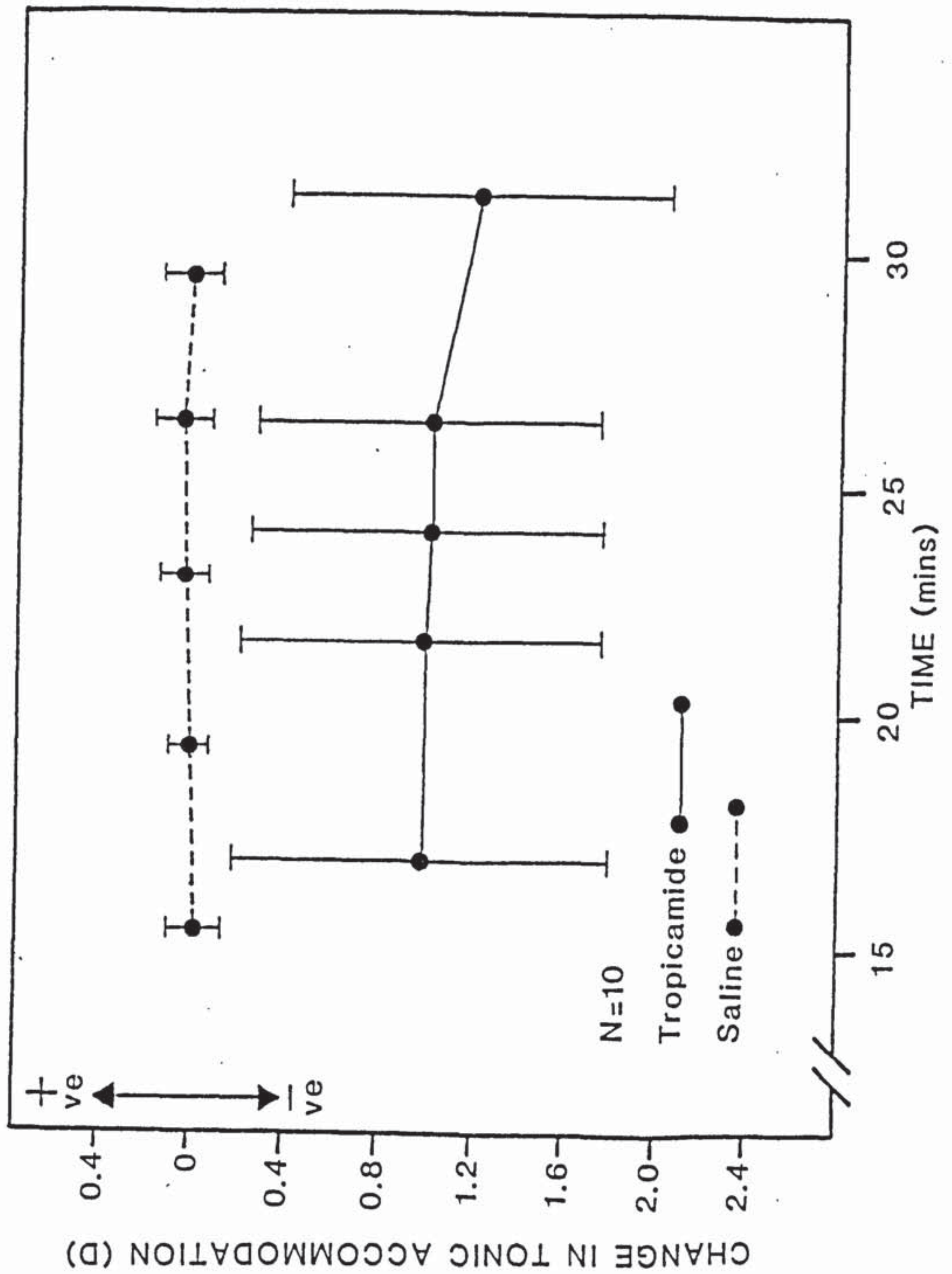

Figure 6.7 - The effect of Tropicamide (0.5%) and a Saline control on the distribution of TA. The error bars represent ± 1 standard deviation.

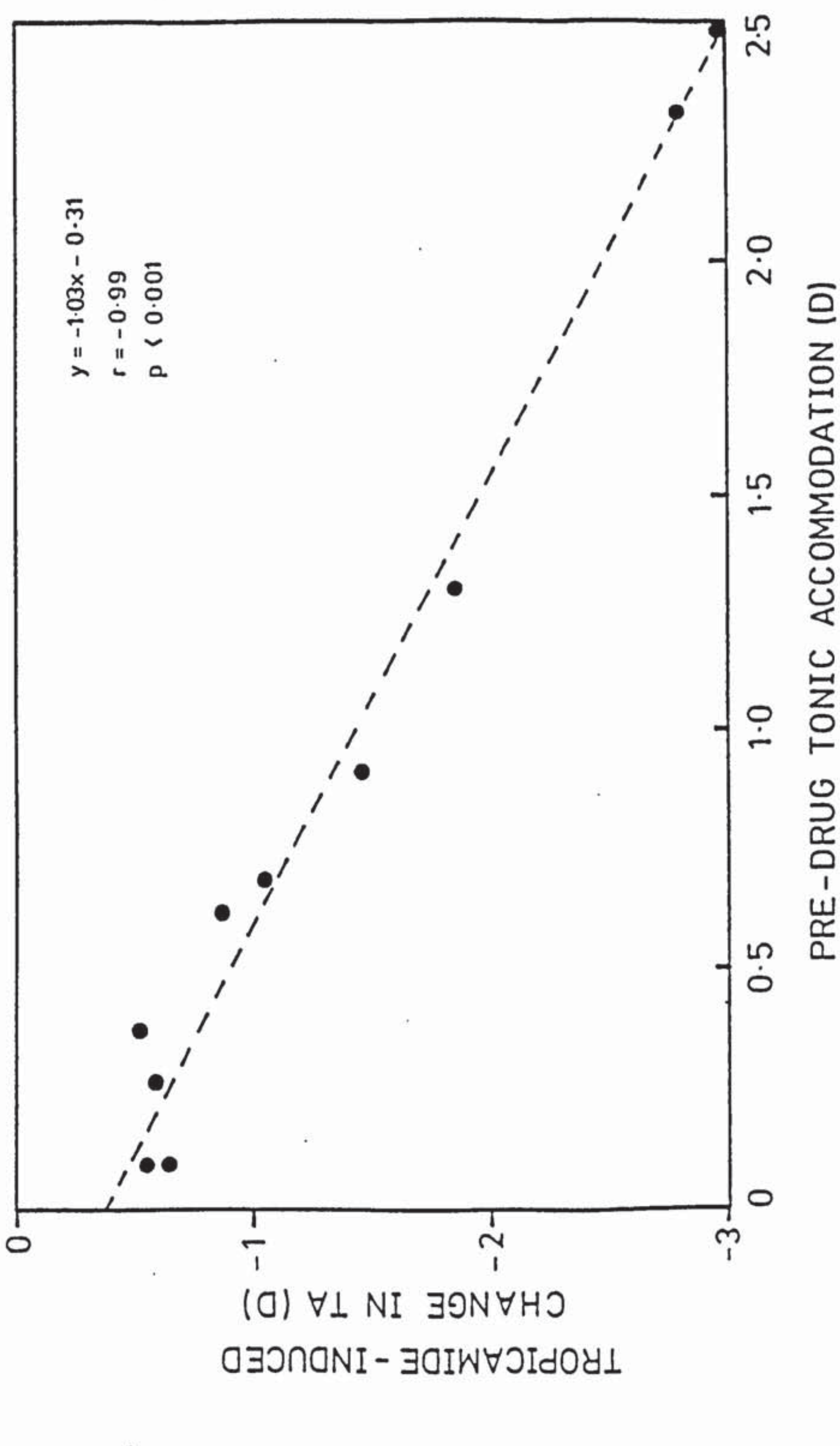

Figure 6.8 - The significant relationship between pre-drug levels of TA and the induced effect of Tropicamide.

Inspection of Figure 6.8 indicates that the hyperopic shift induced by Tropicamide, is directly proportional to the pre-drug level of TA, which in turn is responsible for a significant change in pre- to post-Tropicamide standard deviations: pre-drug s.d. = 0.87; post-drug s.d. = 0.14.

A 2-way ANOVA of the TV data (of Tables XX.3 and XX.4) shows no significance in the effect of drug (F = 0.01, p = 0.94, df 1, 5) or time (F = 0.01, p = 0.99, df 5, 5).

Tropicamide was found to induce a mean increase in TP of 1.14mm, with little change in the pre- to post-drug s.d.: pre-drug s.d. = 0.49; post-drug s.d. = 0.53 (data taken from Table XX.5). A 3-way ANOVA demonstrates this result to be highly significant (see Table 6.12). The relatively small mean mydriatic effect is due to the fact that the pupils were already significantly dilated after 10mins in the dark.

Table 6.12 - The effect of Tropicamide and a Saline control on mean levels of TP (mm). A 3-way ANOVA indicates the effects of drug and time to be highly significant.

TONIC PUPIL

	TROPICAMIDE		SALINE	
	Pre	Post	Pre	Post
MEAN	7.28	8.42	7.33	7.33
SD	0.49	0.53	0.54	0.57

ANOVA DETAILS				
	DRUG EFFECT	F = 54.55	p < 0.001	df 1, 9
	TIME EFFECT	F = 66.77	p < 0.001	df 1, 9
	DRUG/TIME EFFECT	F = 66.77	p < 0.001	df 1, 9
	SUBJECT EFFECT	F = 19.50	p < 0.001	df 9, 9

Tropicamide was found to induce a mean hyperopic shift of -0.50D in the distance best-sphere Rx (see Table XX.6), with negligible effect on the pre- to post-drug s.d.'s. 1-way ANOVA of this data, however, demonstrates the shift to be non-significant (see Table 6.13, below). It is interesting to note that Tropicamide was earlier shown (in Table 6.11) to produce a significant -1.28D hyperopic shift in TA. Tropicamide was found to produce a mean reduction of -8.18D in the amplitude of accommodation (see Table XX.6). This cycloplegic effect can be demonstrated to be highly significant (see Table 6.13). The pre- to post drug s.d's were reduced from 1.71D to 0.39D, demonstrating a constancy of response to the drug for the group as a whole. The 0.80D mean level of residual accommodation is evidence of the effectiveness of Tropicamide as a cycloplegic. Distance visual acuity was unaffected by the cyclolegic (and mydriatic) effect of Tropicamide.

Table 6.13 - The effects of Tropicamide and a control on mean levels of L-eye best-sphere distance Rx (D) and L-eye AA (D). A 1-way ANOVA indicates the cycloplegic effects on AA to be highly significant.

	MEAN-SPHERE DISTANCE Rx		AMPLITUDE OF ACCOMMODATION	
	TROPICAMIDE		TROPICAMIDE	
	Pre	Post	Pre	Post
MEAN	-2.00	-1.55	8.98	0.80
SD	2.50	2.54	1.71	0.39
F	0.16	df 1, 18	217.48	df 1, 18
p	0.70		< 0.001	

6.4D - Discussion of the effects of Tropicamide (0.5%) on TA, TV and TP.

Although Timolol Maleate (0.5%) induced a significant mean myopic shift of +0.82D in TA, Figure 6.5 indicates that the s.d.'s of the pre- to post-drug distribution did not differ significantly. Similarly, Isoprenaline (0.3%) produced a significant mean hyperopic shift of -0.55D in TA, although Figure 6.6 demonstrates

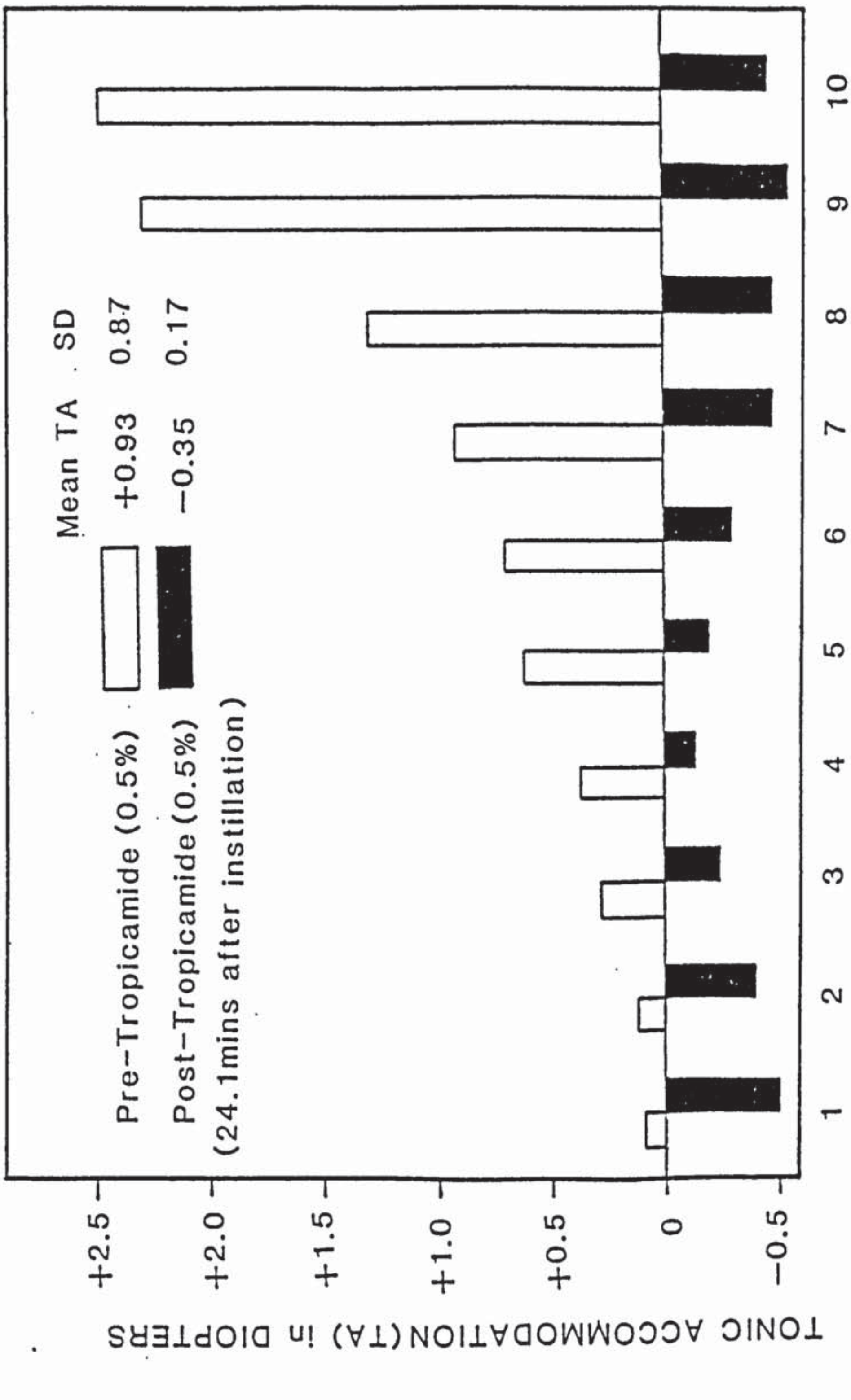

Figure 6.9 - The effect of Tropicamide (0.5%) on the pre- and post-drug sample distributions of TA. Each observer is arranged in a rank order based on the level of pre-drug TA.

that the s.d's of the pre- and post-drug distributions of TA are also largely unaffected. It may be concluded, therefore, that the sympathetic input to the ciliary muscle accounts for approximately 0.8D of TA, and that neither stimulation nor antagonism of this input significantly modifies the distribution of TA: i.e., the sympathetic input to the ciliary muscle is present at a relatively constant level between individuals (the s.d.'s of the mean maximum effects of Timolol and Isoprenaline were 0.28D and 0.26D, respectively).

In contrast, Figure 6.9 demonstrates that the significant Tropicamide-induced hyperopic shift in TA of -1.28D is accompanied by an equally significant reduction in the s.d. of the pre- and post-drug TA distributions (from 0.87D to 0.14D, respectively).

This would indicate that the parasympathetic input to the ciliary muscle provides a positive tone that varies significantly between observers, and it is this variation in parasympathetic innervation that accounts for the distribution in TA reported in the literature (see Table 1.2).

6.5 - GENERAL DISCUSSION ON THE RELATIONSHIP BETWEEN TA AND CILIARY MUSCLE INNERVATION.

The drug-induced changes in TA observed in the present studies were not accompanied by significant changes in TV and, although changes in TV were not particularly expected under the astimulus conditions of total darkness, this is nevertheless, an important observation: it offers support for the earlier proposal (discussed in section 4.6E) that in the tonic state, there is no synkinetic neural interaction between TA and TV.

The anatomical, physiological, pharmacological and clinical literature outlined earlier, together with the results of the present studies, (see sections 1.4A - 1.4E) provide compelling evidence for a sympathetic input to the ciliary muscle: it has not gone unnoticed (Cogan, 1937) that the great majority of autonomically innervated structures have dual-innervation. Much of the previous work from either or both monkey and human studies (Tornqvist, 1966; 1967; Kern, 1970; Hurwitz et al., 1972a; and Van Alphen, 1976) has demonstrated that antagonism of this sympathetic innervation induces a positive or myopic accommodative response, whilst stimulation will produce a negative or hyperopic response. The results of these studies have indicated that the induced modification of the accommodative response is mediated via inhibitory beta-adrenoceptors.

The stimulus-free nature involved in the measurement of tonic accommodation has been utilised to much advantage in the studies of the present chapter. Removal of the accommodative system from the constraints of stimulus-dependency, together with the application of a suitable methodology (laser-optometry), has simplified the investigation of ciliary muscle autonomic pharmacology, via the use of readily-available and topically-applied autonomic effector drugs. A 50-microlitre topical instillation of the non-selective adrenoceptor antagonist, Timolol Maleate (0.5%), was found to induce a significant +0.82D myopic or positive shift in the pre-drug levels of TA of 10 observers, whilst a similar application of a non-selective adrenoceptor agonist, Isoprenaline Sulphate (3%), produced a significant -0.55D hyperopic or negative shift in TA.

Without repeating the studies using various strengths of the drugs, the relative percentage of ciliary muscle adrenoceptors affected remains unknown. Even so, the results of these studies on intact, living human subjects indicate that a sympathetic input to the ciliary muscle plays a significant role in determining the TA position and, furthermore, that this innervation is mediated by inhibitory beta-adrenoceptors: offering support for the findings of previous work reported in the literature.

It is interesting to note that the results illustrated in Figures 6.5 and 6.6 demonstrate that the drug-induced shifts in TA were unaccompanied by significant changes in the distribution of pre-drug TA. If it is assumed that Timolol and Isoprenaline had respectively induced maximal beta-adrenoceptor blockade and stimulation, it would be possible to conclude that the sympathetic input contributes a fairly constant, yet relatively small (approx. 0.8D) input to the the distribution of TA.

It is perhaps not surprising that the smooth muscle of the ciliary sphincter exhibits significant variations in tone, as this is a feature of all smooth muscle. The wide variation in TA values encountered is, therefore, more likely to be due in part to variation in ciliary muscle parasympathetic tone. The results of the Tropicamide study confirm the validity of this assumption and reference to Figure 6.9 demonstrates that the Tropicamide-induced hyperopic shift of -1.28D is accompanied by a significant reduction in the s.d. of the distribution of TA (from 0.87D to 0.14D). This would indicate that the parasympathetic input provides a positive tone that varies significantly between individuals and, that it is this variation that accounts for the wide distribution in TA.

The most important implication of the present study concerns the functional significance of sympathetic innervation of the ciliary muscle to the accommodative system. Much of the evidence (e.g., Tornqvist, 1967) indicates that, due to its slow reaction and apparent dependence on the level of concurrent background parasympathetic activity, the sympathetic system is unlikely to play a significant role in the rapid modifications in the ciliary muscle, essential for the appropriate accommodative responses in normal visual environments. This evidence, together with the observations that there was no significance in the concurrent effects of either Timolol or Isoprenaline, on standard optometric refractive measures, has led to the speculation that the function of the sympathetic nervous system in human accommodation is more relevant to those tasks requiring a sustained effort of accommodation, rather than to those tasks requiring a rapid change in accommodative response.

Recent studies (e.g., Ebenholtz, 1983) have demonstrated that the state of an individual's TA may be influenced by the level of prior accommodative activity. It is understandable that some degree of smooth muscle tone is retained after a sustained period of accommodation response and that such "hysteresis" effects will be evident in subsequent measures of TA. It is possible that accommodative hysteresis effects may be due to a temporary imbalance in the ciliary body autonomic tone, induced by the fixation conditions.

With respect to the potential role of sympathetic input, it is interesting to note, therefore, that the studies of Ebenholtz (1983) and those of chapter 7, were both able to detect non-linearities in the hysteresis effects, dependent upon the level of accommodative demand required by tasks at various dioptric distances. Ebenholtz (1983) noted that 8 mins fixation on a "far point target" at a mean of 0.98D beyond the initial mean TA position of his 12 observers, induced a -0.12D shift; whereas fixation of the "near point target" at, on average, 5.12D closer than the initial mean TA position, only produced a shift of +0.34D. It is concluded from the studies of Chapter 7, that the task-induced hysteretic changes in TA are significantly related to the differences between the dioptric distance of the stimulus and the individual pre-task TA position, except for those individuals with the lowest initial TA levels and where the difference to the near task exceeded 1.5 - 2.0D: in these cases, the magnitude of the anticipated positive hysteretic shifts were greatly reduced.

It is proposed that such attenuated shifts in TA may be due to the involvement of an inhibitory sympathetic input, induced by the high levels of background parasympathetic activity, consistent with sustained near visual task interaction. The accommodative system may utilise TA as a central reference point for the monitoring of post-task hysteresis effects. In functional terms, the role of this inhibitory sympathetic input may be to attenuate, and therefore minimize, the risk of accommodative hysteresis inducing manifest myopia following sustained and demanding near vision tasks. The implication is that autonomic homeostasis facilitates sustained accommodative effort.

It is not uncommon for patients of ophthalmic practioners to present with "pseudo-myopic" changes specifically induced by periods of intense close work, often at VDTs. One may speculate that simple or "school" myopia might fall into this category due to the combination of cognitive stress (see section 1.4E) and a predisposition to hysteresis effects, causing autonomic imbalance during sustained near visual tasks (possibly due to some failure of the attenuative sympathetic mechanism, coupled with a low individual TA). Should this neo-myope subsequently use a prescribed distance refractive correction for close work, he will be obliged to accommodate more than was previously necessary prior to the introduction of this correction. The resultant increase in parasympathetic ciliary muscle tone may, in the absence of an adequate compensatory mechanism (i.e., an effective sympathetic input), induce further conditions conducive to progressive increases in manifest myopia.

Although a degree of reticence should accompany the notion that autonomic factors can alone, account for the mechanism of ametropia (many factors may be implicated in the process of emmetropization - e.g. heredity), it is interesting to speculate that, at some time in the future, beta-adrenoceptor drugs (preferably free from the complication of concurrent systemic side-effects) may be utilised to control simple myopia.

CHAPTER 7

AN INVESTIGATION INTO THE ADAPTIVE PROPERTIES OF TONIC ACCOMMODATION AND VERGENCE TO SUSTAINED VISUAL TASKS

7.1 - Introduction.

The previous chapters have illustrated that the responses of the accommodative and vergence systems are systematically biased towards intermediate tonic positions of rest, under conditions where the stimulus characteristics of the visual task have become degraded; this would suggest that tonic accommodation (TA) and vergence (TV) are key factors in the neural and motor control of the vergence and accommodative systems. Current control theory modelling of the accommodative and vergence systems (e.g. the interactive dual-feedback system of Hung and Semmlow, 1980 - see fig 4.7) provides further support for this suggestion; i.e., in the absence of feedback information (i.e. in the "open-loop" state) the accommodative and vergence states are considered to be derived purely from the input of the bias controller, namely tonic innervation. TA and TV might thus be considered as the calibration points or positions of bias of the accommodative and vergence systems.

As will become evident shortly, the accommodative and vergence systems are both capable of adapting to sustained stimuli. It might be presumed that this property is necessary to reduce the potentially strainful effort that would be required during the sustained interaction with a visual task near to the extremes of the ranges of the system, whilst maintaining optimal interaction with the sustained visual task. In order that this property of adaptation be effective, yet not disruptive (i.e., an orthophoric emmetrope remains an orthophoric emmetrope), it is anticipated that most of the plasticity be as a result of a temporary shift in the bias-points: namely TA and TV.

It has been generally assumed (see section 3.5D) that these tonic resting states are stable characteristics of the individual. Recent studies have shown however, that the level of both TA and TV may indeed be influenced by previous visual activity (Ebenholtz, 1983; Owens and Leibowitz, 1980; Schor et al., 1984). This adaptation of the levels of TA and TV has been described as "hysteresis" by Ebenholtz (1981; 1983) following the recommendation of Fender and Julesz (1967):

> "This dependence on an earlier state....is simply a lagging of effect behind cause and we call it....hysteresis or an hysteretic phenomenon. In our opinion this name should be assigned to all phenomenon in which effect lags behind cause" (p.829).

Although the adaptation of TA and TV has only recently been investigated, the effects of prior activity on the accommodative and vergence systems, using standard optometric techniques, have been under investigation for many years. It will be apparent however, that measurements of the shift in the levels of TA and TV in total darkness are the more suitable metrics of the extent of accommodative and vergence adaptation, as they are free from the stimulus-dependent characteristics exhibited by the more usual parameters, such as amplitude of accommodation or heterophoria (see the General introduction).

7.1A - Adaptation of the accommodative system.

Much of the literature concerning this aspect is based on studies of the fatigue of accommodation following prolonged visual tasks at various stimulus distances.

Nearly three centuries ago, in writing about the diseases of printers, sedentary workers, learned men and those who do fine work, Ramazzani (1700) stated;

> "It would help such workers very much if besides wearing spectacles they would give up the habit of keeping the head constantly bent and the eyes fixed on what they are making; if they would now and again drop their work and turn their eyes elsewhere or snatch a respite from their task and rest their eyes by looking at a number of different things: and we know what Plautus says: 'Sitting hurts the loins, staring your eyes.'"

Donders (1864) however, is usually credited with the first suggestion that eyestrain (asthenopia) resulted from excessive close work, producing "fatigue of the muscular system of accommodation". Those who have accepted that explanation (e.g., Simmerman, 1950; Romaine, 1951; Weston, 1954; Fitzpatrick and Hansen, 1973) have assumed that the ocular physiological effort required for close work leads to a temporary decrease in the ability of the ciliary muscle to contract, with an accompanying decrease in the amplitude of accommodation, manifested as a recession of the near point. Interest in this aspect of accommodation dates from the early 1900's and opinion has been fairly equally divided, with some workers concluding that close work does indeed lead to such near point recession (e.g., Ferree, 1913, 1914; Howe, 1916; Berens and Sells, 1944; Berger and Mahneke, 1954; Fitzpatrick and Hansen, 1973), whilst others have presented evidence to the contrary (Lancaster and Williams, 1914; Berens and Stark, 1932; Berens and Sells, 1950; Heaton, 1966): for a review of these aspects see Smith (1979).

More recently, however, a study by Saito et al. (1981) monitored the effect on the binocular amplitude of accommodation of a "highly-paced" inspection task on factory workers during an 8 hr working day, over a two month period. It was found that the mean amplitude of accommodation of the workers increased during the morning and gradually decreased from mid-day onwards, finally reaching a level less than that of the 9.00am measurement. This study also monitored the effect of a 'normal' working day on the amplitude of accommodation of a group of clerical workers. The changes found for this group were similar to, yet smaller than, those of the inspection workers, but without the mid-morning increment. They postulated that the accommodative changes may be due to "circadian periodicities in accommodative activity" and that the differences between the two groups may be due to differences in their work environment and occupation.

Gunnarsson and Soderberg (1983) measured the near points of accommodation and convergence during a three to six hour working period at a visual display unit or terminal (VDU or VDT). They found that both near points became closer, the change being directly proportional to the intensity of work. It is noteworthy however, that none of these studies have actually measured ocular power changes, mostly relying upon inferences drawn from changes in acuity or perception of blur.

The study by Ostberg et al. (1980) was one of the first that involved actual measurements of the refractive state: they utilised laser optometric measures of the accommodative responses of their subjects before, during and after two hours of work at a radar screen. During the task, an increase was found in the "lead" and "lag" of accommodation responses for both distance and near stimuli, respectively. After work, their subjects tended to be myopic for far stimuli and hyperopic for near stimuli. An increase of between 0.94 - 1.62D in the level of resting accommodation was also found following near work. Their results were interpreted as indicating a work-induced shift of accommodation towards its resting state.

Malmstrom et al. (1981) utilised an infra-red optometer (similar in design to that of Crane and Cornsweet, 1970) to monitor the change in accommodative response of six subjects, who viewed a black "X" target (via a Badal optical system) as its position was sinusoidally varied over a dioptric range from 0.00 to 4.00D at a frequency of 0.4 Hz over a period of 6.5 min. The mean accommodative response (2.76D) was found to decrease linearly (to 1.98D) at a rate of 0.11D/min. The shift was described as being "overwhelmingly towards the visual far point". An alternative interpretation may be that the shift in accommodative response is more related to the intermediate resting position than to the far point, as it is conceivable that the target was an insufficient accommodative stimulus to maintain the response at the original level. Unfortunately, no information is given as to the resting points of the six subjects used. Malmstrom et al. (1981) unsuccessfully attempted to relate their results with the pupil constriction found to follow visual fatigue (Geacintov and Peavler, 1974) and an earlier suggestion (Malmstrom et al., 1980) of an autonomic model intended to explain intraocular fatigue involving a general sympathetic arousal mechanism.

A study by Kintz and Bowker (1982), monitored the accommodative response to a 60 min period of viewing a V.D.U. screen whilst performing a visual search task. They observed that the initial accommodative response "represents a compromise between the theoretically correct response and their own, individual resting focus" and found that this level of "inaccuracy" or "lag" did not develop over the session, but was demonstrable at and maintained from, the onset of the task.

The studies of Shahnavaz and Hedman (1984) and Hedman and Briem (1984) utilised laser optometry to monitor the accommodative response to six hours work at a VDU at four stimulus distances;

0.25, 0.5, 1 and 6m. Both studies monitored accommodative accuracy to the visual tasks at various stimulus distances using a laser optometer and were able to detect over-accommodation for far visual tasks and under-accommodation for the near visual tasks. The Hedman and Briem study reported no significant deviations in the near points of either accommodation or convergence following the six hours of VDT work. This latter study also measured tonic accommodation in darkness using the laser optometer: the only significant result they obtained was a slight increase in TA in the youngest subjects (less than 21 years) at mid-day which dropped again to the pre-session level by the end of the VDT period. This latter observation would suggest that some degree of adapation in TA had taken place.

Fatigue effects are generally thought to be muscular in origin, produced by overwork. Relaxed muscles, however, by most definitions should not cause fatigue. According to the traditional concept of accommodation (Fincham, 1937; Duke-Elder, 1970) the ciliary muscle is relaxed when focussed for infinity and the lens assumimg its minimal refractive state. This concept also assumes that the accommodative increases in the eye's refractive power are due to parasympathetically innervated changes in the ciliary muscle. According to this concept, ciliary muscle contraction is directly proportional to the level of parasympathetic innervation of the ciliary muscle and that fatigue of the ciliary muscle would be expected to affect close work only.

As has already been discussed (section 1.4), the "dual-innervation theory" of accommodation presents a somewhat different definition of the "resting state". According to this theory, the resting state represents a tonic state, a balance between tonic levels of sympathetic and parasympathetic innervation to the ciliary muscle (Cogan, 1937; Schober, 1954; Melton et al., 1955; Toates, 1970, 1972; Leibowitz and Owens, 1978; see also chapter 6). It is this tonic state that the eye assumes in the absence of an adequate visual stimulus for accommodation.

In its most contraversial form, this theory maintains that increases in parasympathetic innervation induce increases in refractive power, whilst increases in sympathetic activity lead to decreases in refractive power; both types of change viewed as active processes. Applying this concept therefore, fatigue effects may be seen as decreasing the range of accommodation in either direction around this tonic position of rest, a view supported by the studies of Ostberg et al. (1980). It may also be expected that the level of fatigue for a task at a particular distance is dependent upon the difference between the task position and the accommodative rest position. A further consequence of this theory is that tasks that offer no accommodative stimuli or are placed at a distance equivalent to the rest position, should not produce fatigue effects.

The technique of laser optometry is, in itself, a tedious and potentially fatiguing visual task, although it does not theoretically present an accommodative stimulus to the observer (see sections 3.1B i and 3.5A). It would be expected, therefore, that an observers accommodative state would remain at his TA position. A study conducted by Miller et al. (1983) monitored the results of 10 observers as they performed several psychophysical variants of the laser optometry technique (e.g. double-staircase), over a three hour period. Miller and his co-workers were unable to detect a significant deviation in the TA levels over this period of time. There can be no doubt that such a task was indeed demanding but, as it offered no stimulus to the accommodative system, no demands were placed by the task on accommodation. No report was given in the study of any effect of this task upon the usual optometric parameters of accommodative far and near points.

A further prediction of the dual-innervation theory is that the performance of a task at any distance other than the accommodative resting position may, by affecting the tonic balance of ciliary muscle autonomic innervation, induce adaptation of the resting state itself. A report by Ebenholtz (1983) addresses this very point: in his study, 12 refractively-uncorrected subjects monocularly viewed a fixation target placed at their individual accommodative far (FP), near (NP) and pre-task resting points (via a Badal-optical system) for a period of eight minutes. Laser optometry was utilised to measure the level of tonic resting accommodation immediately before and after interaction with the task. The difference in TA measurements between pre- and post-fixation periods shown in fig 7.0 clearly indicates the presence of hysteresis effects. Near fixation elicited a significant myopic increase in mean TA of 0.34D ($t=4.25$, $df=11$, $p < 0.01$), whereas fixation at the rest position produced a nonsignificant mean myopic shift of 0.06D. In contrast, fixation at the FP yielded a mean hyperopic shift in TA of 0.21D ($t=4.20$, $df=11$, $p < 0.01$). A non-linearity was evident however, between both the mean level of hysteresis and decay time constants, following NP and FP fixation. Ebenholtz regarded this as evidence for the existence of two sub-systems in the control of the accommodative system: one for negative accommodation and one for positive accommodation, although he does not implicate the autonomic input to the ciliary muscle.

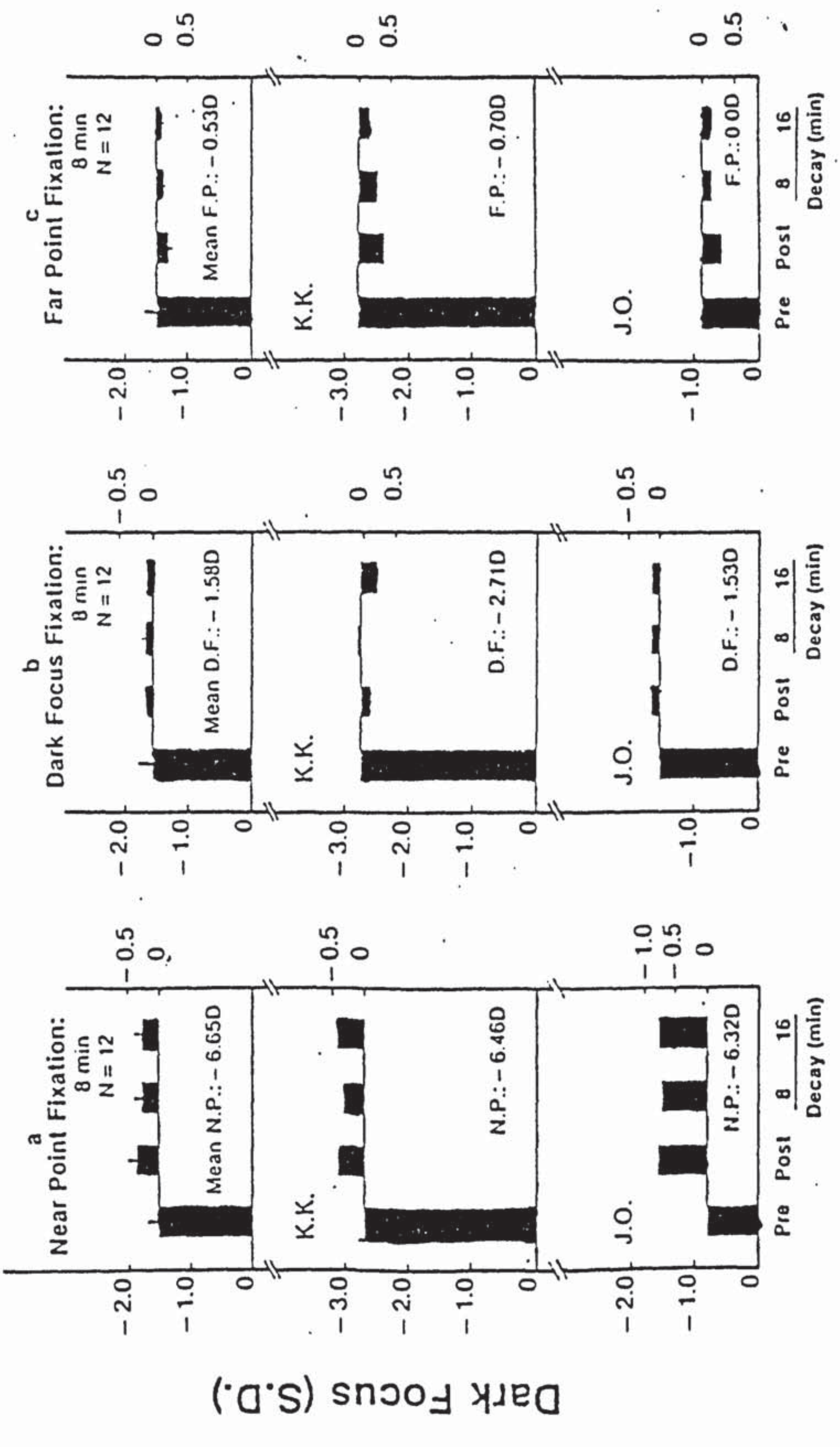

Figure 7.0 - TA levels for pre- (left-most bars) and post-fixation periods (other bars). The ordinates represent the induced-change in TA, whilst the abscissae represent time. The upper three graphs illustrate the mean (n=12) results, whilst the lower graphs illustrate the results for the two observers with the highest (K.K.) and the lowest (J.O.) initial TA values.

In a very recent study, Ebenholtz (1985) monitored the level of TA over a 24min period following 8min viewing of a 10.9 cpd horizontal square wave pattern target at 5 different dioptric distances: a) the FP; b) a point mid-way between the observer's initial TA position and the FP; c) the initial TA position itself; d) a point mid-way between the observer's TA position and the NP; and e) the NP itself. Ebenholtz found the shift in TA to be a positive linear function of the dioptric distances. Once again, he found the hysteresis decay times following FP fixation to be less than those following NP fixation. He concluded that, although initial levels of accommodative hysteresis for both FP and NP fixation reflect a common underlying mechanism, the decay data would suggest two separate mechanisms.

Baker et al. (1983) monitored the dynamic accommodative state of two observers in total darkness over the 20s period immediately after they had attained a clear, stable image of an accommodative stimulus (a Landolt "C", 20 min arc in diameter) held at four stimulus distances of 0, 1, 2 and 3D. From their results, these workers postulated the existence of a zone of "inactive accommodation" of a about 1.0D within which the focus mechanism is relatively stable in darkness, rather than a single accommodative resting position. When the stimulus was closer to the eye than the observer's "rest zone", accommodation drifted to a rest position "towards the near edge of the zone". If the eye had been initially focussed beyond the "rest zone", there was a drift of accommodation towards the far edge of the zone. For initial stimulus levels within the rest zone, there was little change in accommodative state of the eye when stimulus was withdrawn.

Schor et al. (1984) utilised an infra-red optometer to monitor the level of TA for 60s in total darkness, immediately before and after the 9 subjects observed a visual target placed nearer or further than their baseline tonic resting position, for time periods of less than 2min. Schor and his co-workers were unable to show consistent changes in TA following fixation at either distance. In the second part of their study, however, a 0.5D mean myopic increase in TA ($t=2.46$, $df=8$, $p < 0.025$) was found, following a 30min reading task at a stimulus distance of 33cm and through -3D spectacle lenses (i.e. a total stimulus demand of 6D).

Two studies by Owens and Wolf (1984) and Wolf et al. (1985) report myopic shifts in both TA and TV near visual tasks. The results of both studies would indicate that near work induces uncorrelated increases in the initial TA and TV levels, suggesting independence in the resting states. The changes were found to be transient, decaying within minutes.

Much of the earlier work depended upon the use of standard consulting-room optometric techniques (e.g. measurement of the amplitude of accommodation) in the attempt to detect adaptive changes in the accommodative system. As mentioned earlier however, the results obtained with these techniques depend on many factors (e.g. stimulus content of the technique, the level of illumination and observer motivation) and, as they invariably involve the measurement of one extreme of the accommodative range, are not perhaps, the best choice of techniques available to the modern researcher. The use of TA as a metric of accommodative adaptation offers many advantages over the standard optometric techniques. Studies utilising measures of TA (such as that of Ebenholtz, 1983) have indeed detected and measured small but significant adapative changes in the resting level of accommodation.

7.1B - Adaptation of the vergence system

Much of the previous literature suggests that unusual or prolonged demands on fusional-vergence result in subsequent changes in vergence behaviour: including transient changes in heterophoria, fixation disparity and fusional reserves. The demands may involve the effects of standard optometric procedures (such as the effect of measurement of fusional reserves) on heterophoria (Alpern, 1946; Morgan, 1947). A large portion of the reports in the literature are based on observations of the response of the vergence system to the fusional stress induced by the introduction and sustained presence of prism.

Most of the studies applying prisms and forced vergence in an investigation of the effects of fusional stress have demonstrated that an observer will, after some period of time, often exhibit the same level of heterophoria or fixation disparity that was present prior to the initial introduction of prism. The change in heterophoria has been found to occur within 3 to 10 mins following exposure to 2Δ of vertical prism (Ogle and Prangen, 1953; Henson and North, 1980), and within 15 to 30 mins following the exposure to 10Δ base-in and 32Δ base-out of horizontal prism (Carter, 1957; 1965). Ogle and Prangen (1953) concluded that the visual system was capable of adjusting its level of innervation in an attempt to reduce the strain on fusional-vergence.

If the stimulus to fusion is disrupted following the period of adaptation, the relative position of the eyes is found to change: fairly rapidly at first and then more slowly, back to the original or former heterophoria position (Ellerbrock, 1950; Ogle and Prangen, 1953; Mitchell and Ellerbrock, 1955; Ludvigh et al., 1964; Vaegan and Pye, 1979; Hensen and North, 1980). The rate of this apparent decay in the level of adaptation was found to depend on the exposure duration to the vergence stimulus. Ludvigh et al. (1964) showed that when the duration of the induced forced vergence (at 8.8 deg of adduction) was maintained for 5 sec, the total decay of any induced adaptation occurred within 15 sec; the decay rate was found to be slower when the forced vergence was maintained for 30 sec. Mitchell and Ellerbrock (1955) demonstrated that the rate of adaptation decay was inversely proportional to the duration of forced vergence, for horizontal prism values between 2 and 12Δ.

Carter (1963; 1965) found that the adaptive changes in heterophoria and fixation disparity to continuous exposure to prism remained stable for many weeks. However, upon removal of the prism, the after-effects of adaptation were observed to decay over a period of 15 mins to several hours; depending on the post-adaptation viewing conditions. In general, rapid decay (or re-adaptation back to normal) was obtained for those observers who experienced normal binocular fusion immediately following the removal of prism: whilst prolonged after-effects were obtained when normal binocular fusion was prevented through sleep (Carter, 1963), or through the diplopia resulting from the abrupt removal of high-powered prism (Carter, 1965).

Carter (1965) interpreted these changes in heterophoria and fixation disparity as reflections of adaptive changes in the "tonicity of the motor centres". Acknowledging an earlier suggestion by Maddox (1893), Carter proposed that the changes in "tonicity" reduced ocular discomfort by relieving the unusual stress on fusional-vergence. Moreover, he concluded that sensory fusion was necessary for both the adaptation to and the recovery from, the effects of prism. Carter noted that a few of his observers were incapable of adapting to the effects of horizontal prism. He suggested that they may lack normal sensory fusion and may, therefore, be more prone to oculomotor problems; this suggestion has since been confirmed by the results of studies by Ogle et al. (1967), North and Henson (1981), and Schor (1979b). Carter further proposed that:

> "...with most persons some factor is acting to maintain approximate orthophoria. The adaptation to prism vergence...may be a manifestation of this basic adaptive mechanism of normal binocular vision."

The above observations may be explained by an adoption of tonic vergence (TV) as the "starting point" for all vergence movements. The unusual fusional demands of prism adaptation might (somehow) induce an adaptive shift in this tonus position. The introduction of horizontal prism would serve to displace the tonic position towards one extreme of the functional range. Consequently, increased fusional effort would be necessary to fixate in one direction from the tonic position, whilst decreased effort would be required to fixate stimuli in the opposite direction; i.e., base-out prism increases the demand on convergence while decreasing the demand on divergence responses. Initially, this asymmetry of fusional effort would be accompanied by an anomalous heterophoria and/or fixation disparity, as the vergence responses are biased towards the prior TV position. Following the onset of adaptation, TV would progressively resume its original position, relative to the functional range of stimulation, with the result that the fusional effort required to fixate any given distance returns to normal levels and measures of vergence accuracy, lateral heterophoria and fusional reserves regain their original values.

On removal of the prism, the vergence system is faced with a similar situation to that when the prism was originally introduced and, providing fusion remains possible, it may re-adapt to the new demands. The process of re-adaptation has been termed as "hysteresis" (Ebenholtz, 1981).

The apparent plasticity of the vergence system has also been implicated as an explanation for the effects of prism or sustained convergence on the perception of distance (Owens and Leibowitz, 1980; Ebenholtz, 1981; Ebenholtz and Fisher, 1982). One of the recurrent findings of research into space perception is that, under conditions of low illumination, most observers tend to underestimate the distance of far objects and to underestimate the distance of near objects (Grant, 1942; Foley, 1980). Gogel refers to this perceptual bias as the "specific distance tendency" (SDT) and has proposed that it represents some fundamental metric" of visual space. He has demonstrated that, in the absence of contextual cues, objects tended to be localized at an intermediate distance (Gogel, 1969; 1976; 1977a; 1977b; 1978), of around 2m, with a range from 30cm to 8m (Gogel and Teitz, 1973).

There are numerous reports that viewing through horizontal prism or exerting sustained and abnormally high levels of vergence may both induce changes in distance perception that are qualitatively similar to the effect of prism adaptation on vergence eye movements (e.g., Wallach et al., 1972; Craske and Crawshaw, 1974; Von Hofsten, 1979; Owens and Leibowitz, 1980; Ebenholtz, 1981; Ebenholtz and Fisher, 1982; and Heuer and Luschow, 1983). It is typical for observers to initially misperceive distance on the introduction of prism, but then to adapt to the new situation, regaining normal distance perception. On removal of the prism, the observers once more misperceive distances, but this time in the opposite direction to their earlier errors.

The similarity of motor and perceptual adaptataion to unusual fusional demnds would suggest the involvement of a common underlying mechanism[1]. Von Hofsten (1976) has proposed a

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[1] Owens and Leibowitz (1976a) were able to demonstrate a significant relationship between the SDT and TV ($r = 0.76$, $p < 0.01$) but not between SDT and TA ($r = 0.19$, $p = ns$).

theory of the role of vergence in the perception of distance which allows a simple interpretation of the adaptation phenomena outlined above. In this theory, Von Hofsten (1976) suggests that perceived distance is not directly related to the vergence angle, but is rather dependent upon the extent to which a vergence response departs from the physiological resting state. Thus, Von Hofsten's theory implies that the perception of distance is influenced by the level of effort required for binocular sensory fusion.

In conclusion therefore, tonic vergence would appear to be quite plastic in nature and capable of adjusting to excessive demands on fusional vergence. The adaptive changes in tonic vergence are correlated with the recovery of normal space perception and vergence accuracy, which suggests that both perceptual and oculomotor adaptation depend upon the same basic process: i.e., the re-calibration of the tonic resting position of the vergence system.

7.2 - The effect of sustained visual tasks on TA and TV.

The previous sections have outlined evidence to show that the accommodative and vergence systems both exhibit an effective adaptive capacity. This property imparts extensive plasticity, enabling the systems to adjust to the sustained demands of a visual task. In this way, particularly stressful effort may be effectively minimised.

It is proposed that the bias positions of TA and TV represent the fulcra from which all accommodative and vergence movements are made, and that any potential modification to either system, in response to demands, is initiated by a recalibration of its bias-level, designated TA and TV respectively. Most previous studies have observed adaptive changes in accommodative or vergence ability using parameters that are known to be stimulus dependent (e.g., far and near points, heterophoria and fusional reserves - see the general introduction). The sensitivity of an investigation into accommodative or vergence plasticity would be enhanced by the specific observation of the induced changes in TA and TV themselves. For these reasons, the present study will observe TA and TV alone, immediately before and after interaction with a sustained visual task.

7.2A - Experimental design.

This study was designed to compare the pre- and post-task TA and TV levels, of a group of normal observers, following interaction with a sustained visual task viewed binocularly at three separate distances: 33, 100 and 275cm. Table 7.1 illustrates the accommodative and vergence stimuli that these distances represented: the vergence stimuli have been calculated for an IPD of 65mm.

Table 7.1 - The stimuli to the accommodative and vergence systems represented by the task located at three distances. The vergence stimuli are calculated for an IPD of 65mm.

	STIMULI	
TASK LOCATION (CM)	ACCOMMODATION (D)	VERGENCE (°)
275	0.36	0.68
100	1.00	1.87
33	3.00	5.57

It will be evident that, for the majority of observers, the 33cm task stimuli will be closer than their pre-task TA or TV positions and, if the general adaptive paradigm outlined in sections 7.1A and 7.1B is affirmed, it would be expected that the post-task tonic positions would have moved closer to the observer. Conversely, the 275cm task stimuli will be beyond the pre-task TA and TV positions for most observers, thus the post-task tonic positions would be expected to have shifted beyond their original position. The resultant effect on the pre-task TA and TV levels of the 100cm task would then depend on the relative differences between this and the individual's tonic resting position.

7.2B - Observers.

Twenty seven observers (16 males and 11 females) participated in the study. Their ages ranged from 19 to 24 years with a mean of 20.5 years. Each observer was given a full ophthalmic examination which screened for both ocular and binocular defects and provided an infinity-balanced and centred refractive correction which each observer was required to wear throughout the study; each observer was required to attain a visual acuity of at least 6/6 in each eye, and to exhibit no sign of fixation disparity at 6m and 33cm. All observers utilised were experienced in the measurement techniques used; most had participated in at least one of the previous studies of this thesis.

7.2C - The visual task.

Most previous studies (e.g., Ebenholtz, 1983; Schor et al., 1984) have utilised static visual tasks, such as fixation targets or newsprint. In the present study it was decided to use a highly interactive visual task that was rich in cognitive detail and would encompass the range of spatial frequencies and orientations essential to guide the accommodative and vergence response (see Charman and Tucker, 1977; and Tyler, 1983). The visual task selected was an "arcade-type" of computer game[1], the output of which was presented to the observer via a 14inch Sony Trinitron television monitor. This form of task was chosen for its

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[1] The game used was "Zoom", a product of Image Games Co., U.K.

interactive qualities, requiring a constant high level of visual attention essential for the successful participation of the "game". A "Kempston" joystick was interfaced to a Spectrum microcomputer which "ran" the program, enabling the interaction of the observer with the visual task.

A few days before the participation in the study, each observer was given an equal chance to familiarise themselves with the requirements of the task. During each phase of the study, the observer was encouraged by the examiner to participate fully in the task and were told that a record was to be kept of their performance or "score" and furthermore, that a prize would be given for the highest score.

Each observer wore their full refractive correction and was given 15min interaction time with the visual task at each of the task locations. At the end of 15min the room lights were extinguished and the measurement of TA and TV commenced. The order of task locations was chosen for each observer on a random basis and a time period of at least two days allowed before participating in the further phases.

7.2D - The measurement of TA and TV.

Measures of TA and TV were taken in total darkness from each observer, immediately prior to the commencement of, and over a 15min period immediately following, the cessation of interaction with the sustained visual task and the onset of total darkness.

TA was measured using the laser optometer and protocol, as previously described in sections 3.1C i, 3.1C ii and 3.4 respectively. TV measures were taken using the vernier alignment device and protocol, as previously described in sections 3.2B i, 3.2B ii + iii and 3.4 respectively.

7.3 - Results.

The results have been tabulated within Appendix XVI. Figure 7.1 illustrates the task-induced effects on the level of TA as a function of the pre-task TA value, following 15min interaction by the 27 observers at a stimulus distance of 275cm (or 0.36D). Similarly, Figure 7.2 shows the effect on the pre-task level of TA of 15mins interaction by the 27 observers with the visual task at a stimulus distance of 100cm (or 1.00D). Figure 7.3 demonstrates the effect on the pre-task level of TA following 15mins interaction by the 27 observers with the visual task at a stimulus distance of 33cm (3.00D). All data points for each observer in Figs. 7.1, 7.2 and 7.3 are calculated as the mean of the post-task induced changes in TA as given in Appendix tables XVI.8, XVI.9 and XVI.10 respectively, thus representing the mean hysteresis effects over the 15min post-task measurement periods.

Figure 7.4 shows the effect on the initial TV level of 15min's interaction by the 27 observers with the visual task at 275cm (0.68deg for an average IPD of 65mm). Figure 7.5 demonstrates the mean task-induced change in the initial level of TV over the 15 min measurement period following 15min interaction by the 27 observers with the visual task at 100cm (or 1.87deg). Figure 7.6 shows the mean hysteretic effect on the initial TV levels of 27 observers over a 15min post-task measurement period following 15 min interaction with the visual task at 33cm (5.57deg). As in the case of TA, the data points displayed in Figs. 7.4, 7.5 and 7.6 are the mean changes in TV over the 15min post-task period, as given in Tables XVI.11, XVI.12 and XVI.13 respectively, thus representing the mean hysteretic effects for each observer.

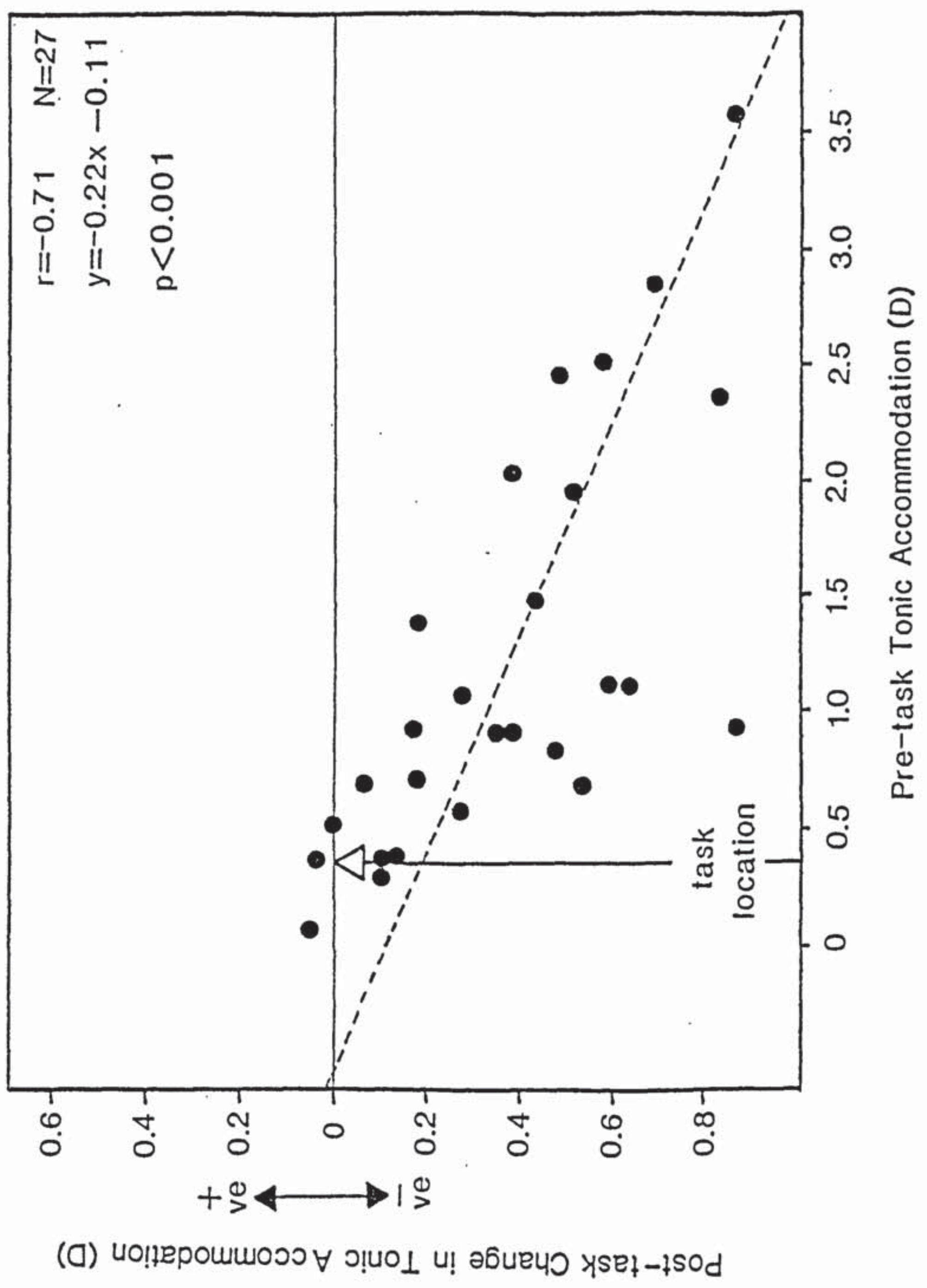


Figure 7.1 - The mean post-task induced change in TA(D at 632.8nm) for the 27 observers, following 15min interaction with a visual task at 275cm (0.36D).

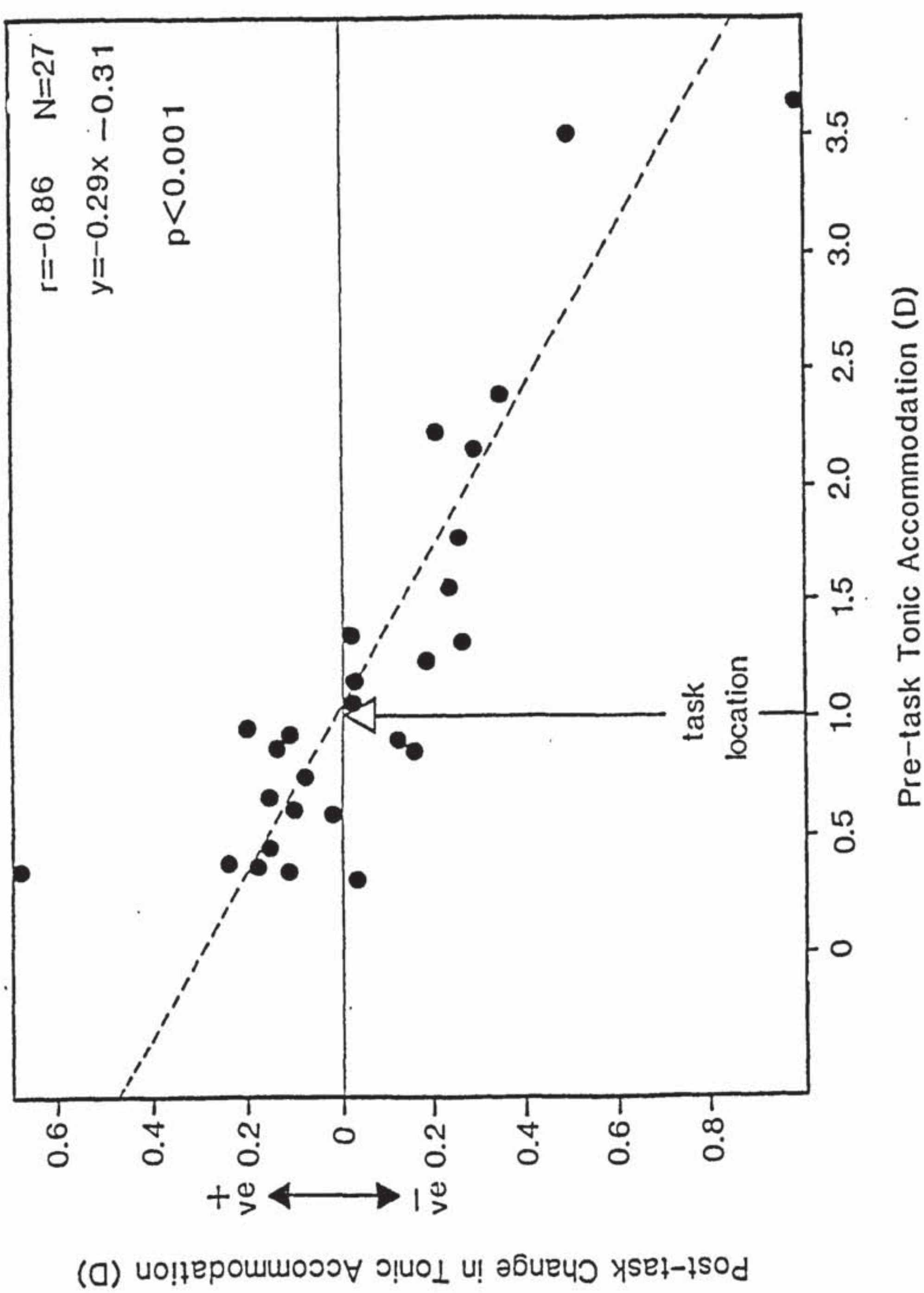


Figure 7.2 - The mean post-task change in TA (D at 632.8nm) for the 27 observers, following 15min interaction with a visual task at 100cm (1.00D).

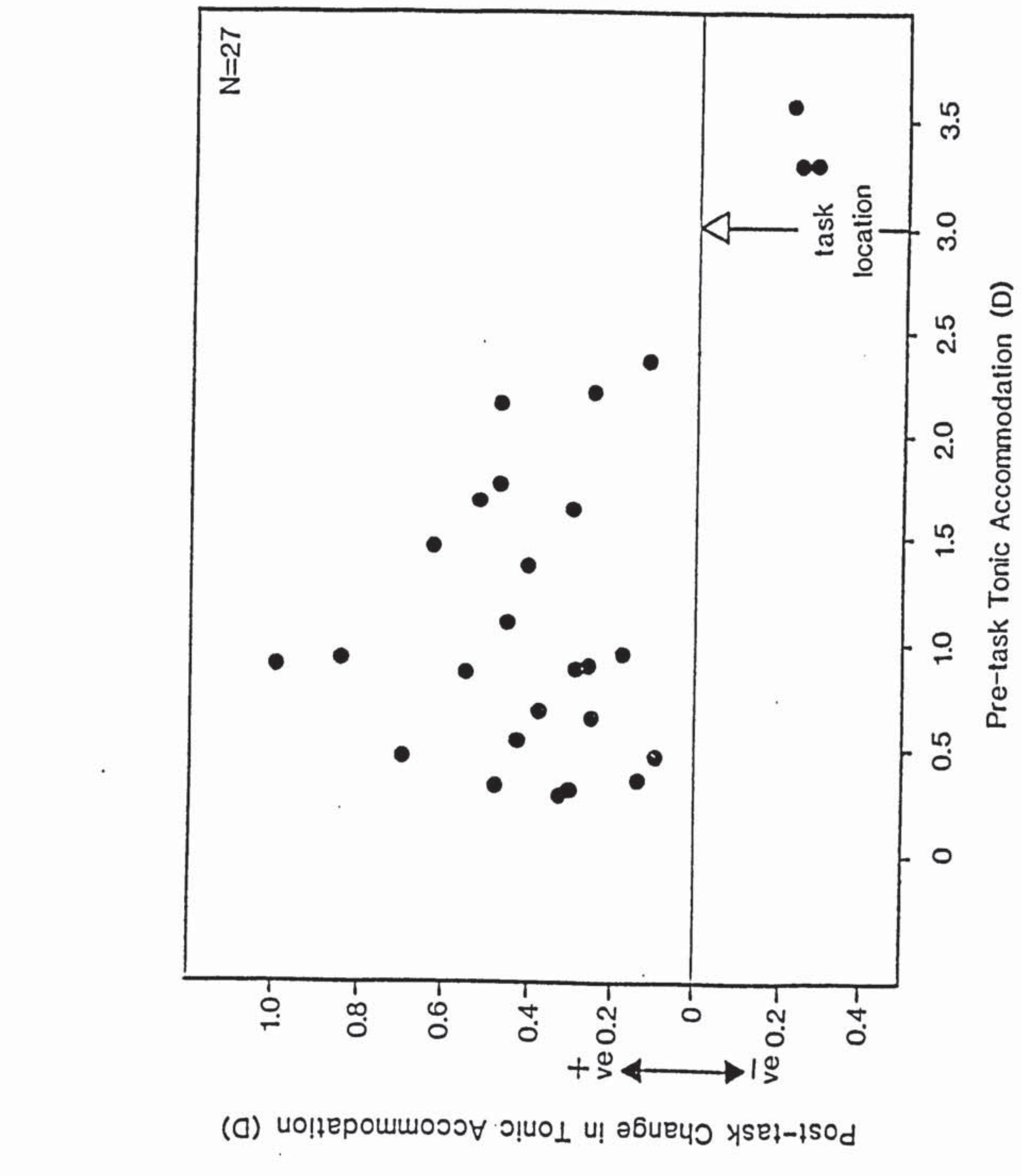


Figure 7.3 - The mean post-task change in TA (D at 632.8nm) for the 27 observers, following 15min interaction with a visual task at 33cm (3.00D).

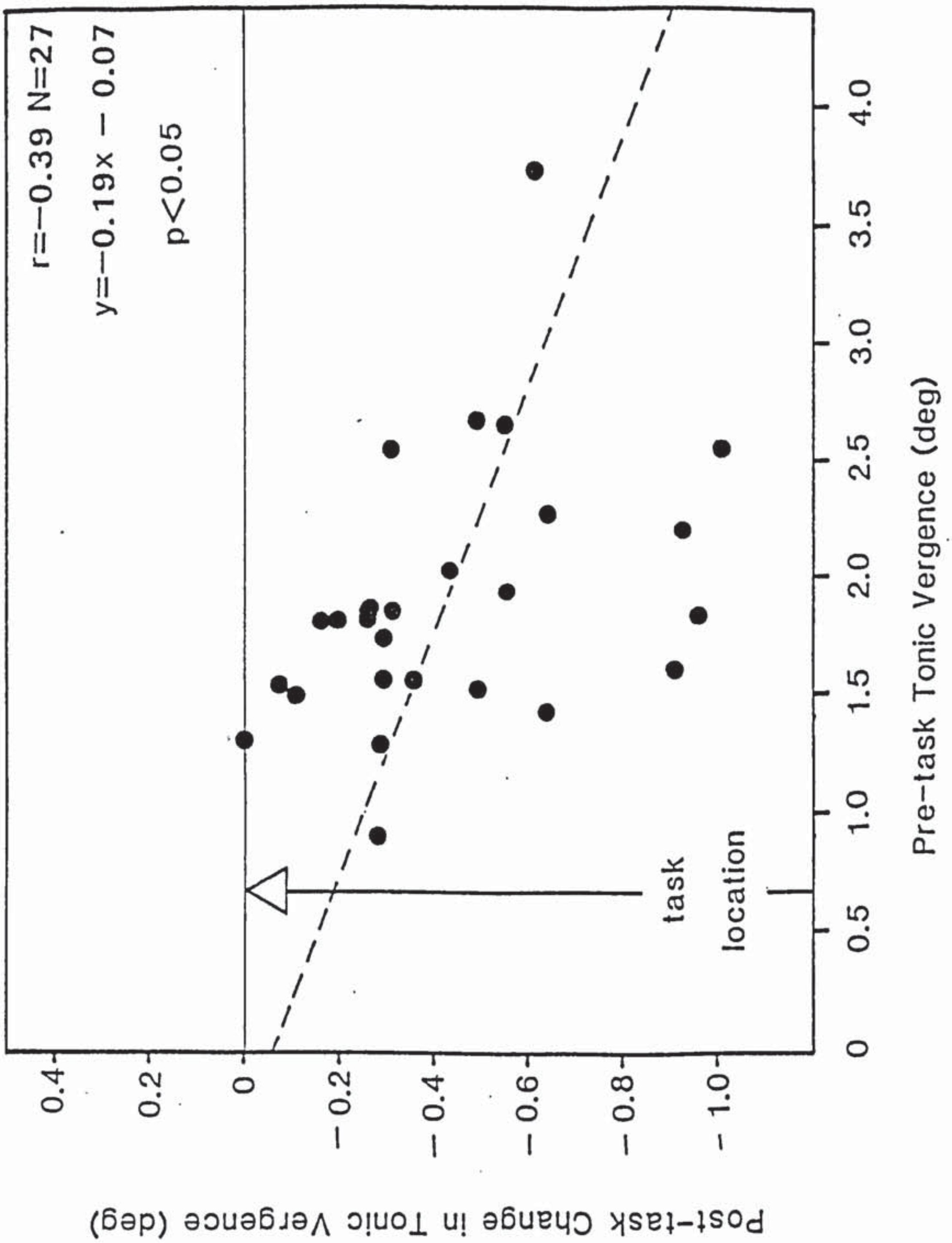


Figure 7.4 - The mean post-task change in TV (Deg) for the 27 observers, following 15min interaction with a visual task at 275cm (0.68deg).

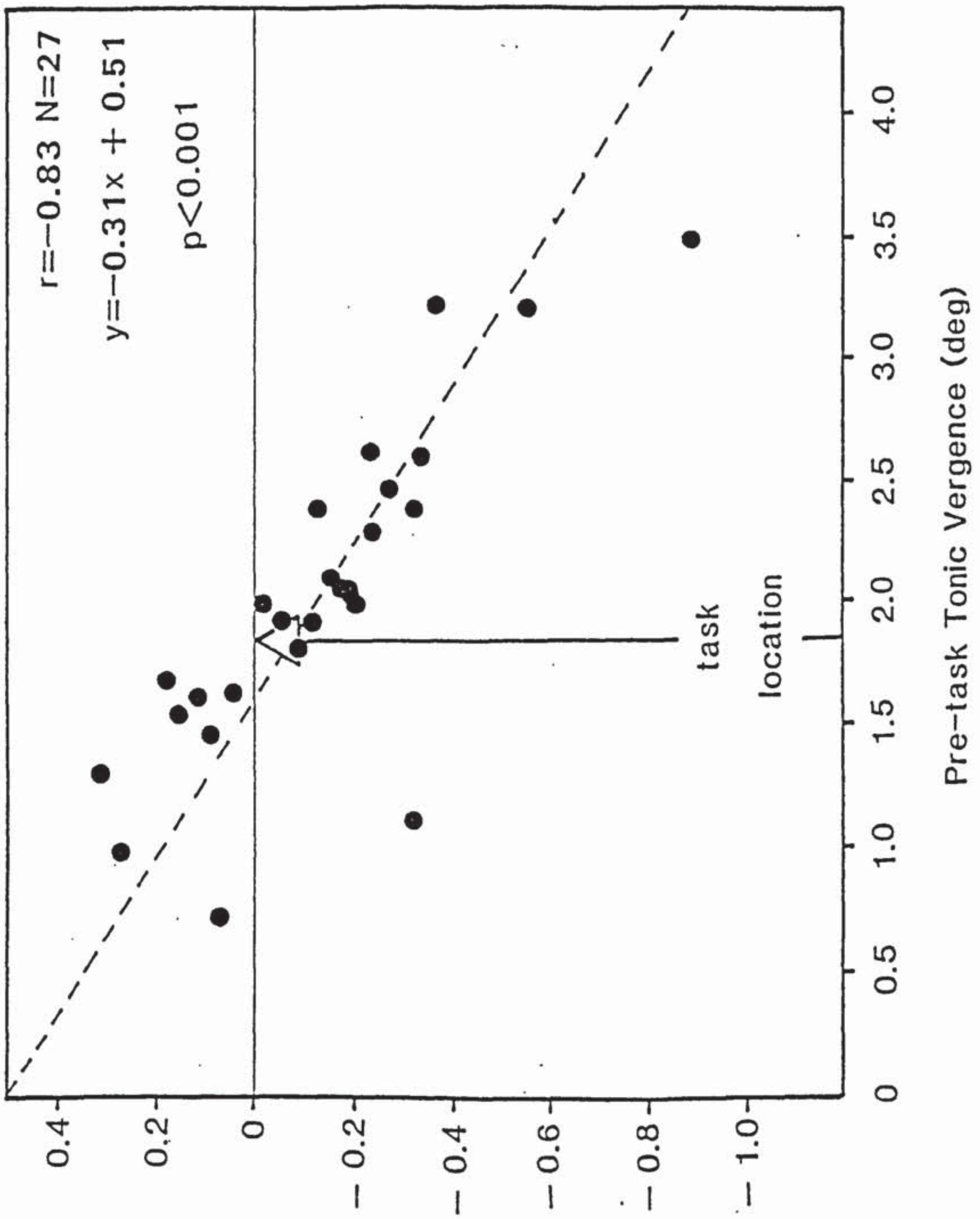


Figure 7.5 - The mean post-task change in TV (Deg) for the 27 observers, following 15min interaction with a visual task at 100cm (1.87deg).

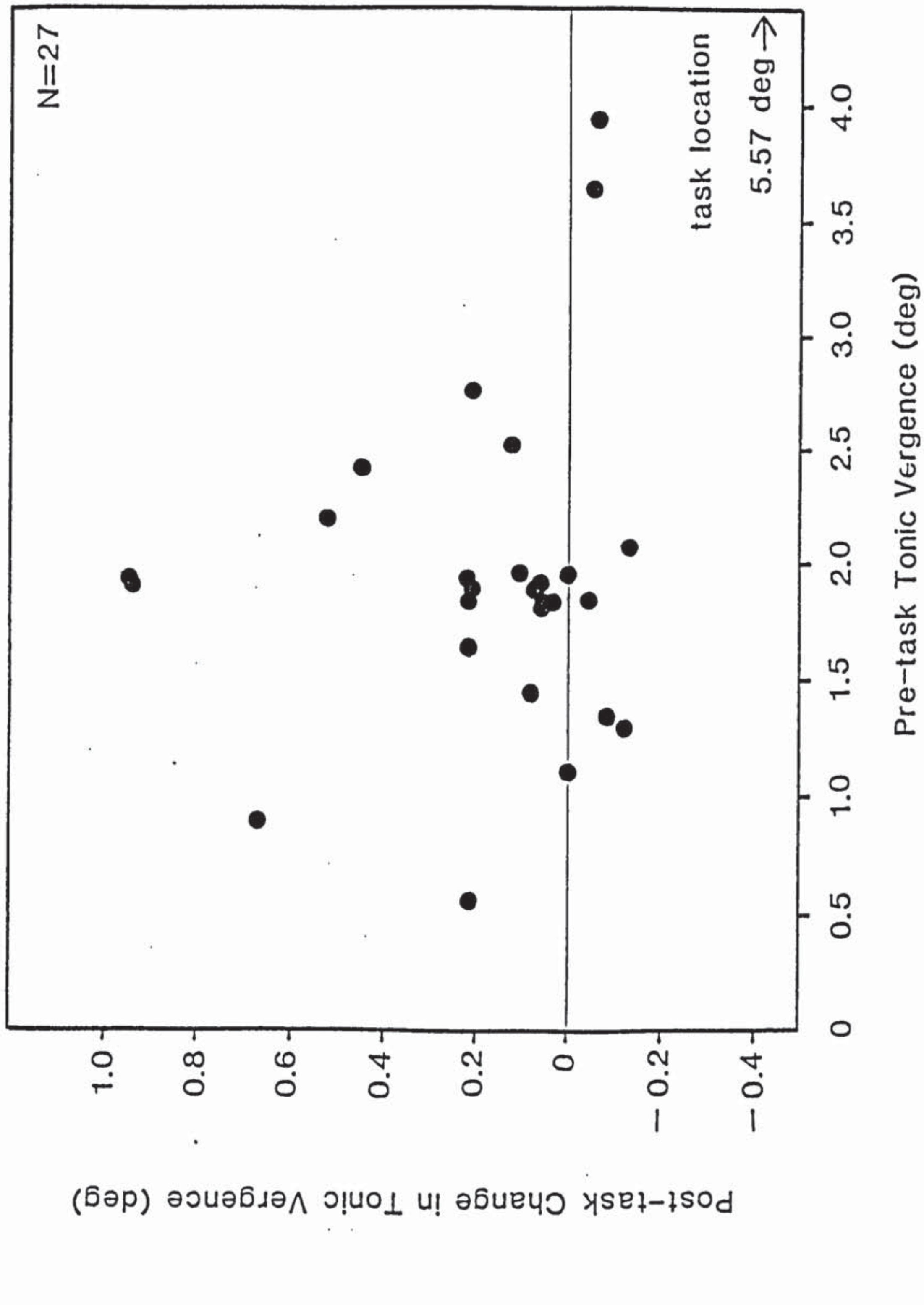


Figure 7.6 - The mean post-task change in TV (Deg) for the 27 observers, following 15min interaction with a visual task at 33cm (5.57deg).

7.4 - General Discussion.

Appreciation of sections 7.1A, 7.1B and 7.2A would suggest that the adaptive effect of a particular task would be dependent on the difference between an individual's tonic resting state and the nominal stimulus offered by that task. It will be evident from the above results that the expected effects have been largely demonstrated. Reference to Figure 7.1 illustrates that the interaction with the visual task at 275cm (representing a stimulus of 0.36D), induced a mean hysteretic change in TA that is in direct proportion with the initial pre-task level of TA. For the majority of observers, the task distance of 275cm is beyond their initial TA and, in all but three observers, is found to induce a negative hysteretic shift in TA which can be demonstrated to be significantly related to the initial pre-task TA level ($r = -0.71$, $p < 0.001$).

Figure 7.2 demonstrates the TA hysteresis induced by interaction by the 27 observers with the visual task at 1m and illustrates the mean change in TA varies as a function of the pre-task TA level. It is evident from the significant relationship between the induced hysteretic change and the pre-task TA levels ($r = 0.86$, $p < 0.001$), that the induced hysteretic changes are directly proportional to the difference between the initial TA level and the 1.00D stimulus offered by the task at 1m. Those observers with initial TA levels closer than the task distance have exhibited negative hysteresis changes in their mean TA levels over the 15mins post-task period, whereas those observers with initial TA levels beyond the task position of 1m exhibit positive hysteresis changes in their TA levels. The proportional nature of the this relationship is enhanced by the observation that the intersection of the regression line with the abcissa (1.07D) is very close to the point represented by the task location (1.00D).

Twenty four of the twenty seven observers had pre-task TA levels beyond the stimulus represented by the third task location at 33cm (3.00D); one might expect that this group of observers would exhibit positive induced hysteresis proportional to their pre-task TA levels, whilst the remaining three observers with pre-task TA levels closer than the task would exhibit proportional negative induced hysteresis, following the 15min interaction period. It will be seen from figure 7.3 that whilst this expectation is qualitatively fulfilled, the quantitative expectations appear to fail for those observers with pre-task TA levels greater than 2.00D beyond the 3.00D stimulus distance of the task: for all other observers the expectations are found to be fully realised. This group of observers with relatively low pre-task TA values have exhibited less positive hysteresis than would be expected following the indications of the results of the interaction with the task at other stimulus distances. The significance of this observation will be discussed later.

The vergence results are similar to that of TA, in that they indicate that the induced hysteretic changes in the tonus position (TV) are also significantly related to the difference between the task location and the pre-task levels. The task location of 275cm represents a theoretical vergence stimulus of 0.68 deg, which is beyond the pre-task TV of the 27 observers. It would be reasonable therefore, to expect a systematic negative hysteretic change in the initial resting states. It will be evident from figure 7.4, that this expectation has been realised and although the correlation is not as significant ($r = 0.39$, $p < 0.05$) as that for TA under the same task conditions, the general paradigm is maintained.

Figure 7.5 illustrates the mean induced hysteretic changes in the TV levels of the 27 observers following interaction with the visual task at 100cm, over the 15min post-task interaction period. With the exception of one observer, all those with initial TV levels beyond the 1.87deg stimulus distance of the task exhibited systematic positive hysteretic changes from their initial TV levels. Without exception, all those observers with initial TV levels greater than the 1.87deg stimulus offered by the task exhibited systematic negative hysteretic changes over the 15min post-task period. The systematic nature of the relationship is illustrated by the high level of significance ($r = -0.83$, $p < 0.001$), and it is of interest to note that the regression line intersects the abcissa at a position (1.65 deg) very close to that of the task location (1.87 deg).

The theoretical vergence stimulus offered by the location of the visual task at 33cm is 5.57deg (for an average IPD of 65mm). The greatest pre-task TV level exhibited by the observer group was 3.97deg, one would expect, therefore, from the results of previous situations that all the observers would exhibit systematic degrees of positive induced hysteresis, following 15min interaction with the task at 33cm. It will be evident from figure 7.6 that this expectation was not fulfilled and, more specifically, it would appear that the expected relationship breaks down for those observers with a difference of greater than 2.5deg between their initial TV level and that represented by the task (5.57deg). It is to be noted that an analagous breakdown in the relationship was observed in the measurement of TA after interaction at 33cm for those observers with the lowest pre-task resting levels. Before this aspect is discussed more fully, it will be of interest to investigate the possiblity of any correlation between the induced hysteresis changes in TA and TV at the three task locations utilised.

Previous and present investigations into the relationship between the tonic resting states of accommodation and vergence have been outlined in the earlier section (4.6A of chapter 4). The studies of chapter 4 were able to demonstrate a significant correlation ($r = 0.80$, $p < 0.001$) between TA and TV and it was proposed that this relationship was a consequence of the motor effects of the synkinesis between accommodation and vergence under normal visual conditions. Although there is no sensory innervational link between TA and TV during conditions of total darkness, it is further proposed in chapter 4, that a stimulus independent residual memory or muscle tonicity would remain. Figures 7.7, 7.8 and 7.9 illustrate the relationships between the induced changes in both TA and TV, following interaction by the 27 observers with the visual task at the three distances 275, 100 and 33cm respectively.

Correlational analysis of the initial or pre-task levels of TA and TV for the 27 observer group at the three task locations 275, 100 and 33cm, reveal relationships between pre-task TA and TV levels as follows: at 275cm $r = 0.73$, $p < 0.001$; at 100cm $r = 0.39$, $p < 0.05$; and at the 33cm distance $r = 0.58$, $p = 0.002$. Although the product moment coefficients are slightly less than the 0.80 found for the TVA relationship of the N=60 study of chapter 4, they are still found to attain a reasonable level of statistical significance.

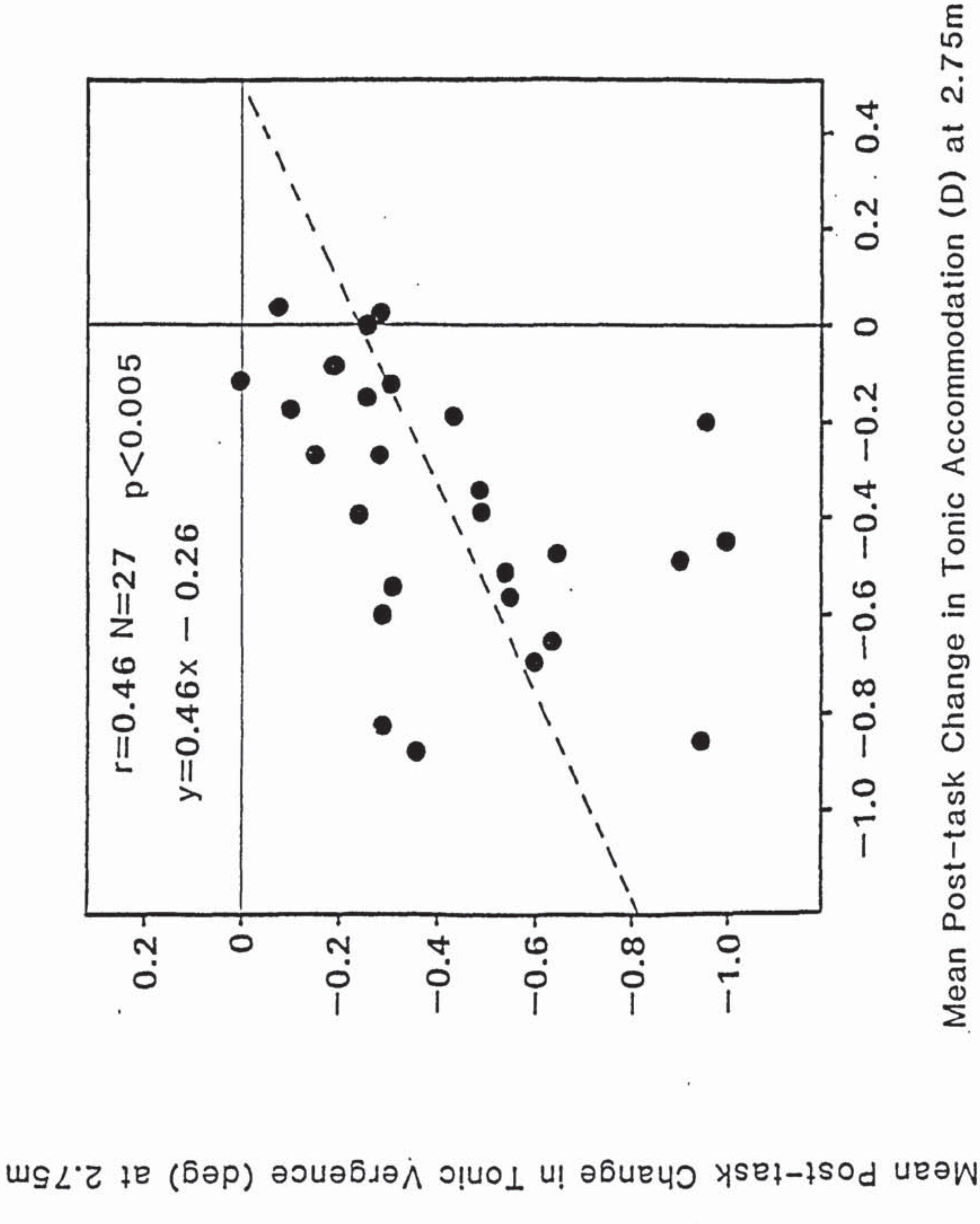


Figure 7.7 - The relationship between the mean post-task hysteretic changes of TA (D) and TV (deg), following 15min interaction with the visual task at 275cm (N=27).

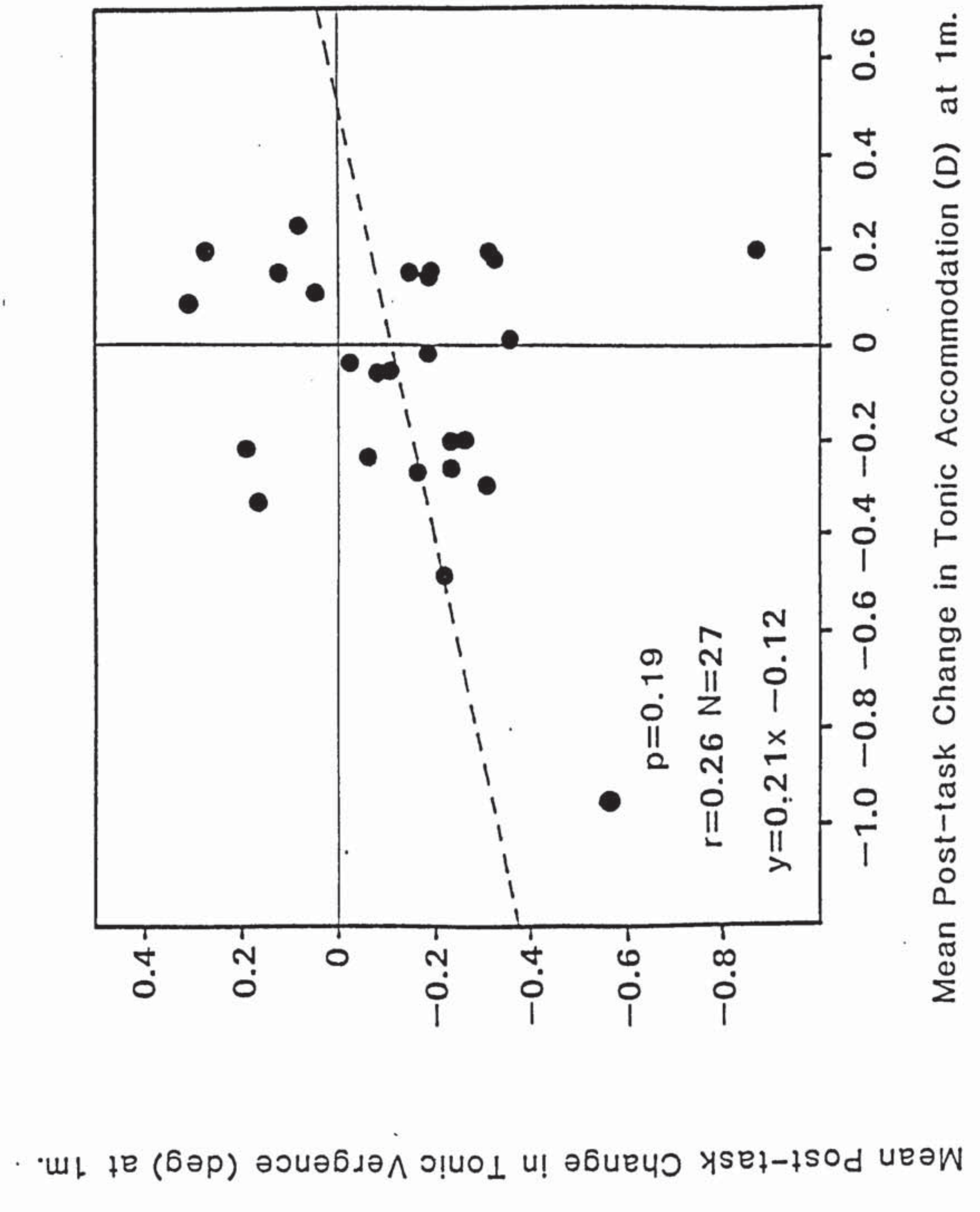


Figure 7.8 - The relationship between the mean post-task hysteretic changes of TA (D) and TV (deg), following 15min interaction with the visual task at 100cm (N=27).

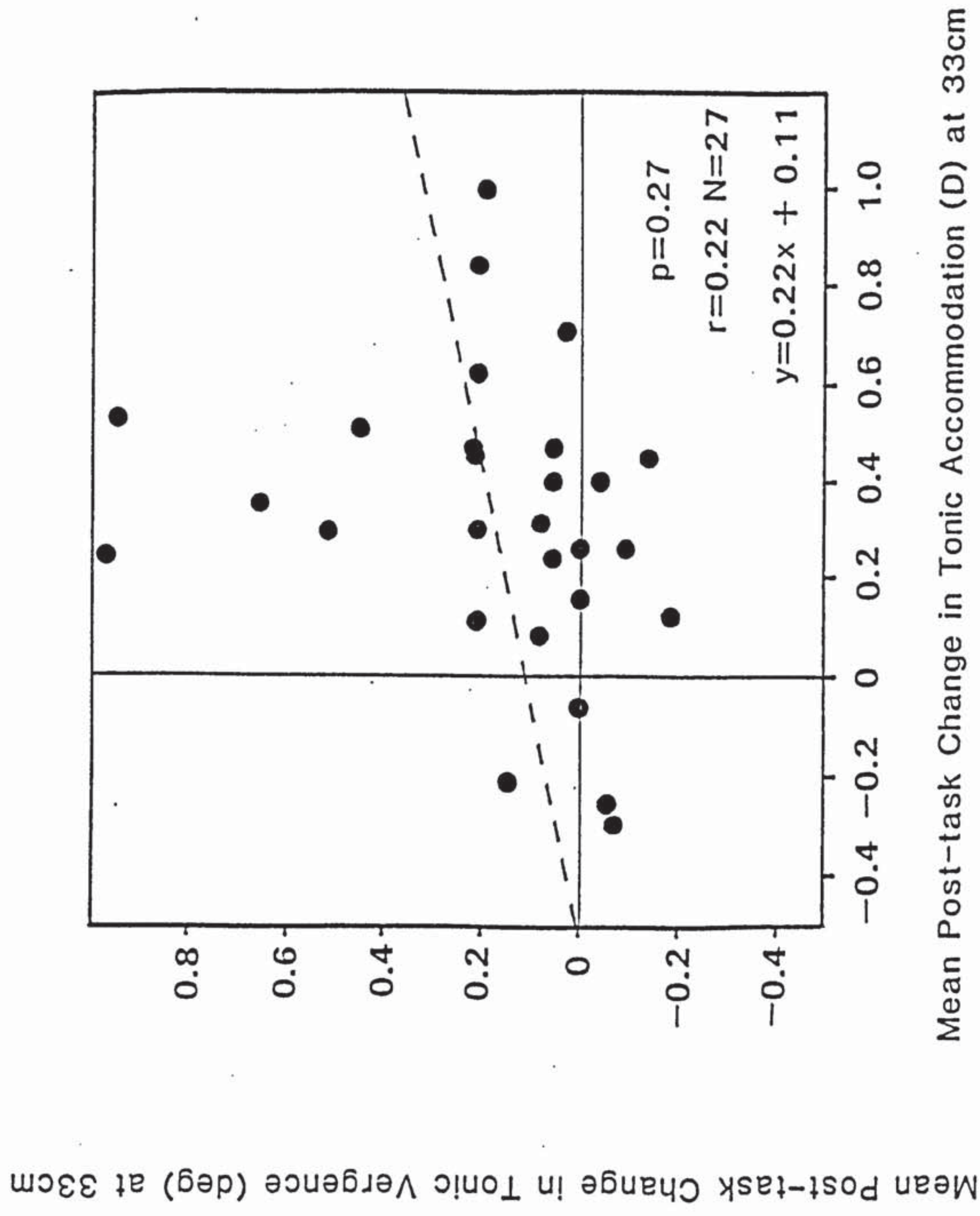


Figure 7.9 - The relationship between the mean post-task hysteretic changes of TA (D) and TV (deg), following 15min interaction with the visual task at 33cm (N=27).

Although it is evident from figure 7.7 that the pre-task relationship for the 275cm task location has reduced from r = 0.73 to r = 0.46, it will become apparent that 15min interaction with the visual task at 275cm has induced a significantly correlated level (p = 0.005) of induced hysteresis between TA and TV. For the majority of observers, those with pre-task TA and TV values nearest to the stimuli offered by the task at 275cm exhibited the lowest levels of induced hysteresis, whilst those observers with the higher TA and TV values exhibited the greatest negative induced hysteresis.

Although the correlation between the pre-task levels of TA and TV, following interaction by the 27 observer group with the visual task at 100cm, was the lowest of all the pre-task relationships, it was significant at the 5% level (r = 0.39, p = 0.04). Figure 7.8 illustrates the low level of correlation observed between the mean post-task induced hysteresis of TA and TV (r = 0.26, p = 0.19), following interaction by the 27 observer group at the 100cm task distance. It is of interest, however, to note that if the observer BS (with coordinates of +0.20, -0.84) was excluded from the analysis, then the relationship is found to improve and the pre-task correlation is exceeded by that of the new post-task (r = 0.43, p = 0.03).

The 33cm pre-task correlation between TA and TV was found to be r = 0.58 (p = 0.002). After the 15min interaction period at the 33cm task distance, the correlation between the mean induced hysteresis of TA and TV was found to be r = 0.22 (p = 0.27): this is the lowest of the post-task relationships (see fig. 7.9). This observation is not surprising, however, in view of the attenuated, non-linear distributions that were found to exist for both TA and TV (see figs. 7.3 and 7.6 respectively).

It would appear therefore, that there is reasonable evidence to suggest that 15min interaction with a binocularly viewed visual task is capable of inducing hysteretic changes in the accommodative and vergence resting states that are correlated. These correlations are found to reduce following interaction with the task at 33cm, especially for those observers with the lowest resting states and where there exists a difference of 2.0D and/or 2.5deg between their tonic resting states and the nominal accommodative and vergence stimuli, respectively.

It will be interesting to further analyse the observed hysteretic changes in TA and TV, by dividing the 27 observer population into three groups of nine: a "far", an "intermediate" and a "near" group, on the basis of their mean pre-task TA and TV levels. The three group means and standard deviations are given in table 7.2.

Table 7.2 - The means and standard deviations (S.D.) of the mean pre-task TA (D) and TV (deg) levels for the "far", "intermediate" and "near" analysis groups. It is interesting to note the comparatively high S.D.s of the near TA and TV groups.

	ANALYSIS GROUPINGS	MEAN	S.D.
	FAR	1.1	0.22
TA	INTERMEDIATE	1.6	0.25
	NEAR	2.9	0.81
	FAR	1.4	0.37
TV	INTERMEDIATE	1.9	0.39
	NEAR	2.5	0.63

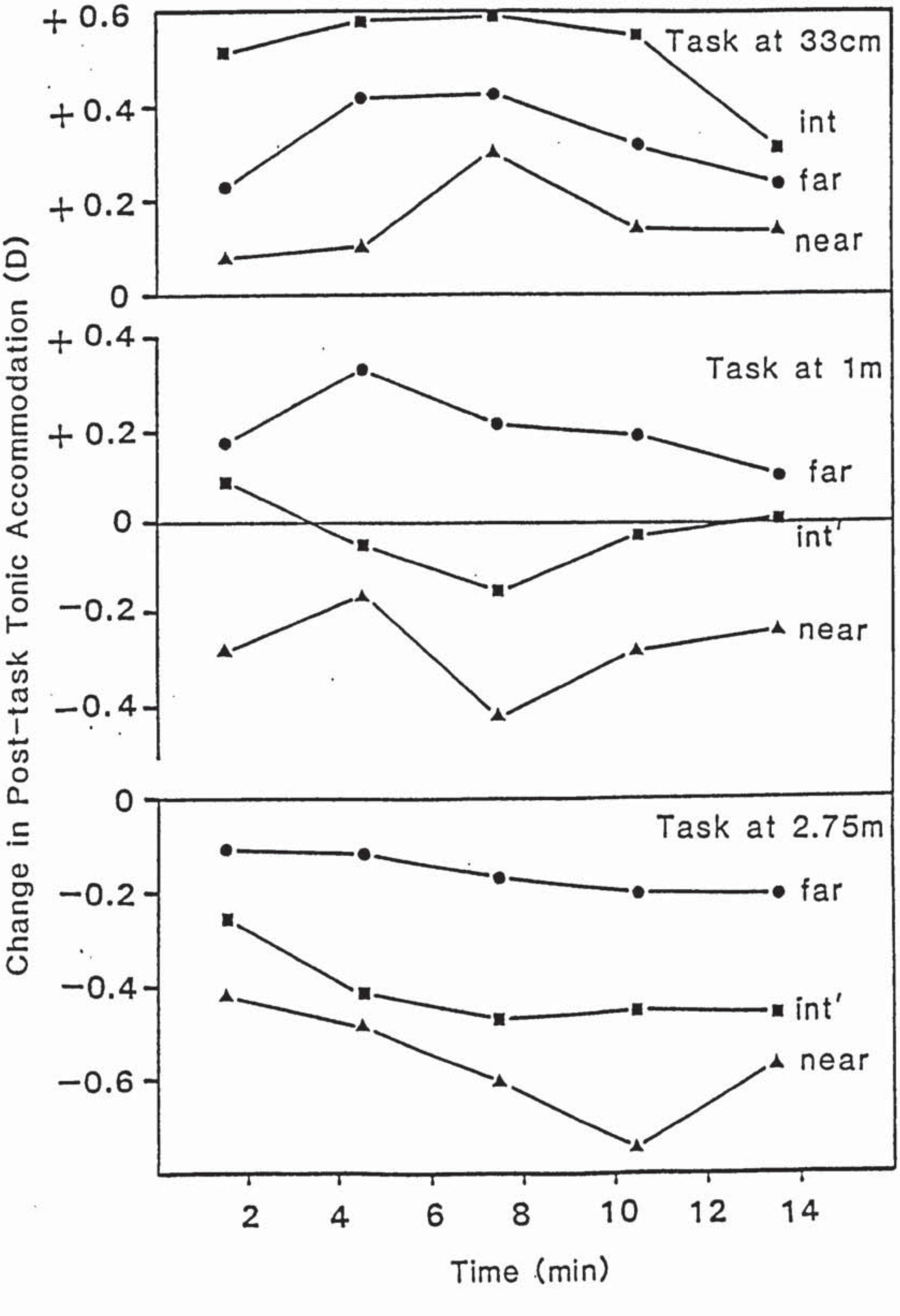


Figure 7.10 - Illustrating the time course of the hysteretic changes in TA over a 15min post-task period. The 27 observers have been divided on the basis of their pre-task TA levels into 3 groups: "far" (represented by circles), "intermediate" (represented by squares) and "near" (represented by triangles). The 15min post-task period has been divided into 5 equal and consecutive periods: 1-3, 4-6, 7-9, 10-12 and 13-15 mins. The abcissa presents time in minutes and the ordinate gives the mean hysteretic changes in TA (D) from its pre-task level.

The data within tables XVI.8, XVI.9 and XVI.10 of the appendix can be reset under the above three TA headings, "far", "intermediate" and "near" into five equal and consecutive time divisions, 1-3, 4-6, 7-9, 10-12 and 13-15mins, on the basis of the time of measurement. All induced changes of TA measured during the first 3min form the basis of the first division, with all those measured during the next 3min forming the second division, and so on until 5 divisions are formed. The re-organised data is displayed in table XVI.14 and illustrated in figure 7.10.

Figure 7.10 illustrates the mean time-course and magnitude of the post-task hysteretic changes in the initial TA levels, for the three observer groups: "far", "intermediate" and "near". It will be apparent from the lower section of figure 7.10 (with the task located at 275cm) that the theoretical 0.36D stimulus has induced systematic negative hysteresis in all three groups: the least in the "far" group (mean = -0.16D), a greater level in the "intermediate" group (mean = -0.45D) and the greatest hysteresis in the "near" group (mean = -0.55D). This observation may be explained on the basis of the order of the relative mean pre-task TA levels for the three groups (see table 7.2); i.e., the task offered less potential for hysteresis for the "far" group than for the "intermediate" and "near" groups respectively. It is to be expected therefore, that the "near" group of observers would exhibit a greater level of negative hysteresis than the "intermediate" and "far" groups respectively.

If attention is next drawn to the middle section of figure 7.10 (i.e., with the task located at 100cm), it will be apparent that the theoretical stimulus of 1.00D offered by the task has induced relative positive hysteresis in the "far" group (mean = +0.21D), little change in the "intermediate" group (mean = -0.02D) and relative negative hysteresis in the "near" group (mean = -0.28D). Once again, these changes may be explained by comparison of the mean initial resting states of the three groups (see table 7.2).

The upper graph of figure 7.10 depicts the relative hysteretic changes in the initial resting states of the three observer groups following interaction with task at 33cm. It would be expected from the order of the pre-TA levels and subsequent differences in potential hysteresis that all groups would exhibit relative positive hysteresis and in the following order; "far", "intermediate" and "near". It will be evident from the graph, however, that the expected order of progression has been rearranged. As expected, the "near" group exhibit the least positive hysteresis (mean = +0.15D), the relative expected positions of the "intermediate" and "far" groups are found to be reversed: the "intermediate" group have exhibited a mean positive hysteretic increase of +0.52D, whilst the "far" group exhibit somewhat less at a mean level of +0.37D. It would seem reasonable to conclude that there has been an apparent attenuation in the magnitude of the expected hysteretic effect for the "far" group following interaction with the task located at 33cm. The relevance of such an attentuation will be discussed later.

Figure 7.10, together with the data of table XVI.14, provides some limited indication of the time course of the hysteretic effects. One problem, however, that has been encountered with Badal-laser optometric estimates of the tonic resting state of accommodation has been the time taken, following the onset of darkness, for the the observer to provide stable, reliable and reproducible results. It is not unusual for an observer to require around 5min in order that he may become confident of the motion of the speckled nature of the reflected laser light. This observation may be due to several factors such as: the reduced exposure duration utilised in the present study (see section 3.5A and Hogan and Gilmartin, 1984b); the dark adaptation period; or the temporal requirements for motion detection while under conditions of sudden total darkness. It will be apparent from figure 7.10 that the maximum hysteretic effect is sometimes not be observed until a post-task period of between 6 and 10mins has elapsed. It would appear as if there is either some delay in the onset of hysteresis or that there is some element of doubt concerning the validity of the measurements over the first few minutes immediately after the onset of darkness. The latter possibility might be due to the factors outlined earlier in this paragraph and could be further investigated using an objective measurement technique, such as an infra-red optometer (see Bullimore et al., 1986).

Ebenholtz (1983) estimated that the decay of the hysteretic effects induced in his 12 observers, following 8min of fixation at their far-points, would be completed much faster (72min) than the decay of the hysteresis following fixation at their near-points (10.26hrs). Whilst it is difficult to apply Ebenholtz's "time-constant" approach to the present results (in view of the apparent building-up of hysteretic effect over the immediate post-task period), it may be appreciated from visual extrapolation of the curves of figure 7.10 that the decay periods would be somewhat less than those found by Ebenholtz. Wolf et al. (1985) found the hysteretic changes in TA following near fixation to be transient and to decay "within minutes".

The induced changes in TV can be similarly analysed.

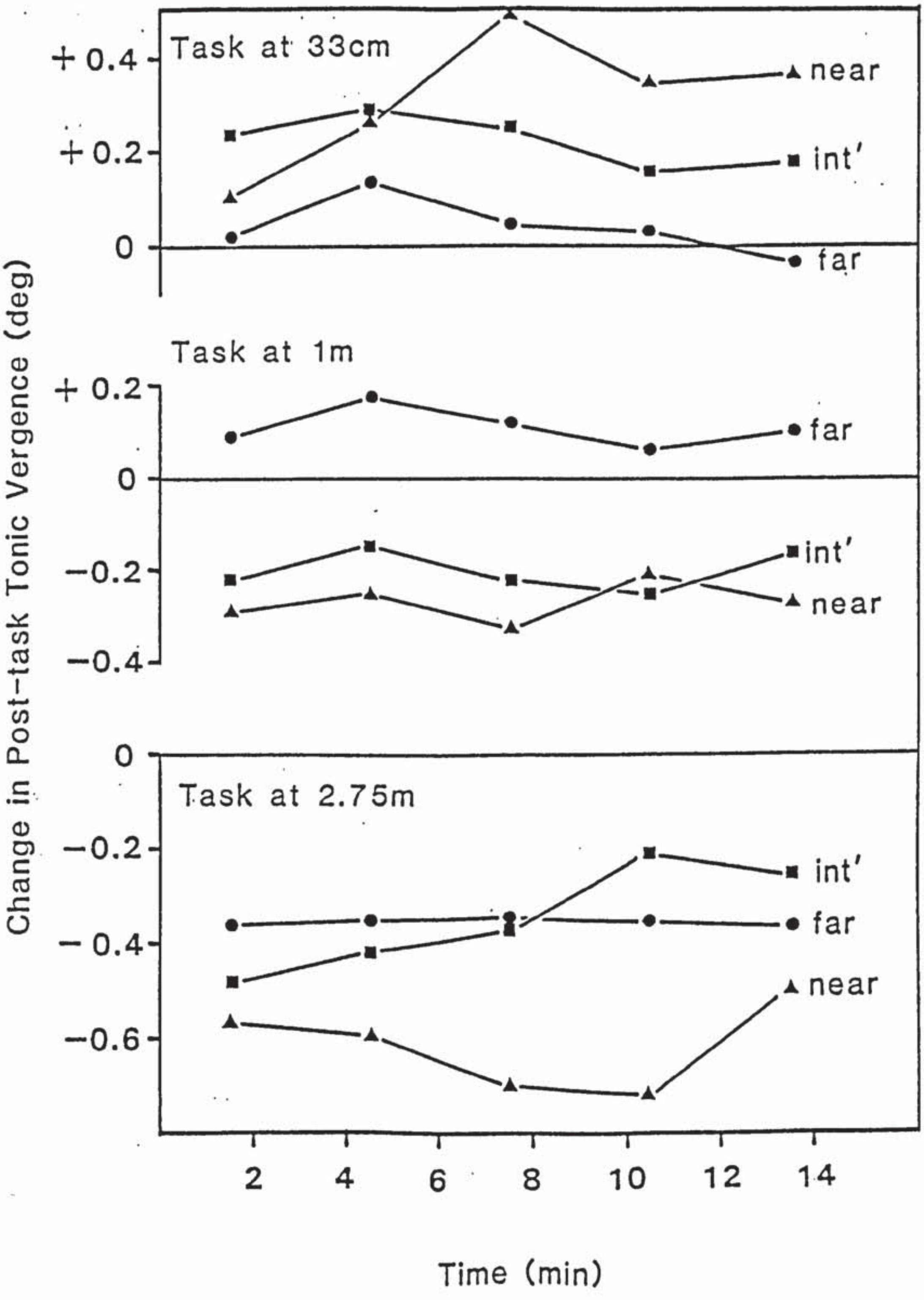


Figure 7.11 - Illustrating the time course and magnitude of the hysteretic changes in TV over the 15min post-task period. The 27 observers have been divided on the basis of their pre-task TV levels into 3 groups: "far" (represented by circles), "intermediate" (represented by squares) and "near" (represented by triangles). The 15min post-task period has been divided into 5 equal and consecutive periods: 1-3, 4-6, 7-9, 10-12 and 13-15 mins. The abcissa presents time in minutes and the ordinate gives the mean hysteretic changes in TV (deg) from its pre-task level.

The data within tables XVI.11, XVI.12 and XVI.13 of the Appendix, can be formed into five equal and consecutive time divisions: 1-3, 4-6, 7-9, 10-12 and 13-15 mins, and the 27 observers formed into the "far", the "intermediate" and the "near" TV groups (on the basis of their intial TV levels). The re-organised data can be found in table XVI.15 and is illustrated in figure 7.11.

Figure 7.11 illustrates the time-course and mean magnitude of the post-task hysteretic changes in the initial TV levels for the three observer groups following interaction at the three task locations; 275, 100 and 33cm. It will be apparent from the lower section of figure 7.11 (with the task located at 275cm) that the theoretical 0.68deg vergence stimulus has systematically induced levels of negative hysteresis in all three observer groups. It will be evident from table 7.2 that the "near" group of observers has the closest initial mean TV value (2.5deg) which, together with its high level of potential negative hysteresis, would account for the highest negative hysteresis level (mean = -0.61deg) observed amongst the three observer groups. Somewhat surprisingly, the "intermediate" and "far" groups have exhibited equal levels of mean negative hysteresis (-0.35deg). It would have been expected from the initial TV levels of table 7.2 that the "intermediate" group would have exhibited a greater level of negative hysteresis than the "far" group, although it is acknowledged that this expectation was indeed demonstrated during the first nine minutes of post-task measurement.

With the task located at 100cm (see the middle section of figure 7.11) the systematic nature of the hysteresis effects is again observed. The 1.87deg theoretical stimulus has induced the greatest negative hysteresis in the "near" observer group (mean = -0.26deg), a lesser amount in the "intermediate" group (mean =

-0.19deg) and positive hysteresis in the "far" group (mean = +0.11deg). The relative order and amount of the hysteresis effects is in accordance with the mean initial TV levels of the observer groups (see figure 7.11).

The upper graph of fig. 7.11 depicts the relative hysteretic changes in TV following interaction by the three observer groups with the task at 33cm. It would be expected from the relative order of the initial TV levels (see table 7.2) and their subsequent effect on the potential levels of hysteresis when compared to the theoretical stimulus of 5.57deg, that all observer groups would exhibit positive hysteretic changes, with the "far" group showing the highest level, followed in turn by the "intermediate" and "near" groups respectively. It will be evident from the graph, however, that this expectation was not found. As was found for TA and the "far" group at 33cm (see fig. 7.10), the "far" group have, in fact, exhibited the lowest levels of positive hysteresis (mean = +0.04deg). It is in the results of the "near" group that the highest positive hysteresis is found (mean +0.33deg), with the "intermediate" group being so at mean = +0.23deg. It would appear that vergence hysteresis for both the "far" and "intermediate" groups has been attenuated, following interaction with the task at 33cm.

As was found with the time course of the hysteresis of TA, there is insufficient data to enable the calculation of time-constants for the decay of the vergence hysteretic effects. Visual comparison of figures 7.10 and 7.11 would suggest, however, that under certain conditions (e.g. the 33cm task location) accommodative hysteresis is most likely to decay faster than vergence hysteresis. This would appear to be in contrast with the results of Wolf et al. (1985) who found that the decay rates for the shift in TA and TV averaged 10 and 3 mins, respectively. It is interesting to note that Ebenholtz (1985), however, found a decay rate for TA of 4.63 min.

It is not uncommon for Optometrists to encounter certain patients presenting with "pseudomyopic" changes, specifically induced by periods of intense close work. It is possible that TA represents the "fulcrum" or central reference point of accommodative change within the range of the accommodative far and near points; if so, a temporary "myopia" might be induced by the unacceptably excessive myopic hysteretic shifts in TA that would follow prolonged close work in the absence of an "attenuative mechanism".

The low level of significance for the relationship between the mean induced changes in TA and TV produced by interaction with the visual task at 33cm, is in order with the earlier observation that the tonic accommodative and vergence hysteresis levels at 33cm were found to be attenuated from the expected values, for those observers with the lowest initial TA and TV values. It may be speculated that some mechanism is operating, in order that the accommodative and vergence resting states, of this "far" group of observers, are protected from the potentially large and harmful, induced hysteretic changes that might otherwise be expected, following near tasks.

It was outlined earlier in the present chapter, that levels of heterophoria and vergence fusional reserves can be affected by adaptation to base-out prism or excessive levels of convergence. If it is accepted that TV represents the "fulcrum" for vergence eye movements, it may be proposed that some mechanism exists for vergence, which reduces the potentially large and harmful changes in TV (and therefore heterophoria), that might follow prolonged exposure to close visual tasks possessing adequate vergence cues.

These observations beg the question: might the observed adaptive changes (including the attenuated observations) in TA and TV be due to a common and central control mechanism and, if so, how are the changes mediated at the end organs?

In answer to this question, this study provides some evidence to suggest that there might indeed be a central basis for the attenuation of hysteresis changes in TA and TV, following prolonged near tasks, possibly via the third cranial nerve. We have already observed the reduced significance in the relationships between the mean induced changes in TA and TV, as the task is brought closer to the observer (see Figures 7.7, 7.8 and 7.9). Furthermore, Six of the nine observers in the "far" TA and TV groupings, belong to both groups: the remaining three observers had initial TA or TV levels just greater than upper limits for the "far" groups. All six of these observers (S.B., M.D., I.H-T, I.L., M.M. and M.W.) are found to exhibit attenuated levels of hysteresis in both TA and TV, following interaction with the task located at 33cm. It is acknowledged, however, that previous studies have found little correlation between the levels of induced accommodative and vergence hysteresis, following near visual tasks (Owens and Leibowitz, 1976a + 1980; Owens and Wolf, 1984; Wolf et al., 1985).

A possible explanation for the peripheral effector mechanism of the adaptive changes in TA invokes the involvement of a sympathetic innervation to the ciliary muscle (for an outline of the relevant literature see sections 1.4A, B, and C of chapter 1). In chapter 6 it was demonstrated that a sympathetic innervation to the ciliary muscle plays a significant role in the determination of the TA position, and it was concluded that this innervation is mediated by inhibitory beta receptors. The results of the studies conducted in the previous chapter confirm the action of the sympathetic nervous system (SNS) as antagonistic to that of the parasympathetic nervous system (PSNS); i.e., that stimulation of the SNS reduces the accommodative power of the eye.

The two observations reported by Tornqvist (1967): that, a) stimulation of the cervical sympathetic nerve in monkeys produces a reduction in refractive power only after a period of 10 - 40sec (which may be considered too slow to be of effective accommodative use in the normal visual environment); and b) that the maximal inhibitory effect (1.5D in monkey) is found only in the presence of high levels of background parasympathetic activity, led to the speculation (discussed in the previous chapter) that a possible role for the SNS in human accommodation is to attenuate the positive accommodative hysteresis effects that would follow prolonged near visual tasks.

It was concluded in the previous chapter that the wide distribution in the TA level was due to the inter-subject variations in parasympathetic innervation (and its effect on ciliary muscle tonus), rather than to the effect of a variation in sympathetic innervation. It may be inferred from this observation, that subjects with higher levels of parasympathetic innervation would exhibit higher levels of TA, whilst those subjects with the lower levels of parasympathetic innervation would exhibit lower levels of TA. Although modification of the inhibitory beta-receptor activity was found to induce significant shifts in the individual level of TA, it failed to produce a significant variation in the pre-modification distribution of TA. One interpretation of these findings may be that, in comparison to the effect of the PSNS, the effect of the SNS on the level of TA is relatively weak and is present in each individual at a constant level.

One might ask the question: "Is it reasonable to assume therefore, that activation of this relatively constant sympathetic innervation (by the potential stress involved in the interaction with a very near visual task) would have a greater relative effect on the TA levels of those observers with the initially lower parasympathetic tone?" Prolonged interaction with a close task would demand high levels of sustained parasympathetic innervation to the ciliary muscle: exactly the conditions that Tornqvist found would permit maximal sympathetic effect. Under these conditions of temporarily induced high parasympathetic activity, the relatively constant level of sympathetic innervation would have comparatively less inhibitory effect on the ciliary muscle tone of those observers with the higher TA levels, whilst it would have a greater inhibitory effect on the ciliary muscle tone of those observers with the lower TA levels.

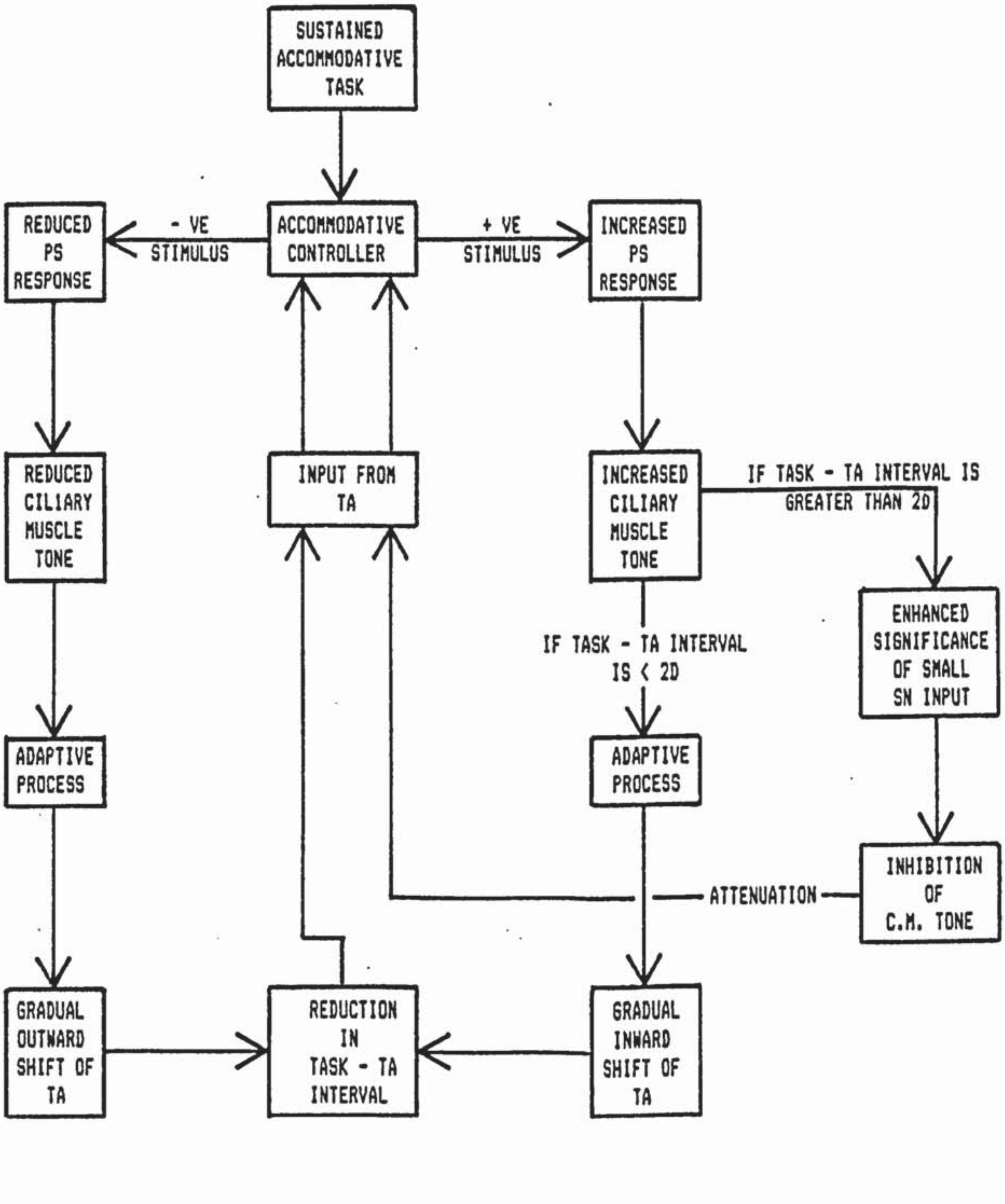
On cessation of interaction with the sustained near visual task and with the subsequent "relaxation" of accommodative effort, one would expect a reduction in the parasympathetically-induced high ciliary muscle tone. One might also expect some difference in the recovery times of the shifts in TA for those observers whose ciliary muscle tone had been reduced by the effect of sympathetic activity, when compared to the recovery times of the shifts in TA in those observers whose cilary muscle tone had been affected chiefly by parasympathetic activity. It is unfortunate, however, that due to the limited post-task measurement period utilised in the present study, this latter expectation could not be investigated.

The level of measured hysteresis, following interaction with the visual task at a relatively far distance (in this case, 275cm), is largely found to be proportional to the difference between the task location and each observer's TA position. Under this "far" condition, the effectivity of the tonic sympathetic innervation would have relatively less effect on the adaptation of TA than under the "near" viewing conditions, because of the reduced level of background parasympathetic activity. This would also appear to be case for the "intermediate" viewing condition.

A non-linearity in response to interaction with sustained visual tasks at varying levels of accommodative demand was observed in the studies of Ebenholtz (1983). He found that a mean far point target 0.98D beyond the mean pre-task TA position produced a -0.21D shift, whereas a mean near point target 5.12D closer than the mean pre-task TA position only produced a +0.34D shift in TA. Whilst not implicating the parasympathetic or sympathetic systems specifically, Ebenholtz attributed the effects to independent sub-systems governing accommodative increase and decrease.

It is thus proposed that the accommodative system utilises pre-task TA as a central reference point for monitoring the extent of adapation to a sustained visual task and uses this monitoring function to initiate beta-inhibitory sympathetic input to the ciliary muscle in order to attenuate unacceptable changes in positive hysteresis produced by sustained near visual tasks. A model has been devised in an attempt to illustrate this proposal (see fig 7.12).

Figure 7.12 - A schematic model illustrating the adaptation of the accommodative system to sustained visual tasks. The model (based on the results of the present chapter) suggests a dominant role for the parasympathetic input (PSNS) in the modification of TA for all task positions, except where the task - TA interval exceeds 2 dioptres; whereupon, the significance of the inhibitory input of the small but constant sympathetic input (SNS) is enhanced, resulting in an attenuation in the level of tonic adaptation.

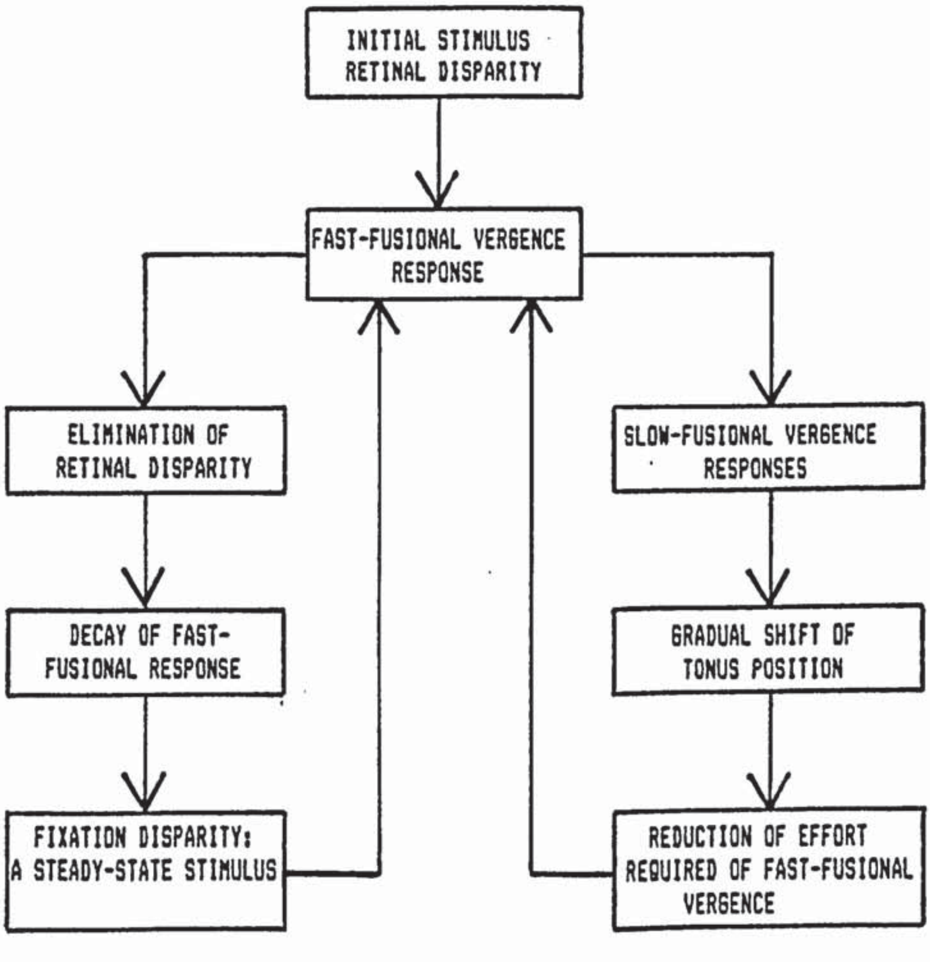


An explanation of the adaptive changes in TV may be found by consideration of the model of vergence proposed by Schor (1980), who, building on a concept first proposed by Hofmann and Bielschowsky (1900) and Ogle and Prangen (1953), accounted for the adaptive changes through the activity of two vergence sub-systems: the fast- and slow-fusional vergence systems.

The fast fusional system is capable of reducing retinal image disparity within one second (Rashbass and Westheimer, 1961a; Schor, 1979a; Henson and North, 1980) to less than 28 sec of arc (Riggs and Niehl, 1960; Hebbard, 1962), whilst the slow-fusional system is not directly affected by the stimulus but rather by the effort of the initial fast-fusional response. When the fast-acting system is forced to respond vigorously (as with prism vergence tests, prism adaptation procedures, and sustained near convergence), its output initiates gradually increasing activity in the corresponding slow-acting mechanism. The increased slow-fusional activity serves to reduce the effort required by the fast-fusional system, yet continues to influence vergence posture after the fast acting response ceases (Schor, 1979a, b).

Schor's model has direct relevance in the control of "steady-state" or tonic vergence. The necessary stimulus for both initiating and maintaining fast-fusional responses is retinal disparity. Consequently, precise binocular registration eliminates the necessary stimulus for fast fusion. The fast-fusional response would then decay (with a time constant of 10 sec - Krishnan and Stark, 1977) causing vergence to drift until retinal disparity reached a magnitude (around 28sec of arc, Riggs and Niehl, 1960) that would stimulate an increasing innervation, which would cancel or compensate for the decay of the fast-fusional response.

Figure 7.13 - Schematic representation of Schor's (1980) model of the relationship between fast- and slow-fusional vergence, fixation disparity and tonic vergence. The results of the present chapter would, however, suggest that the adaptation of TV is attenuated when the vergence-stimulus offered by the task is greater than 4 degrees per eye.



This vergence error, generally known as fixation disparity, is then maintained as a constant stimulus to prevent further decay of the fast-fusional response. Thus Schor's model characterises fixation disparity as the error signal necessary for sustained fusion, rather then an anomaly of the vergence system. Schor's model is schematically represented in figure 7.13.

It will be evident that Schor's model suggests explanations for both, the progressive deterioration of vergence accuracy under conditions of reduced stimulation or enhanced oculomotor stress, and for the adaptive changes in TV that follow prolonged fusional demands. Since fixation disparity is the error signal (or the stimulus for sustained fast-fusional vergence), the model predicts that any condition that either decreases the sensitivity to retinal disparity (e.g., low luminance) or increases the stress on the vergence control centres (e.g., anoxia or ethanol - see chapter 5) will result in larger "steady-state" errors (i.e., fixation disparity). This prediction is consistent with the view (presented in chapter 2) that any decrease in the efficiency of vergence control will produce an increased lag (or lead) in the vergence responses toward the resting or tonus position. Schor's model also implies that TV is, at least, partly determined by the slow-fusional vergence mechanism.

Strong fusional demands (such as those introduced by prisms or excessively prolonged visual tasks) require greater effort from the fast-fusional system and are therefore accompanied by faster decay of the fast-fusional response. According to Schor's model, this increased decay would have two effects: 1) an increase in the steady state fixation disparity, which prevents further decay by stimulating additional fast-fusional effort, which in turn induces, 2) increased output from the corresponding slow-fusional mechanism, which supplements and thus relieves the effort required of the fast-fusional system. In effect, modulation of the activity of the slower mechanism by unusual stress of the faster acting system serves to readjust the tonus position so that less fast-fusional effort is required to maintain fusion. Thus, a smaller error signal is required to maintain fusion, allowing the fixation disparity for steady-state stimuli to decrease. In addition, since the slow-fusional response decays slowly, the altered level of tonic innervation continues for some time after the unusual stimuli demands have ceased. Modulation of the slow-fusional mechanism can account, therefore, for the phenomenon of fixation disparity reduction during prism adaptation, and the hysteresis of the TV position following interaction with, and the subsequent adaptation to, a prolonged visual task.

In spite of the enormous number of mechanical, neural and sensory variables that determine the position of the eyes, it is remarkable that the "fusion-free" vergence posture (i.e., heterophoria) is nearly orthophoric in most normal people (Hirsch et al., 1948). This high incidence of orthophoria has been compared to the high incidence of near-emmetropic refractive states (Crone and Hardjowijoto, 1979). Where the emmetropization process co-ordinates the optical components that determine the refractive status of the individual, it has been suggested that a similar process of orthophorization might co-ordinate the neuromuscular mechanisms that control binocular alignment (Crone and Hardjowijoto, 1979). The collective phenomenon of prism-adapation and vergence-hysteresis would seem to impart the degree of flexibility necessary for the maintainance of this binocular process.

7.5 - CONCLUSION

It can be demonstrated from the results of the studies reported in this chapter that the tonic levels of both accommodation and vergence are capable of exhibiting significant levels of hysteresis following relatively short periods of interaction with a visual task at various stimulus distances. The induced changes in TA and TV were found to be significantly related to the differences between the stimulus distances and the individual tonic resting positions. If however, the difference between the nearest stimulus distance and the individual's tonic resting state exceeded 1.5 - 2.0D (for TA) and 3.5 - 4.5deg (for TV), then it was found that the magnitude of the anticipated postive hysteretic shifts were greatly reduced.

It is proposed that, in those observers with the lowest tonic resting states, some mechanism has been activated (perhaps in an attempt) to reduce the possibly harmful effects of a potentially disruptive hysteretic effect. With respect to the accommodative system, the inhibitory role of the SNS has been demonstrated in chapter 6 and it has been suggested in the present chapter that this has a functional significance with respect to near visual tasks. Whilst for the vergence system, the adaptation results are explained with reference to a model of vergence first proposed in 1900 by Hofmann and Bielschowsky, but later adapted by Schor (1980).

CHAPTER 8

GENERAL DISCUSSION AND CONCLUSIONS

8.1 - Introduction.

> "Accommodation is one of those subjects which much that is supposed to be known has yet to be discovered. The anatomy is controversial, the mechanisms theoretical, the innervation doubtful, the stimulus debated, the resting state in flux, the pharmacology uncertain, the clinical syndromes inneffectual and the treatment empirical." (Michaels, 1975).

Although the above quote is a comment on the accommodative system, much the same can be said of vergence: of particular relevance to the present thesis is the controversy concerning the state of rest assumed by each of the systems in the presence of inadequate stimulation and tonic levels of innervation.

Traditional "uni-directional" theories (see sections 1.2 and 2.2) place the respective tonic resting states at the extremes of infinity (for accommodation) and with visual axes parallel (for vergence). However, with the advent of control-theory modelling, it is proposed that the tonic resting states represent the intermediate positions of bias, from which accommodative and vergence adjustments are made (see Toates, 1972; Owens and Leibowitz, 1983). The experimental data of this thesis offers additional support to this intermediate-bias proposal.

The terms "tonic accommodation" (TA) and "tonic vergence" (TV) have been used throughout the present study in preference to others such as, "resting-position", "dark-focus", or "dark-vergence". Although the term "tonic accommodation" was first introduced by Heath (1956b), it has not been widely used. The present study has preferred to use it, because it (and tonic vergence) most appropriately represent the system as being in a state of innervational tonicity: it is now tending to be used by other authors also.

This study has shown that measurements of TA and TV provide the visual researcher with invaluable information concerning the state of accommodation and vergence, whilst free from the constraints of stimulus-dependency and thus avoids the complication of having to define the stimulus characteristics offered by the more standard optometric techniques.

All measurements of TA, TV and tonic pupil size (TP) were made using the techniques of Badal-laser optometry (see sections 3.1 to 3.1Cii), vernier-alignment (see sections 3.2 to 3.2Biii); and infra-red pupillometry (see sections 3.3 to 3.3B), respectively. Due to the methodological difficulties associated with total darkness all measurements of TA, TV and TP have been controlled via the programming of a microcomputer and an analogue-to-digital interface unit (see sections 3.4 to 3.4Aii).

8.2 - Review of experimental results.

The above techniques have been used to investigate a variety of experimental topics: e.g. the effects of menstruation on TA and TV; the longitudinal chromatic aberration of the human eye; the effects of ethanol on binocular vision; the autonomic pharmacology of the ciliary body; and the effects of sustained visual tasks on accommodation and vergence. The majority of these investigations have been published (or are in press). A brief review of the contributions made by this programme of research is provided below.

1) The studies of Section 3.5A indicate an optimal laser-optometer shutter-speed of 300msec (see also Hogan and Gilmartin, 1984b).

2) The optimal LED exposure time for the vernier alignment device was found to be 125msec (see section 3.5B).

3) The studies of Section 3.5C indicate a greater level of correction factor for the ocular longitudinal chromatic aberration of the human eye, than the +0.33D typically applied to He-Ne laser-optometer measures of TA: +0.91D for a reference wavelength of 555nm; +0.62D for a reference wavelength of 578nm; and +0.50D for a reference wavelength of 589nm (see also Gilmartin and Hogan, 1985d)

4) Measures of TA and TV were found to be remarkably stable during 1 hour periods in total darkness, although the longitudinal stability was found to diminish slightly with increases in the test-retest interval over several months (see Section 3.5D).

5) The results of the studies into the effects of the menstrual cycle on the longitudinal stability of female TA and TV, indicate that significant variation might be expected during the pre-menstrual and menstrual phases, with slightly less variation during the ovulatory phase and very little variation during the pre-ovulatory phase. At no time during the 28-day cycle was there a significant difference between the effects on TA and TV (see section 3.5E).

6) Sections 4.2B, 4.3B and 4.4B provide a reference database of normative values for TA, TV and TP (37 males, 23 females; mean age = 21.6yrs): the mean TA level (at 632.8nm) was found to be 1.58D with a s.d. of 1.11; the mean TV was 2.18 deg' with a s.d. of 1.03; whilst the mean TP was 7.02mm, with s.d. of 0.56. Section 4.6 demonstrates a significant positive relationship between concurrent measures of TA and TV ($r = 0.80$, $p < 0.001$, $N=60$), although no significance was evident for the relationships between the measures of TA and TV and those of the oculomotor

balance (see sections 4.6B, 4.6C and 4.6D).

7) The mean best-sphere refractive error (Rx) of the N=60 group was found to be -0.79D of myopia. Section 4.7C demonstrates that measures of TA taken in the refractively-uncorrected state were found to be significantly related to the best-sphere Rx ($r = 0.84$, $p < 0.001$), whilst measures of TA taken in the refractively-corrected state were not found to be significantly related to the best-sphere Rx ($r = 0.18$, $p = 0.16$).

8) The results of Chapter 5 demonstrate that the ethanol-induced changes in oculomotor function (see Hogan and Linfield, 1983) represent a shift in vergence towards its tonic resting state, as measured in total darkness (see section 5.3 and Hogan and Gilmartin, 1985a).

9) A 50-microlitre topical instillation of the non-selective adrenoceptor antagonist, Timolol Maleate (0.5%), was found to induce a 0.82D mean myopic shift in TA (see section 6.2). The induced change in TA was found to be significantly related to the pre-drug level of TA (see fig 6.2). Intra-ocular pressure (IOP) was significantly reduced, although there was no relationship between the changes in TA and IOP, and no effect was found on TV, TP or Rx (see Gilmartin et al. 1984; and Gilmartin and Hogan 1984).

10) A 50-microlitre topical instillation of the non-selective adrenoceptor agonist, Isoprenaline Sulphate (3.0%), produced a significant 0.55D mean hyperopic shift in TA (see section 6.3). There was no significance in the effects on TV, TP, IOP or Rx. The results of the Timolol and Isoprenaline studies have demonstrated the presence of inhibitory beta-adrenoceptors within the ciliary muscle (see Gilmartin and Hogan, 1985a).

11) A 50-microlitre topical instillation of the muscarinic receptor antagonist, Tropicamide (0.5%), was found to induce a

1.25D mean hyperopic shift in TA (see section 6.4). The relationship between the induced changes in TA and the pre-drug level of TA was highly significant (see fig 6.8). As expected, Tropicamide was found to significantly increase TP and to decrease the amplitude of accommodation. There were no significant concurrent effects on TV (see also Gilmartin and Hogan, 1985b).

12) Tropicamide was found to significantly reduce the pre- to post-drug variation in TA, whilst neither Timolol nor Isoprenaline had any significant effects on this variation. Hence the inter-observer variation in TA is due to the parasympathetic input, rather than to the sympathetic input to the ciliary muscle. (see Gilmartin and Hogan, 1985c).

13) 15mins sustained viewing of a visual task placed at three stimulus levels, was found to induce hysteretic changes in the TA and TV levels of 27 observers, that were significantly and linearly related to the dioptric difference between the stimulus distance and the individual pre-task tonic resting state (see section 7.3). This relationship was found to break-down during the near visual task for those observers with the lowest tonic resting states, in whom the TA-to-task difference exceeded 1.5 - 2.0D (for accommodation) and 3.5 - 4.5deg (for vergence): in these situations, the magnitude of the anticipated positive hysteretic effects was found to be greatly reduced (see figs. 7.3 and 7.6) - see also Hogan and Gilmartin (1985b).

8.3 - Discussion.

As it's title suggests, the present thesis has considered various aspects of tonic accommodation and vergence: these have encompassed four main areas: a) the measurement of TA and TV, and other oculomotor and refractive parameters, to provide a profile of normative, baseline data; b) an investigation into the relationship between TV, oculomotor stress and binocular vision; c) an investigation into the autonomic pharmacology of the ciliary muscle and its role in the determination of TA; and d) the utilization of measures of TA and TV to establish the effect of sustained visual tasks on accommodation and vergence.

8.3A - Baseline, normative data.

The normative values obtained in Chapter 4 compare reasonably well with those of previous studies: the slight differences in the mean values obtained may be accounted for by various weaknesses of previous studies such as; weak methodological design and control (e.g. difference in shutter speeds), the narrow range of values encountered, the poor refractive control and the relatively low numbers of observers used in some of the earlier studies.

The present study demonstrates that successive measures of TA and TV show a significant positive correlation; although few previous studies have reported similar findings. This relationship would most probably be predicted by the clinician on the basis of the synkinesis that exists between accommodation and vergence under normal visual conditions. Measures of TA, TV and the correlation between TA and TV were found, however, not to be related to the individual AC/A ratio.

The AC/A ratio is a highly stimulus dependent metric and may be considered as, merely reflecting the ratio between the stimulus-related accommodative-vergence response, and the stimulus-related accommodative response, to the stimulus-characteristics of the particular measurement technique selected. Furthermore, models of the accommodation-vergence interaction (such as the "interactive dual-feedback" of Semmlow and Hung, 1983) illustrate that TA and TV represent the bias or tonic levels of innervation to the accommodative and vergence systems, in the absence of sensory stimulus. It may be concluded, that in the tonic state and therefore, in the absence of any innervational interaction between TA and TV, the relationship found is merely evidence of the effect of concomitant accommodative and vergence activity on ciliary and extraocular muscle tone.

It is interesting to speculate on what would happen to the relationship between TA and TV if the visual system was deprived of any stimulation for a great length of time. If the relationship beween TA and TV was a product of the interaction between accommodative and vergence under normal visual conditions, it would be expected to decay with the increase in time that the stimulus for accommodation and vergence was removed (e.g. in total darkness). The effect of prolonged stimulus-free environments might prove an avenue for further research.

The observation that measures of TA, from the refractively-uncorrected eye, are highly correlated to the far-point indicates that such measures of TA may be utilised to predict spherical refractive error and offers support for those studies (e.g. Mohindra, 1977a; Braddick et al., 1981; Bullimore et al., 1986) that have shown that techniques such as photo-refraction and near retinoscopy may be used to measure TA.

The present study was unable to demonstrate a significant relationship between measures of TA, taken from the refractively-corrected eye, and the visual far-point. It has been proposed (e.g. Van Alphen , 1961) that ametropia might be accounted for, in part at least, by individual variations in the inherent tonus of the ciliary muscle: a high tone in hyperopia and a low tone in myopia. Certain previous studies (e.g. Maddock et al., 1981) have reported weak relationships in favour of this proposal, and theoretical discussions (e.g. Charman, 1982) have implicated an autonomic basis for this tonal variation: it has been suggested that a strong sympathetic / weak parasympathetic innervation should cause hyperopia, whilst a weak sympathetic / strong parasympathetic should induce myopia. The empirical evidence to date is contradictory, indeed, the present study found a weak trend for myopes to have a higher TA than hyperopes. There is a need for a carefully controlled study into this aspect and several experimental variables warrant further attention: the dioptric class interval used to define refractive groups; the influence of heredity; the age of onset of myopia; and the effects of use and non-use of the required refractive correction.

8.3B - Tonic vergence and its relationship to oculomotor stress.

Ethanol has been shown, even in small dosages, to disrupt oculomotor co-ordination, resulting in esophoric changes in the distance heterophoria, yet exophoric changes in the near heterophoria. Previous workers have been at a loss to explain these effects (e.g. Cohen and Alpern, 1969); although Hogan and Linfield (1983) proposed that the normal cortical control on vergence is released by ethanol, producing a tendency for the visual axes to align at an intermediate resting position. The results of the present study have, indeed supported this proposal, by demonstrating a reduction in the range of vergence about its tonic resting state (TV). The ethanol-induced distance esophoric and near exophoric changes in heterophoria are analogous to the enhanced lead and lag of the accommodative response that occurs with impoverished stimuli.

Although no relationship was found between TV and heterophoria, the results clearly demonstrate a linear relationship between the extent of the induced change in heterophoria and the initial tonic vergence level. This would support the proposal that TV represents the bias position of the vergence system and determines the extent of vergence eye movements. The results offer unique evidence for a common basis to the effects on vergence of degraded vergence stimulation (e.g. darkness) and oculomotor stress (e.g. ethanol). It will be interesting to repeat the study with alternative oculomotor stressor agents (such as barbiturates, marijuana, and minor and major trtranquillisers).

8.3C - The relationship between tonic accommodation and autonomic innervation of the ciliary muscle.

The stimulus-free nature of tonic accommodation has been utilised to advantage in the studies of Chapter 6, and has proved to be a particularly appropriate method of investigating the autonomic pharmacology of the ciliary muscle. The topically applied autonomic adrenoceptor agents used in the present studies were found to significantly modify the tonic resting state, in the absence of any concurrent effects on the distance refraction or amplitude of accommodation.

It has been proposed (e.g. Toates, 1972) that the intermediate accommodative resting state results from a balance between tonic levels of the sympathetic and parasympathetic input to the ciliary muscle: sympathetic acting to reduce ocular power and parasympathetic acting to increase ocular power. The results of the present study have demonstrated that the non-selective beta-adrenoceptor antagonist, Timolol, shifted TA in a myopic direction whilst the non-selective beta-adrenoceptor agonist, Isoprenaline, induced a hyperopic shift in TA. The drug-induced changes were found, in each case, to have had little effect on the pre- to post-drug variance of TA which would suggest that there is indeed a relatively small, but consistent, sympathetic input to the ciliary muscle, mediated via inhibitory beta-adrenoceptors and, furthermore, that the variance in the distribution of TA is due instead to variation in parasympathetic tone. The results of the Tropicamide study confirm this latter suggestion.

The function of this relatively small sympathetic input to human accommodation remains open to speculation. Much of the evidence (e.g. Tornqvist, 1966; 1967; Hurwitz, et al., 1972a) indicates that the temporal characteristics of the sympathetic innervation are too slow too provide an effective and dynamic opponent to the comparatively faster and more dominant parasympathetic input, and it has also been shown that the inhibitory effects of sympathetic stimulation are greater against a background of high parasympathetic activity. This evidence, together with the lack of a drug-effect on standard optometric refractive measures, has led to the speculation that the inhibitory sympathetic input might serve to attenuate the potentially harmful hysteresis effects on accommodation found to follow sustained fixation at close working distances (see Ebenholtz, 1983; and Chapter 7).

It is important to note that TV was unaffected by the induced drug-effects on TA. This supports the earlier proposal that there is no innervational interaction between accommodation and vergence in the tonic state.

8.3D - The adaptation of tonic accommodation and tonic vergence to sustained visual tasks.

The studies of Chapter 7 demonstrate that the tonic levels of both accommodation and vergence are capable of exhibiting significant levels of adaptation and hysteresis, in response to relatively short, but sustained periods of interaction with a visual task at various stimulus distances. The induced changes in TA and TV are found to be significantly related to the differences between the stimulus distances and an individual's tonic resting state.

The relationship between task position and the tonic state is greatest for the relatively distant stimuli, becoming weaker as the stimulus approaches the observer: especially where the difference between the stimulus position and the individual's pre-task tonic resting state exceeds 1.5 - 2.0D (for TA) and 3.5 - 4.5deg (for TV). It is in these latter instances, where the highest potential levels of positive hysteresis are theoretically possible, that the lowest levels of hysteresis are empirically found.

The results of the present study would suggest that accommodative and vergence systems utilize the pre-task tonic states as central reference points for monitoring the effects of post-task hysteresis. It is proposed that, in those observers with the lowest pre-task tonic positions, some inhibitory mechanism has been activated in an attempt to attenuate the potentially harmful and disruptive effects of positive hysteresis.

As suggested earlier for accommodation, the hypothesis is that beta-inhibitory input to the ciliary muscle might function to reduce the potential increase in tonus following sustained near visual tasks. The studies of Tornqvist (1966; 1967) and Hurwitz et al. (1972a) have shown that sympathetic stimulation produces its greatest inhibitory effects against higher levels of background parasympathetic activity (e.g. between 2.0 - 4.0D): similar to the near task utilised in the present study. A schematic model illustrating the dependence of accommodative adaptation on the level of pre-task TA may be found in Figure 7.12.

The demonstration of a similar attenuation of "near task/low TV" hysteretic effects for vergence would suggest the existence of an analagous mechanism to that of accommodation. It is speculated that its role would be to protect the vergence system and its central reference point (TV), from too great an excursion from a "normal zone" of adaptation. The differing temporal adaptive characteristics of the fast- and slow-fusional vergence responses (Schor, 1980) may function in this role (see figure 7.13).

In spite of the many sensory, neural and mechanical variables that determine ocular focus and poise, it is remarkable to note the high incidence of emmetropia in the typical refractive state (Crone and Hardjowijoto, 1979) and orthophoria in the average so-called "fusion-free" vergence posture or heterophoria (Hirsch et al., 1948). Where the emmetropization process co-ordinates the optical components that determine the individual refractive state, it has been suggested that the **analogous** process of orthophorization might coordinate the neuromuscular mechanisms that control binocular alignment (Crone and Hardjowijoto, 1979). The adaptative capacity of the central reference points TA and TV, and their hypothesized attenuative mechanisms would provide the degree of flexibility necessary for the maintenance of the accommodative and binocular processes.

It is understandable that some degree of smooth muscle tone is retained after a sustained period of fixation and that this accommodative hysteresis will become evident in subsequent measures of TA. It is possible that, if the sustained period was a regular occurence, the tonus of the ciliary muscle might increase sufficiently to induce symptoms, such as blurred distance vision; it is not uncommon for Optometrists to encounter patients presenting with symptoms of "late-onset myopia", presumably induced by the proximal nature of their occupations (e.g. VDU-operators).

Such patients are not always, however, affected to the same degree; which would suggest the involvement of some individually-determined factor or factors.

The present study has demonstrated the dependence of the magnitude of hysteresis on the level of the tonic resting state. The presence of an effective attenuative mechanism should protect those individuals with the lowest tonic resting states, whilst viewing at close working distances. One might speculate, that those individuals with task-to-TA differences of slightly less than the attenuative-mechanism threshold of 1.5 - 2.0D and who participate in sustained close work, would be most at risk: these were the conditions that induced the greatest levels of hysteresis. A long-term study into the effects of sustained visual tasks on the accommodative mechanism and ametropia is clearly required. It will be interesting to investigate the effects of beta-adrenoceptor antagonists on the level of task-induced hysteresis.

8.4 - Concluding remarks.

Although the reliance on subjective methodology is a possible criticism of this study, the techniques utilised have been shown to be ideally suited to the requirements of research: they have been relatively simple and cheap to build and operate; easy to comprehend for the observer, they only require binary decisions; they do not offer cues of size or relative-position to the observer; and have readily lent themselves to the application of psychophysics. Yet, despite these advantages, the technique of laser-optometry would most likely be replaced by a fast objective technique, such as infra-red (see Bullimore et al., 1986) and the vernier-alignment device would be replaced by an objective oculometer.

Apart from the N=60 normative-data study and the hysteresis study (N=27), the sample size in the remaining studies was relatively small (N=10 or less). The final study of the research programme demonstrated that the duration and dioptric demands of tasks carried out prior to the measurement of TA and TV, could systematically modify the values of TA and TV found. Subsequent studies should therefore impose some level of control over the type of visual task that subjects engage in before the commencement of the experimental session.

Further research is required to elucidate how TA and TV relate to normal and abnormal refractive and oculomotor control. What would happen to TA and TV if the visual system was deprived of information over a relatively long period of time? Would TA recede towards infinity and would TV become divergent? If so, it would add support to the hypothesis that TA and TV represent an average of all the ciliary and extraocular muscle activity over some prior period of time.

The results of this study have demonstrated similar attenuative mechanisms for both accommodation and vergence. Further research is required to establish the nature of these mechanisms: e.g. the attenuative mechanism of the vergence system demands further investigation. If the inhibitory beta-sympathetic input to the ciliary muscle is responsible for the attenuation of accommodative hysteresis, then beta-adrenoceptor antagonists would be expected to diminish its effect. This then leads to the interesting concept of the control of ametropia by pharmacological agents. The techniques utilised in the present study could be used to further define the nature of the inhibitory beta-adrenoceptors via the use of specific beta-1 and beta-2 beta-adrenoceptor antagonists.

Additional areas for investigation would be the assessment of TA and task induced hysteresis in those individuals taking systemic sympathetic effector agents (e.g. propranolol, for angina). It would also be interesting to investigate the possibility of relative differences between the levels of hysteresis exhibited by sufferers of Horner's Syndrome and more normal observers. A further area for investigation would be an attempt to reduce the level of accommodative and vergence hysteresis, via the provision of an appropriately-powered spectacle correction: e.g plus-lenses for near-task TA-hysteresis and base-in prisms for near-task TV hysteresis. It is most likely that, measures of TA and TV will find much use in the assessment of VDU ergonomics and workstation analysis and in the optimal selection of operatives.

This thesis has measured the tonic resting states of accommodation and vergence and applied them to more than one of the areas mentioned in Michael's quote at the beginning of the section. It was appreciated that the content of the quote could easily describe vergence and it is to be hoped that this work will have gone some way towards dispelling some of the uncertainty, with respect to the systems of accommodation and vergence, that was evident from Michael's comments.

APPENDIX I

THE BEAM EXPANDER/COLLIMATOR UNIT

In the typical Badal-laser optometer (e.g. Hennessy and Leibowitz, 1970), the output of the laser is diverged via a low-powered, negative spherical lens. This arrangement possesses a number of disadvantages: e.g., that the field size and luminance of the reflected laser-speckle patch tends to change with the alteration in drum distance. The beam expander/collimator (B.E.C.) unit (Fig. I.1) is designed to overcome these problems, by providing a collimated beam patch of constant width (25mm) and luminance ($6cd/m^2$).

Essentially, beam expansion is provided by a x32 magnification microscope objective and collimation using a +16D ophthalmic lens. Both lenses are enclosed at opposite ends of an expandable tube; the length of which is adjusted such that the negative vergence of the laser light (emmitted from the microscope objective) is neutralised by the +16DS lens to provide parallel or collimated laser light. The expansion end of the B.E.C. unit has been designed to enclose the emmision exit of the laser, thus providing an almost light tight joint between the laser and the unit. The collimation pole of the unit abuts against the electronic shutter, in such a manner that when the shutter is closed, little or no laser light escapes into the room. This was a further problem in the "single lens" design, incorporating unenclosed lenses, because of the illumination of the (supposedly) dark room by ambient laser light.

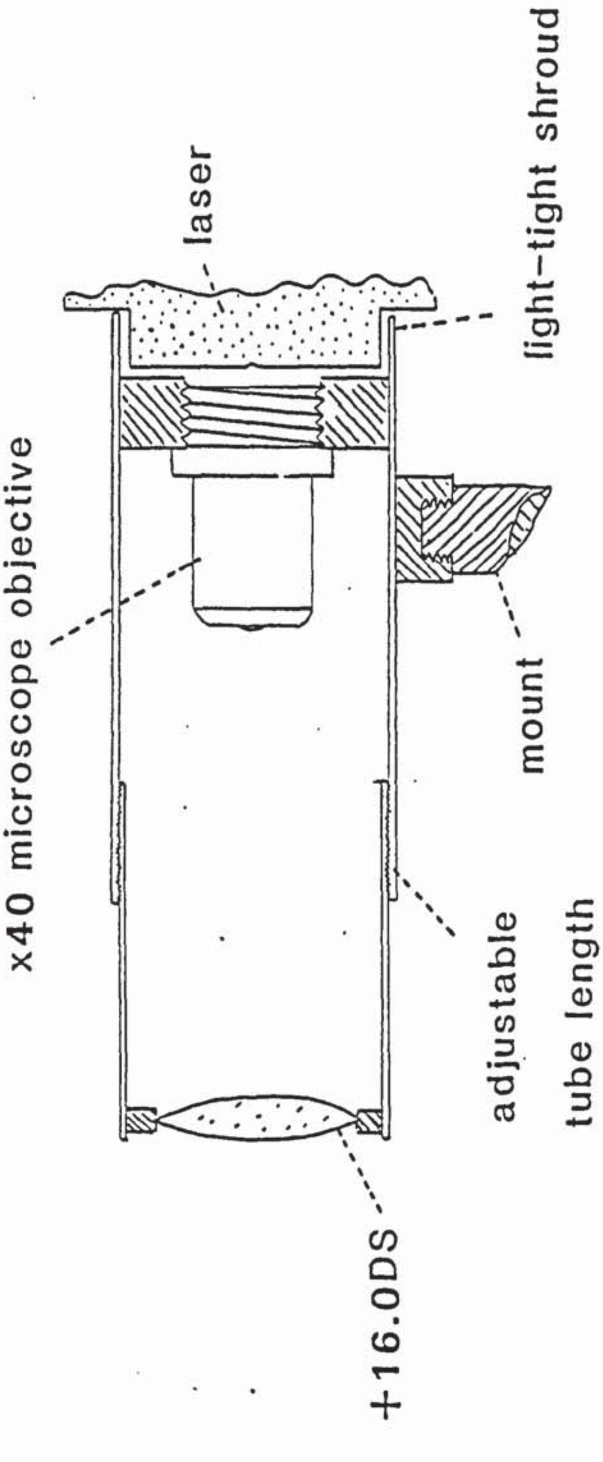


FIGURE I.1 - The design of the beam expander/collimator unit (B.E.C unit)

APPENDIX II

METHODOLOGICAL CONSIDERATION OF THE LASER DRUM COATING

Rigden and Gordon (1962) noted that the quality of laser speckle depended upon the characteristics or properties of the surface from which the laser light was reflected. Many types of surface have since been utilised in attempts to optimize the quality of the laser-speckle, including: a brass drum (Knoll, 1966); a brass drum covered with white bond paper (Baldwin and Stover, 1968); a drum covered with aluminized contact paper (Long, 1974); an aluminium can sprayed with gold gloss paint (Hennessy and Leibowitz, 1971); and an aluminium can sprayed with silver gloss paint (Whitefoot, 1977).

The present study involves a personal comparison of the effect of seven different types of coating on the subjective quality of laser speckle. A 6.6cm diameter 'soft-drinks' seamless can was used for all coatings. The results are discussed in Table II.1.

Table II.1 - The effect of the drum surface on the quality of laser-speckle.

SURFACE	RESULTANT SPECKLE CHARACTERISTICS
1) White emulsion paint	few speckles produced (surface too smooth)
2) Silver paint	as for 1)
3) as 1), sprayed silver	as for 1) and 2)
4) White bond paper	numerous dull speckles
5) as 4), sprayed black	as for 4)
6) as 4), sprayed silver	bright clear conspicuous speckles
7) as 4), sprayed white	as for 6), although not as clear

The optimal surface was judged to be 6), i.e. white bond paper sprayed with silver gloss paint.

APPENDIX III

A CONSIDERATION OF SPLIT-FIELD SPECKLE MOTION REVERSAL

An attempt was made early on in the study, to enhance both the perception of speckle motion either side of the end-point, and the absence of speckle motion at the end-point, via the incorporation of a 90:45:45 degree prism into the optical system of the optometer, such that the lower half of the reflected laser patch would be seen by the observer through the prism.

This arrangement effectively divides the speckle patch into two halves, and reverses the direction of speckle motion within that part of the patch influenced by the prism. Either side of the end-point, the speckles would be seen to emanate from or be drawn to, the dividing midline, and the end-point would be conspicuous by its relative absence of speckle motion.

In practice, considerable difficulty was experienced in obtaining a suitable configuration and prism size, necessary to achieve the required horizontal and vertical field of view. Most difficulty was, however, experienced in the discrimination of the particular direction of speckle motion during the 300msec exposure duration utilised in this study. It is considered that this exposure duration does not provide sufficient time to compare the motionof the two field-halves. It is interest to note that Ukai et al. (1978) who used a similar device to split their speckle field in the vertical direction, used a shutter speed of 400ms.

The split-field idea was subsequently abandoned in favour of the more conventional arrangement, used in conjunction with the shorter shutter duration (300msec).

APPENDIX IV

MICROPOTENTIOMETER CALIBRATION AND LINEARITY

The relative positions of the laser drum and the VAD unit were monitored in total darkness via the output of two 5 volt micropotentiometers. It was essential that the linearity of the output from the micropots' was established. This was checked in-situ within the laser optometer and the VAD unit on the rack system. Both systems were first calibrated.

IV.1 - Calibration of the laser optometer.

According to the Badal principle (see section 3.1B ii), for the drum surface to be seen at optical infinity it would need to be placed at the anterior focal point of the lens. For a lens of +5.00D this would be 20cm from the lens (assuming a thin lens calculation). However, it is known that the plane of stationarity of a cylindrical drum is not at its surface, but approximates to a distance of half the drum-radius in from its surface (see section 3.1A iii). As the drum used in the present study has a diameter of 6.6cm and to account for the plane of stationarity, the laser optometer was calibrated for optical infinity with the drum surface 18.35cm from the Badal lens. For a +5.00 Badal lens, each centimetre that the drum surface is moved towards the lens is equivalent to an optical change of 0.25D; thus for a subject whose TA was +1.00D (i.e. whose ocular power had increased myopically by 1.00D) the drum would need to be moved towards the lens by 4cm.

A cog was attached to the spindle of the micropot and was driven by the same rack that moved the drum, in response to rotation of the pinion drive (see section 3.1Ci). The rack, therefore, moved the drum and the micropot'-cog by exactly the same amount. The analogue voltage output from the micropot was converted into digital information and fed into an Apple IIe microcomputer via the programming of a PCI 6000 interface unit. The resultant value of the micropot' output voltage is utilised as the term R(1) in the computer program TVA 10 (for details see Appendix VII), and used to compute a value for TA (see below). With the drum was set 18.35cm and 2.35cm from the Badal lens (corresponding to an accommodative focus of zero and +4.00D), the R(1) values are 300 and 967 respectively. TA may be calculated from the R(1) value for a particular drum position as given by the function:

TA in dioptres = ((R(1) - 300) / 667) * 4

IV.2 - Calibration of the vernier alignment device (VAD).

In the laser optometer, the drum is moved by rotation of the pinion-drive over the sliding rack, whilst in the vergence wing of the experiment the VAD unit and it's micropot' are moved over a fixed rack. Thus the micropot' cog was adjusted by the same distance travelled by the VAD unit. The contact point of the micropot cog was 8cm in front of the plane of the nonius lines, therefore with the lines at 100cm the cog will be at 92cm. The VAD position is calculated from the micropot output by the function R(2) in a second portion of the TVA 10 program:

Nonius line position in centimetres = (R(2) * 0.1907) + 8

When the contact point of the micropot' cog is placed at 100cm, the R(2) value = 525. Therefore, when the micropot is placed at 100cm the actual nonius line position = (525 * 0.1907) + 8, which equals 108cm.

IV.3 - Linearity of the micropotentiometer output.

The linearity of the micropot' output was tested in-situ, by a comparison of the voltage output at the micropot terminals to the computed data provided by the computer, for various positions of the drum and VAD unit (see Table IV.1.

Table IV.1 - An assessment of the linearity of the output of the micropot's used in the laser optometer and the NAD.

LASER DRUM POSITION		NAD UNIT POSITION	
Micropot output (v)	Program data (cm)	Micropot output (v)	program data (DS)
0	205.76	0	-1.82
0.5	187.86	0.5	-1.23
1.0	169.55	1.0	-0.61
1.5	149.70	1.5	+0.02
2.0	128.34	2.0	+0.59
2.5	110.04	2.5	+1.22
3.0	89.85	3.0	+1.84
3.5	69.98	3.5	+2.46
4.0	50.53	4.0	+3.09
4.5	30.69	4.5	+3.66

APPENDIX V

TV CALC 10 - COMPUTER PROGRAM FOR THE CALCULATION OF TV

The program TV CALC 10 (see Fig. V.1) was written in Basic for the Apple IIe microcomputer. It calculates tonic vergence, both in degrees and in centimetres from the keyed-in data of the the distance between the VAD unit and the observer, the separation of the nonius lines (when apparently aligned), the individual inter-pupillary distance, and the full astigmatic refractive correction. Account is taken of any induced prismatic effect on the nonius lines due to convergent visual axes looking through non-optical-centre portions of the corrective lenses. The results are continuously displayed on the computer monitor.

FIGURE V.1 - Computer Program TV CALC 10

```
50   PRINT: REM Written by R. E. Hogan.
60   HOME: REM clear screen.
100  PRINT "INPUT DISTANCE IPD (MM)"
110  INPUT P : REM let IPD = P.
115  HOME
120  PRINT "INPUT TOP VERNIER-LINE READING"
122  PRINT: REM leave 1 line space on screen.
124  INPUT A: REM let top vernier line = A
125  PRINT "INPUT BOTTOM NONIUS LINE READING"
127  PRINT
130  INPUT B: REM let bottom vernier line = B
132  C = A + B
135  N = 52.5 - C: REM let the separation of the lines = N
160  Q = (P - N) / 2: REM let the deviation of one eye from the primary position = Q: +ve
= convergence, -ve  = divergence.
165  HOME
200  PRINT "INPUT BVD (MM)"
210  INPUT V: REM let BVD = V
215  HOME
220  PRINT "INPUT VERGENCE UNIT POSITION (D)": REM VAD unit placed at position of TA.
230  INPUT Z: let distance of VAD unit from observer = Z
234  A = ((1 / Z) * 100) * 10: REM convert dioptres to mm.
240  C = ((V * Q) / (A - V)) / 10: REM let horizontal difference between O.C.'s and the
image point (in lens plane) = C
245  HOME
246  PRINT "ANY SPECTACLE RX WORN ?, N = 1, Y = 2"
```

```
247  INPUT I: IF I = 1 GOTO 1015: REM if no Rx correction, no prismatic error.
248  IF I = 2 GOTO 250 : REM if Rx corrected goto prismatic error calculation.
250  PRINT "INPUT SPHERE OF RIGHT RX (D)"
252  INPUT S
255  PRINT "INPUT CYL' OF RIGHT RX (D)"
257  INPUT L
260  PRINT "INPUT CYL' AXIS OF RIGHT EYE"
262  INPUT I
365  GOSUB 600: REM goto prismatic error calculation subroutine.
367  X = (J * A) / 100: REM let prismatic error due to (R) Rx = X
400  PRINT "INPUT SPHERE OF LEFT RX (D)"
410  INPUT S
420  PRINT "INPUT CYL' OF LEFT RX (D)"
430  INPUT L
440  PRINT "INPUT CYL' AXIS OF LEFT RX"
450  INPUT I
460  GOSUB 600
480  G = (J * A) / 100: REM let prismatic error due to (L) Rx = G
500  PRINT X
510  PRINT G
520  GOTO 1000: REM goto section dealing with the application of the correction factors to
the calculation of TV.
600  W = ((6.2832) * (I)) / 360: REM converts degrees to radians.
620  K = (SIN (W)) * (SIN (W)) * (L): REM let horizontal power due to cyl' = K
640  F = S + K: REM let the sphere plus horizontal element of cyl' = F
660  J = C * F: REM let prismatic effect of Rx on image position = J
750  RETURN: REM go back to line after last GOSUB command
1000 B = (P / 2) * 0.1: REM let half IPD (in mm) = B
1010 D = N - (X) - (G): REM let the prismatic-error corrected vernier line separation (in
cm) = D
1020 O = (D / 2) * 0.1: REM let half the adjusted vernier line separation (in mm) = O
1025 Z = (1 / Z) * 100: REM convert VAD unit position from dioptres to cm.
1030 U = (Z * B) / (B - O): REM similar triangle calculation.
1050 PRINT "VERGENCE POSITION IS "
1060 PRINT
1070 PRINT U
1080 PRINT
1090 PRINT "CENTIMETRES"
2000 E = 100 / U: REM convert TV to metre angles.
2010 R = E * (P / 20): REM convert TV to prism dioptres.
2018 Y = R * 0.1
2020 M = ATN (Y): REM convert TV to radians.
2025 T = M * (360 / 6.2832): REM convert TV to degrees.
2030 PRINT "VERGENCE IN DEGREES IS ": PRINT T
2032 PRINT
2034 PRINT
2036 PRINT
2038 PRINT
2040 GOTO 100: REM ? next calculation.
```

APPENDIX VI

ALTERNATIVE TECHNIQUES OF METHODOLOGICAL CONTROL

VI.1 - Simple timing.

The first attempt at methodological control required the experimenter to select one of two mini-switches (one for TA assessment and the other for TV). Each switch completed a 5volt circuit: the TA switch opened the laser-optometer shutter for a period of time controlled via the adjustment of a "trim-pot"; the TV switch energized the LED's of the VAD unit for a period of time, again controlled by "trim-pot" adjustment. The timing was checked by a Universal Counter-timer (type-PM 6604).

Although the relative positions of the laser-drum and vergence unit had to be checked (using a pen-torch, after asking the observer to close their eyes), the major problem was the high experimenter work-load (and consequently error rate) involved in the temporal management of such a system.

VI.2 - The event-sequencing unit (ESU).

The ESU was designed to overcome the problems encountered by the simple-timing arrangement yet also, to coordinate the measurement of TA, TV and pupil size under conditions of total darkness. As with the simple-timing, the exposure duration of the shutter and LED unit were controlled by "trim-pot" adjustment, however, the ESU also controlled the time-sequence with which each event occured. After the observer had pressed a footswitch, a bleep (generated by the ESU) was heard by both experimenter and observer (via the head-phones), thus providing a positive feedback signal. After a period of 8 seconds, a second bleep would be heard, warning the observer that, after a randomly generated time period of 1-5 seconds, the shutter would open or the LEDs would flash, depending on which mode the ESU had been selected to run. After the flash of laser or LED, the ESU would wait during the observer's response phase until the footswitch was pressed again before resuming a further cycle. The activation of any combination of shutter, LED or infra-red camera could be selected via a thumb-wheel on the front of the ESU. This unit enabled the experimenter to concentrate on reacting to the responses of the observer, rather than have to additionally initiate and recycle the experimental phase.

The ESU took a year to produce, and when it did arrive it was often found to be less than reliable. During this time, it was decided to explore the possibilities of control of the methodology by microcomputer. This latter system (of microcomputer control) was originally designed as a "back-up" for the ESU, yet it has since proved to be infinitely more flexible, reliable and convenient than the ESU and has been used in all the experiments of this thesis.

APPENDIX VII

METHODOLOGICAL CONTROL PROGRAM, TVA 10

The program TVA 10 (see Fig. VII.1) was written in Basic to provide the methodological control of the apparatus by Apple IIe microcomputer. The Apple IIe does not have an internal clock, so use is made of the "pause-loop" to create calibrated time sequences. The validity of such a technique may be checked by reference to Appendix VIII.

A brief explanation of TVA 10 is now provided, and additional assistance is given by the various "REM" statements at pertinent locations throughout the program.

Lines 8 to 50 provide the title sequence. Lines 100, 153, 197 and 3000 use the subroutine at lines 1000 to 1590 to sample inputs 1 and 2 (on the interface unit) of the micropot' data concerning the position of the laser optometer drum and VAD. Lines 110 to 150 sample input 4, from the left hand switch of the control unit (see section 3.4Ai); if the voltage is "high" (i.e. 5v) then TA has been selected, if the voltage is "low" (i.e. zero volts) then TA has not been selected. Lines 155 to 195 sample the input from the middle switch. Lines 320 to 330 represent the logic phase, deciding which switch(es) have been selected. Lines 400 to 440 represent that part of the program used to activate the shutter and the infra-red camera (if switched on), in the measurement of TA and pupil diameter. Lines 450 to 490 represent that part of the program used to activate the LEDs of the NAD and the camera (if switched on), for the measurement of TV and pupil diameter. Lines 500 to 545 represent that part of the program used to activate the shutter, LEDs and camera simultaneously. Lines 2000 to 2210 represent that part of the program that activates the warning bleep signal in response to the commands "GOSUB 2000" at lines 400, 450, 500 and 3120. Lines 3000 to 3130 represent that part of the main program that recognizes that the footswitch has been pressed to initiate the (next) cycle, in response to the command "GOSUB 3000" at lines 435, 485 and 535.

FIGURE VII.1 - The computer program TVA 10.

```
5    PRINT: REM Written by R.E. Hogan
8    HOME: REM clears screen.
10   PRINT "TA AND TV MEASUREMENT"
20   PRINT: REM leave one line space
30   PRINT "CONTROL PROGRAM"
40   FOR PAUSE = 1 TO 3500: NEXT PAUSE: REM initiate a 5sec pause-loop.
50   HOME
100  GOSUB 1000: REM goto micropot' sampling routine.
110  PR£ 4: PRINT CHR$ (41);"<G0, I4>";: REM sample output of left-hand switch of control unit.
115  PR£ 0: PR£ 4: REM deselects and reselects the addressing of the interface unit.
120  PRINT CHR$ (73);"<";:REM "listen to" interface and access data from input 4.
125  CALL 50373: A(4) = PEEK (6): REM store byte A from input 4.
130  CALL 50373: B(4) = PEEK (6): REM store byte B from input 4.
135  PRINT ">";: PR£ 0: REM "unlisten" to interface.
140  IF A(4) > 7 THEN S(4) = -1: A(4) = A(4) - 8: GOTO 150: REM defines S(4).
145  S(4) = 1: REM defines S(4)
150  R(4) = ((256 * A(4)) + B(4)) * S(4): REM combine bytes A and B.
153  GOSUB 1000
155  PR£ 4: PRINT CHR$ (41);"<G0, I5>";: REM sample output of right-hand switch.
160  PR£ 0: PR£ 4
165  PRINT CHR$ (73);"<";
170  CALL 50373: A(5) = PEEK (6)
175  CALL 50373: B(5) = PEEK (6)
180  PRINT">";: PR£ 0
185  IF A(5) > 7 THEN S(5) = -1: A(5) = A(5) - 8: GOTO 195
190  S(5) = 1
195  R(5) = ((256 * A(5)) + B(5)) *S(5)
197  GOSUB 1000
320  IF R(4) > 500 AND R(5) < 500 THEN GOTO 400: REM logic for selection of TA.
325  IF R(4) < 500 AND R(5) > 500 THEN GOTO 450: REM logic for selection of TV.
330  IF R(4) > 500 AND R(5) > 500 THEN GOTO 500: REM logic for simultaneous selection of TA and TV.
400  GOSUB 2000: REM bleep generation subroutine.
405  D = INT (2000 * RND (1) + 500): REM generation of random time between 1 and 5secs.
407  FOR PAUSE = 1 TO D: NEXT PAUSE
408  PR£ 4
410  PRINT CHR$ (41);"<R11, R21>";: REM open relays 1 and 2, to activate shutter and camera.
412  PRINT CHR$ (41);"<R20>";: REM close relay 2.
415  PR£ 0
420  FOR PAUSE = 1 TO 190: NEXT PAUSE: PR£ 4: REM pause for 300msec.
425  PRINT CHR$ (41);"<R10>";: REM close relay 1.
430  PR£ 0
435  GOSUB 3000: REM goto footswitch routine.
440  GOTO 50: REM recycle.
450  GOSUB 2000
455  D = INT (2000 * RND (1) + 500)
457  FOR PAUSE = 1 TO D: NEXT PAUSE
460  PR£ 4
```

```
465  PRINT CHR$ (41);"<R01, R21>"; REM open relays 1 and 2, to activate the LED's and Camera.
466  PRINT CHR$ (41);"<R20>"; PR£ 0
467  FOR PAUSE = 1 TO 75: NEXT PAUSE: PR£ 4: REM pause for 125msec.
470  PRINT CHR$ (41);"<R00>";
480  PR£ 0
485  GOSUB 3000
490  GOTO 50
500  GOSUB 2000
505  D = INT (2000 * RND (1) + 500)
507  FOR PAUSE = 1 TO D: NEXT PAUSE
510  PR£ 4
515  PRINT CHR$ (41);"<R01, R11, R21>"; REM open relays 0, 1 and 2.
517  PRINT CHR$ (41);"<R20>"; PR£ 0
520  FOR PAUSE = 1 TO 75: NEXT PAUSE: PR£ 4
525  PRINT CHR$ (41);"<R00>"; PR£ 0
527  FOR PAUSE = 1 TO 115: NEXT PAUSE
530  PR£ 4
532  PRINT CHR$ (41);"<R10>";
535  GOSUB 3000
545  GOTO 50
1000 PR£ 4: REM micropot' sampling routine.
1010 PRINT CHR$ (41);"<G0, I1>";: REM samples input 1 from TA micropot'.
1020 PR£ 0
1030 PR£ 4
1040 PRINT CHR$ (73);"<";
1050 CALL 50373: A(1) = PEEK (6)
1060 CALL 50373: B(1) = PEEK (6)
1070 PRINT">";: PR£ 0
1080 IF A(1) > 7 THEN S(1) = -1: A(1) = A(1) - 8: GOTO 1100
1090 S(1) = 1
1100 R(1) = ((256 * A(1)) + B(1)) * S(1)
1110 GOTO 1300: REM goto TA calculation.
1120 PR£ 4
1130 PRINT CHR$ (41);"<G0, I2>";: REM samples input 2 from TV micropot'.
1140 PR£ 0
1150 PR£ 4
1160 PRINT CHR$ (73);"<";
1170 CALL 50373: A(2) = PEEK (6)
1180 CALL 50373: B(2) = PEEK (6)
1190 PRINT">";: PR£ 0
1200 IF A(2) > 7 THEN S(2) = -1: A(2) = A(2) - 8: GOTO 1220
1210 S(2) = 1
1220 R(2) = ((256 * A(2)) + B(2)) * S(2)
1230 GOTO 1500: REM goto TV calculation
1300 F = (R(1) - 300) / 667 * 4: REM calculation of TA (D).
1310 F$ = STR$ (F): REM converts TA result into a string variable.
1320 HTAB 17: REM horizontally positions TA result on screen.
1330 VTAB 10: REM vertically positions TA result on screen.
1340 PRINT LEFT$ (F$, 5): REM prints only the 5 leftmost digits of TA result.
1350 HTAB 18
1360 VTAB 8
1370 PRINT "TA"
1380 GOTO 1120: REM goto TV calibration routine.
1500 V = (R(2) * 0.1907) = 8: REM calculation of VAD unit position (cm).
1510 C = 1 / V * 100: REM converts VAD (cm) to VAD (D).
1520 C$ = STR$ (C) : REM converts VAD position into a string variable.
1530 HTAB 24
1540 VTAB 10
1550 PRINT LEFT$ (C$, 5)
1560 HTAB 25
```

```
1570 VTAB 8
1580 PRINT "TV"
1590 RETURN: REM return to next line after last GOSUB command.
2000 N = 1: REM bleep generation routine: let N = 1.
2010 V = 5: REM voltage output set at 5v.
2020 X = INT (ABS (V) * 204.8)
2030 HI = INT (X / 256)
2040 LO = X - HI * 256: REM calculates the low byte.
2050 HI = HI + 8: REM calculates the high byte.
2060 PR£ 4: PRINT CHR$ (41);"<03";: REM address output 3.
2070 POKE (6), HI: CALL 50426: REM recall high byte.
2080 POKE (6), LO: CALL 50426: REM recall low byte.
2090 PRINT ">";: PR£ 0: REM send 5v to output 3 and then to bleep.
2100 V = 0: REM set voltage to 0.
2110 X = INT (ABS (V) * 204.8)
2120 HI = INT (X / 256)
2130 LO = X - HI * 256
2140 HI = HI + 8
2150 PR£ 4: PRINT CHR$ (41);"<03";
2160 POKE (6), HI: CALL 50426
2170 POKE (6), LO: CALL 50426
2180 PRINT ">";: PR£ 0
2190 N = N + 1
2200 IF N < 4 THEN GOTO 2010: REM recycle bleep 4 times.
2210 RETURN
3000 GOSUB 1000: REM footswitch routine.
3005 PR£ 4
3010 PRINT CHR$ (41);"<GO, I3>";: REM sample input 3 from footswitch.
3020 PR£ 0: PR£ 4
3030 PRINT CHR$ (73);"<";: REM send data to Apple.
3040 CALL 50373: A(3) = PEEK (6)
3050 CALL 50373: B(3) = PEEK (6)
3060 PRINT ">";: PR£ 0
3070 IF A(3) > 7 THEN S(3) = -1: A(3) = A(3) - 8: GOTO 3090
3080 S(3) = 1
3090 R(3) = ((256 * A(3)) + B(3)) * S(3)
3100 IF R(3) < 500 THEN GOTO 3000: REM wait for footswitch to be pressed.
3110 IF R(3) > 500 THEN GOTO 3120
3120 GOSUB 2000
3125 FOR PAUSE = 1 TO 3500: NEXT PAUSE
3130 RETURN
```

APPENDIX VIII

ASSESSMENT OF "PAUSE-LOOP" LINEARITY

Unlike most microcomputers, the Apple IIe does not possess an in-built clock. To overcome this problem a pause-loop was used to provide calibrated time-lags within the main program, enabling the time-sequencing and apparatus latencies to be selected via a software, as opposed to a hardware adjustment (such as a capacitance change at the circuit board or via micropot' rotation). A typical pause-loop is as follows:

```
FOR PAUSE = 1 TO D: NEXT PAUSE
```

Here, the length of the pause depends on the magnitude of "D": with this embedded within a program, the computer will pause for the length of time taken for it to count in units of 1, until it reaches the value chosen for "D", before proceeding on to the next line. As seen in Appendix VII, this stratergy is utilised in TVA 10.

In order that the linearity of the pasue-loop may be checked, PAUSE 1 was written (see fig. VIII.1). Relay 3 (of the interface) is opened for a length of time determined by various sizes of "D", as detected via a 5v circuit and Universal Timer 243.

```
PAUSE 1
5  PRINT "SELECT AND INPUT PAUSE LENGTH"
7  INPUT D
10 PR£ 4
20 PRINT CHR$ (41);"<R31>";
30 PR£ 0
40 FOR PAUSE = 1 TO D: NEXT PAUSE
50 PRINT CHR$ (41);"<R30>";
60 PR£ 0
70 GOTO 5
```

Various values for "D" were selected, from 10 to 3500. The resultant time periods may be checked against Table VIII. 1.

TABLE VIII.1 - Variable pause-loop value versus resultant time period.

VALUE OF "D" i.e. PAUSE	TIME (msec)	VALUE OF "D" i.e. PAUSE	TIME (msec)
0	15	350	544
1	17	400	602
10	28	500	737
15	36	600	872
20	43	700	1012
40	74	800	1150
60	103	900	1288
80	134	1000	1427
100	167	1500	2137
150	246	2000	2852
200	327	2500	3579
250	407	3000	4318
300	477	3500	5057

The selection of successive increases in pause lengths has produced a linear change in relay activation time. It is possible therefore, to predict a computer generated time by cross reference to the pause-loop required.

APPENDIX IX

STATISTICAL PROCEDURES

IX.1 - Analysis of variance (ANOVA)

ANOVA is a parametric statistical procedure for comparing the differences between two or more samples simultaneously within a single test. It is the ratio between the variances of a given sample and an estimate of the error variance (the random or residual variation) for the population. This ratio, the F-ratio, is defined as:

$$F = S_s^2 / S_p^2$$

where, S_s^2 = sample variance

and S_p^2 = error variance

The sampling distribution of F varies as a function of sample size; consequently, the degrees of freedom (df) must be taken into account. Since F is based on two estimates of variance, each based upon a different number of cases, the sample distribution of F is tabled in terms of the df associated with both the numerator and the denominator of the ratio. Tests of the significance of the F-ratio may be made subsequently by reference to the standard published ANOVA tables (e.g. Fisher and Yates, 1974)[1]. Conventionally, a value of F equal to or just greater than the tabulated value for p (the probability that the

---

[1] In this thesis all ANOVAs have performed with the aid of a commercial computer program written for the Apple microcomputer in the Pascal language - JELCSAV:ANOVAR - by JEL Computer services, 3, King's road, Cleethorpes, Humberside.

ratio would have occurred by chance) at the 0.05 level suggests that the null hypothesis, H_o, should be rejected. Where F is equal to or greater than p at the 0.01 level, H_o may be definitely rejected.

It should be noted that in the two-sample case, the F-ratio yields probability values identical to those of the student t-ratio.

IX.2 - Student t-ratio.

The student t-ratio[1] is a test for determining the significance of a difference between means (two-sample case) or for testing the hypothesis that a given sample mean was drawn from a population with the mean specified under the null hypothesis (one-sample case). It is employed when the population standard deviation is not known.

IX.3 - The correlation coefficient and linear regression analysis.

In order to quantitatively express the extent to which two variables are related, it is necessary to calculate a correlation coefficient. For use with interval or ratio-scaled variables, the Pearson product-moment correlation coefficient (r) should be employed. The Pearson r represents the extent to which the same individuals or events occupy the same relative position on two variables, X and Y. For any bivariate distribution, the value r will lie beteen +1.00 and -1.00. For r = +1.00, X and Y are directly or positively correlated; for r = -1.00, X and Y are inversely or negatively correlated.

---

[1] All t-tests were performed with the aid of a commercially available program "STATEASE", written by Bryan Clarke, Department of Genetics, University of Nottingham.

It should be remembered, however, that the Pearson r reflects only the linear relationship between two variables. Failure to find evidence of a relationship may be due to one of several possibilities: a) the variables are, in fact, unrelated; b) the variables are non-linearly related; c) the range of values of one of the variables is too restricted.

The assumption of linearity of relationship is the most important requirement to justify the use of the Pearson r as a measure of relationship between two variables. It is not necessary that r be calculated only with normal distributions. So long as the distributions are unimodal and relatively symmetrical (as revealed by a scattergram), a Pearson r may be legitimately be computed.

Correlational analysis facilitates predictions from one variable to another. The general algebraic formula for a straight line will be remembered:

$$Y = a + bX$$

where X and Y represent variables that change from individual to individual, and a and b represent constants for a particular set of data. More specifically, b represents the slope of a line relating values of Y to the values of X, i.e., the regression of Y on X.

The above formula may be used to predict Y from known values of X. When the correlation is precisely ± 1.00, the predictions are perfect. However, obtained correlations are very rarely perfect, so the 'best-fit' straight line is employed. This is the regression line and is defined as the straight line which makes the squared deviations around it minimal. The standard deviation around the regression line is termed the standard error of estimate.

APPENDIX X

THE EFFECT OF SHUTTER SPEED ON THE VARIATION OF 5 MEASUREMENTS OF TA (D at 632.8nm).

Table X.1 - Measures of TA at 5 shutter speeds, their mean (x) and standard deviation (sd) from 10 observers.

SUBJECT	SHUTTER SPEED (ms)	TA MEASUREMENTS MEAN					x	sd
		1	2	3	4	5		
A.M.	200	-	-	-	-	-	-	-
	300	0.25	0.35	0.57	0.33	0.39	0.38	0.12
	400	0.23	0.07	-0.03	0.03	-0.30	0.00	0.19
	500	0.52	0.20	-0.13	0.03	-0.13	0.10	0.27
R.H.	200	1.78	1.49	1.19	0.99	1.68	1.42	0.33
	300	1.55	1.51	1.45	1.50	1.53	1.49	0.05
	400	2.33	2.26	2.13	2.15	1.76	2.12	0.22
	500	1.90	2.15	1.89	1.90	2.42	2.05	0.24
R.R.	200	-0.08	0.83	0.80	-0.59	-0.54	0.09	0.69
	300	0.20	0.23	-0.14	0.31	0.36	0.19	0.20
	400	0.37	0.58	1.00	0.83	0.43	0.64	0.27
	500	0.60	0.49	0.20	0.35	0.43	0.41	0.15
M.P.	200	0.93	1.00	1.37	0.86	0.78	0.99	0.23
	300	0.92	0.85	0.62	0.65	0.66	0.74	0.14
	400	0.54	0.84	0.89	0.43	0.38	0.62	0.24
	500	0.68	0.67	0.75	0.74	0.46	0.66	0.12
J.W.	200	1.81	1.85	1.88	1.58	1.55	1.73	0.16
	300	2.21	2.51	2.32	2.20	2.15	2.28	0.14
	400	2.54	2.35	2.35	2.53	2.15	2.33	0.16
	500	1.74	1.93	2.13	1.57	2.09	1.90	0.23
M.R.	200	1.11	1.14	1.13	1.25	1.42	1.23	0.14
	300	1.07	1.00	0.97	1.08	1.03	1.02	0.04
	400	1.38	1.37	1.48	1.45	1.61	1.46	0.10
	500	1.40	1.23	1.17	1.26	1.39	1.29	0.10
B.G.	200	1.35	2.20	2.29	2.17	2.33	2.07	0.41
	300	2.60	2.68	2.63	2.73	2.83	2.69	0.09
	400	2.66	2.75	2.63	2.73	2.86	2.73	0.09
	500	2.46	2.42	2.41	2.51	2.31	2.42	0.08
M.W.	200	-	-	-	-	-	-	-
	300	0.91	0.86	0.82	0.95	0.92	0.89	0.05
	400	1.06	0.75	0.72	0.46	0.95	0.79	0.23
	500	0.55	0.61	0.92	0.845	0.95	0.77	0.18
M.F.	200	-	-	-	-	-	-	-
	300	3.76	3.71	3.93	3.81	3.86	3.81	0.09
	400	4.08	4.12	4.13	4.18	4.25	4.15	0.06
	500	3.23	3.24	3.82	3.83	4.18	3.66	0.41
N.Mc.	200	1.16	1.05	-	-	-	1.10	0.08
	300	1.42	1.43	1.55	1.53	1.43	1.47	0.06
	400	1.32	1.12	1.30	1.14	1.38	1.25	0.12
	500	1.19	1.18	0.91	1.33	1.23	1.19	0.16

APPENDIX XI

THE EFFECT OF VARIATION IN LED ENERGIZATION TIMES ON THE STANDARD DEVIATION OF 5 MEASURES OF TV.

TABLE XI.1 - The mean (x) and standard deviation of 5 measures of TV (in degrees) at 5 LED energization periods (in msec) from 3 observers.

		TV MEASUREMENT						
OBSERVER	LED TIME	1	2	3	4	5	X	sd
B.G.	30	2.09	2.02	1.93	2.02	2.16	2.04	0.09
	75	2.19	2.16	2.13	2.18	2.06	2.14	0.05
	125	2.20	2.18	2.13	2.14	2.13	2.16	0.03
	175	2.20	2.19	2.14	2.13	2.23	2.18	0.04
	225	2.12	2.20	2.17	2.17	2.03	2.14	0.07
R.H.	30	1.73	1.70	1.77	1.76	1.68	1.73	0.04
	75	1.72	1.71	1.77	1.72	1.66	1.72	0.04
	125	1.66	1.65	1.66	1.64	1.64	1.65	0.01
	175	1.71	1.69	1.66	1.68	1.70	1.69	0.02
	225	1.56	1.62	1.62	1.56	1.60	1.59	0.03
J.W.	30	2.01	2.04	1.65	1.89	1.82	1.88	0.16
	75	1.97	2.00	2.05	2.00	1.70	1.94	0.14
	125	2.17	2.22	2.35	2.17	2.18	2.22	0.08
	175	2.24	1.98	1.86	2.11	2.02	2.04	0.14
	225	1.96	2.00	2.24	2.04	2.23	2.09	0.13

APPENDIX XII

THE MEASUREMENT OF TA (D) AT 3 WAVELENGTHS 488, 514.6 AND 632.8nm

TABLE XII.1 - The mean ($\bar{X}$) and standard deviation (sd) of 5 measures of TA (D) from 10 observers at 3 wavelengths (nm).

		TA MEASUREMENT (D)						
OBSERVER	WAVELENGTH	1	2	3	4	5	$\bar{X}$	sd
MJ	488	2.94	2.89	3.04	3.16	2.90	2.99	0.11
	514.6	2.27	2.44	2.51	2.24	2.36	2.36	0.11
	632.8	1.12	1.20	1.27	1.28	1.34	1.24	0.08
SH	488	3.13	3.08	3.09	3.03	2.95	3.06	0.07
	514.6	2.35	2.49	2.51	2.35	2.41	2.42	0.08
	632.8	0.99	0.96	1.02	1.12	1.10	1.04	0.07
MR	488	4.08	4.22	4.15	4.07	4.20	4.15	0.07
	514.6	3.88	3.85	3.70	3.63	3.64	3.74	0.12
	632.8	2.20	1.97	2.09	2.17	1.92	2.07	0.12
RH	488	3.18	3.14	2.90	2.96	3.07	3.05	0.12
	514.6	2.69	2.40	2.36	2.63	2.50	2.52	0.14
	632.8	1.36	1.42	1.30	1.21	1.41	1.34	0.09
BG	488	3.84	3.76	3.86	3.86	3.75	3.81	0.05
	514.6	3.25	3.28	3.23	3.14	3.14	3.21	0.07
	632.8	1.98	1.95	2.07	2.17	2.13	2.06	0.10
CT	488	0.93	0.94	0.93	0.92	0.93	0.93	0.01
	514.6	0.69	0.61	0.58	0.66	0.63	0.63	0.04
	632.8	-0.65	-0.68	-0.73	-0.66	-0.63	-0.67	0.04
MP	488	4.33	4.32	4,30	4.29	4.28	4.30	0.02
	514.6	3.94	3.93	3.90	3.88	3.89	3.91	0.03
	632.8	1.94	2.25	2.66	2.65	2.75	2.45	0.35
IL	488	1.75	1.75	1.70	1.69	1.72	1.72	0.03
	514.6	1.41	1.38	1.36	1.42	1.42	1.40	0.03
	632.8	0.21	0.22	0.20	0.19	0.20	0.20	0.01
MM	488	2.84	2.81	2.75	2.78	2.80	2.80	0.03
	514.5	2.27	2.33	2.36	2.37	2.42	2.35	0.06
	632.8	0.86	0.86	0.94	0.84	0.75	0.85	0.07
SS	488	4.91	4.90	4.87	4.93	4.96	4.92	0.03
	514.6	4.10	4.26	4.29	4.24	4.36	4.25	0.10
	632.8	2.54	2.51	2.39	2.45	2.50	2.48	0.06

APPENDIX XIII

MEASUREMENT OF TA AT THE 5 WAVELENGTHS 457.9, 476.5, 488, 514.6 AND 632.8nm.

TABLE XIII.1 - The mean ($\bar{X}$) and standard deviation (sd) of 5 measures of TA (D) from 4 observers at 5 wavelengths.

		TA MEASUREMENT						
OBSERVER	WAVELENGTH	1	2	3	4	5	$\bar{X}$	sd
SH	457.9	4.07	4.05	3.96	3.95	3.98	4.00	0.05
	476.5	3.61	3.68	3.66	3.36	3.60	3.64	0.03
	488	3.45	3.37	3.28	3.36	3.36	3.37	0.06
	514.6	2.96	2.90	2.90	3.12	2.91	2.96	0.10
	632.8	1.51	1.48	1.61	1.46	1.34	1.48	0.10
RH	457.9	3.69	3.66	3.57	3.45	3.62	3.60	0.01
	476.5	3.26	3.14	3.00	3.01	2.77	3.03	0.18
	488	2.59	2.56	2.61	2.61	2.42	2.56	0.08
	514.6	2.15	2.12	2.33	2.17	1.91	2.13	0.15
	632.8	0.92	0.78	0.79	0.98	0.85	0.86	0.09
BG	457.9	4.90	5.04	4.87	5.04	4.94	4.96	0.08
	476.5	4.42	4.41	4.53	4.47	4.51	4.47	0.06
	488	3.86	3.99	3.86	3.92	3.98	3.92	0.06
	514.6	3.39	3.26	3.36	3.44	3.49	3.39	0.09
	632.8	2.15	2.27	2.18	2.23	2.22	2.21	0.05
IL	457.9	3.10	3.05	3.00	3.15	3.07	3.08	0.06
	476.5	2.83	2.77	2.91	2.79	2.81	2.82	0.06
	488	2.51	2.49	2.38	2.51	2.44	2.47	0.06
	514.6	1.98	2.10	1.90	1.83	1.94	1.95	0.10
	632.8	0.52	0.49	0.41	0.51	0.46	0.47	0.07

MEASUREMENT OF TA AT 3 WAVELENGTHS 488, 514.6 AND 632.8nm, FOLLOWING THE INSTILLATION OF 1% CYCLOPENTOLATE.

TABLE XIV.1 - The mean ($\bar{X}$) and standard deviation (sd) of 5 measures of TA (D) from 3 observers at 3 wavelengths.

		TA MEASUREMENT						
OBSERVER	WAVELENGTH	1	2	3	4	5	$\bar{X}$	sd
SH	488	1.36	1.37	1.64	1.34	1.42	1.43	0.12
	514.6	0.83	0.82	1.09	1.19	1.07	1.00	0.17
	632.8	-0.39	-0.37	-0.50	-0.47	-0.42	-0.43	0.05
RH	488	1.38	1.45	1.42	1.31	1.50	1.41	0.07
	514.6	1.07	1.09	1.06	1.02	1.00	1.05	0.01
	632.8	-0.41	-0.51	-0.44	-0.56	-0.64	-0.51	0.09
BG	488	1.74	1.51	1.41	1.38	1.39	1.48	0.15
	514.6	1.11	0.98	0.92	0.89	1.01	0.98	0.08
	632.8	-0.46	-0.46	-0.43	-0.52	-0.42	-0.46	0.04

APPENDIX XV

TONIC, REFRACTIVE AND OCULOMOTOR PROFILE OF THE N=60 OBSERVER GROUP

This appendix includes the data taken from the N=60 group of observers employed in the studies encompassed within Chapter 4.

TABLE XV.1 - Measures of the tonic, refractive and oculomotor profile of a group of 60 observers (O). "Rx" represents the best-sphere refractive correction for the left-eye (D). "TA+Rx" represents the the measure of TA (at 632.8nm in D) taken with the Rx worn in place, whilst "TA-Rx" represents the measure of TA without Rx worn in place. A negative TA value indicates a hyperopic resting state. "IPD" represents the inter-pupillary distance (mm). "TV deg" and "TV cm" represent the measures of TV in degrees and vergence-distance in cm. "TP" represent the measures of horizontal pupil size in total darkness (mm). "Pho'D" and "Pho'N" represent the measures of heterophoria (with Rx worn in place) at 6m and 33cm, respectively. A negative 'phoria result indicates esophoria. "AC/A", "NPC" and "AA" are typical abbreviations for the accommodative - convergence / accommodation ratio, the near point of convergence (cm) and the amplitude of accommodation (D), respectively.

O	SEX	AGE	Rx	TA+Rx	TA-Rx	IPD	TV deg	TV cm	TP	Pho'D	Pho'N	AC/A	NPC	AA
MD	M	21	-1.00	2.40	3.40	69	2.76	71.58	6.70	1.5	12	2.67	6	9
SG	F	25	-0.63	2.99	3.49	68	2.15	90.46	6.50	-2	1	3.67	6	10
KG	M	22	-3.38	2.20	5.74	64	3.29	55.63	8.10	0	6	2	5.5	9
JGro	F	21	-2.38	3.86	5.61	61	4.87	35.76	7.30	1.5	6	4.33	6.5	9.5
PC	F	21	-0.88	2.07	3.08	58	2.97	55.99	6.75	0	0	2.33	3	10.5
MW	M	21	-0.38	0.84	0.21	65	0.94	198.03	7.45	-2	0	3	5.5	12
RD	M	23	-2.75	2.61	3.97	65	3.79	49.01	7.20	-2	-2	3	6	7.5
RN	M	22	-3.63	-0.18	2.64	62	0.82	216.83	7.20	-1.5	-1	1.33	6	10.5
RR	M	23	-0.63	0.88	1.84	66	2.43	77.68	7.50	-2	-5	6.33	6.5	8
AS	M	20	+0.13	3.00	1.84	67	1.93	99.32	6.80	0	2	2.33	5	7.5
SW	F	26	-3.38	1.82	3.90	62	2.73	64.91	6.70	16	8	2	10	8.25
BG	M	36	-6.25	2.72	4.96	63	1.78	101.43	6.70	0	-1	3	6	5
SM	M	20	0.00	0.05	0.05	61	0.77	227.17	7.45	0	4	2	6	9.5
MJ	M	21	+0.25	1.73	1.46	70	2.05	97.81	7.30	0	2	2	7	8.25
JGra	M	21	-4.00	1.41	5.35	65	1.74	106.98	7.55	0	1	3.33	7	11.5

(TABLE XV continued.....)

O	SEX	AGE	Rx	TA+Rx	TA-Rx	IPD	TV deg	TV cm	TP	Pho'D	Pho'N	AC/A	NPC	AA
TC	M	22	+0.75	0.79	0.92	61	1.33	131.12	6.75	-1	3	1.67	6	8.25
LH	F	20	-0.50	0.50	1.30	65	0.93	199.19	5.20	1	-2	3.33	6	9.5
SR	M	22	+0.38	0.85	0.26	68	1.21	160.42	6.80	0	3	3.33	12	8
SB	M	19	-0.25	0.61	0.37	64	1.04	176.48	7.65	-0.5	2	2	6.5	8
BS	M	21	+0.50	1.79	1.78	63	2.94	61.31	8.00	-0.5	1	3	6	9
IJ	M	21	-2.00	1.23	1.99	63	2.14	84.27	6.45	1.5	0	1	5.5	9
WO	M	22	-0.25	0.76	0.83	65	2.25	82.75	7.80	-2	0	3	5	10
AO	M	21	+0.13	1.49	1.49	68	2.52	77.25	6.65	6	6	4	7	9.5
TS	F	26	-4.88	1.14	7.41	60	1.64	104.86	7.50	2	0	4.33	6	12
PM	M	21	+1.25	1.33	0.38	62	2.17	81.82	6.60	-1	0	2	4	7.5
GH	F	21	-1.50	0.15	0.93	64	0.56	327.05	8.25	-0.5	3	3.5	9	8
AD	M	21	-3.38	0.47	3.68	63	0.80	225.45	6.80	2.5	3.5	3.75	10	11.5
MBay	M	21	-0.38	0.75	0.71	65	1.31	142.29	6.75	-2	1	3	10	9
CH	M	20	-0.50	0.85	0.55	69	1.27	155.90	6.90	0	1	4	7	7.5
JD	M	29	+0.25	0.15	0.18	65	0.95	196.91	7.25	-5	0	3.33	6	5.5
SIg	F	21	-2.25	1.03	3.54	67	1.72	111.50	6.80	0	3	3	6	11
MG	M	20	-0.50	0.85	1.65	65	1.40	132.62	7.00	-2	2	3	2.5	10
BC	F	21	-0.88	2.46	3.50	61	3.12	55.92	6.95	-2	-5	6	6	11
AH	M	22	-3.13	1.82	6.11	66	3.13	60.43	6.55	-1	1	2	7	6.5
JL	F	21	-0.13	1.75	1.77	66	2.91	65.03	6.70	0.5	3	2.33	8	9.5
SL	M	20	-3.50	5.27	8.58	69	4.11	48.01	6.90	0	-2	2.67	6.5	8.25
JF	M	24	-2.63	1.94	5.43	71	2.81	72.22	6.90	-1.5	0	2.33	5.5	9.5
LC	F	21	-4.63	1.49	5.62	63	1.55	116.50	7.35	0	1	1.33	6	6.75
MBu	M	20	+0.25	2.32	2.13	64	2.09	87.67	6.65	0.5	1	4	6.5	7
EM	M	21	0.00	1.07	1.07	65	2.63	70.76	6.50	-2	0	2	6.5	7.5
CT	F	23	+0.25	0.74	0.40	65	1.24	150.47	8.10	1	5	6	7	7
SIn	M	19	+0.88	3.23	1.55	64	4.91	37.29	7.20	2	3	1	7.5	7.5
JSc	F	27	+0.50	1.94	1.36	63	2.99	60.34	7.30	0	0	1.67	6	8.5
PP	M	19	-0.88	1.60	2.36	67	2.25	85.30	8.15	-1	2	1.33	8	9.5
JP	M	21	-0.88	0.88	1.41	68	1.28	151.88	6.65	1	0	0.33	7	8.5
MPr	M	22	0.00	0.21	0.21	66	1.08	174.65	7.10	-0.5	1	3	6	8
AW	F	21	+0.50	2.70	1.75	59	2.63	64.10	6.75	0.5	3	3.33	6.5	9
KE	M	21	-0.25	4.14	3.18	72	3.02	68.31	7.25	0.5	2	2.33	10	8.5
KF	M	20	-3.88	2.75	4.86	70	2.24	89.34	6.80	0.5	1	2.33	6.5	12
MBal	F	22	+0.63	1.51	1.36	68	1.41	138.44	6.80	2	7	1.33	8	9
SK	F	30	+0.50	1.99	0.13	62	3.05	58.11	6.40	-0.5	8	1.33	6	7
MPa	M	18	+0.50	3.18	2.32	68	4.03	48.32	6.20	0	6	0.67	6	9
MM	M	19	+0.38	1.17	1.40	62	2.03	87.26	7.45	0	1	1.67	7	8
HM	F	19	+5.75	1.16	-4.00	62	2.07	85.67	7.85	0.75	8	2.33	10	7
SS	F	19	+0.63	2.94	1.97	65	4.37	42.50	7.20	0.5	7	2.67	9	6
RB	F	19	+1.63	1.89	0.98	61	1.77	98.84	6.70	-2.5	5	1.67	11	7
JH	F	20	+0.38	0.58	-0.43	59	1.87	90.40	6.60	0.5	6	2.33	5.5	8
CM	F	19	+0.63	-0.17	-1.08	64	1.46	125.95	6.50	-3	-5	6	6	8
BK	F	20	+2.75	0.21	-2.27	62	1.00	176.75	6.05	-5	-3	2	6	9
JSa	F	18	-0.75	1.12	0.74	60	2.29	74.98	7.40	1.5	2	3.33	5.5	9.5
MEAN		21.6	-0.79	1.58	2.13	64.58	2.18	108.09	7.02	0.01	1.96	2.73	6.72	8.69
sd		3.02	1.99	1.11	2.26	3.15	1.03	58.24	0.56	2.72	3.35	1.28	1.75	1.56

APPENDIX XVI

HYSTERESIS DATA

This appendix presents the results of experiments described in Chapter 7, and indicates the effects on TA and TV of interaction with a sustained visual task.

Table XVI.1 - Refractive data, sex and age of the 27 hysteresis-study observers (O).

			Rx	
O	Sex	Age	R-eye	L-eye
MB	m	22	+2.25 DS	+2.00 DS
RB	f	20	+0.50 DS	+1.75/-0.25x90
SB	m	21	-0.50/-0.50x175	0.00/-0.50x165
TC	m	23	+1.00/-0.50x180	+1.00/-0.50x180
MD	m	21	+0.50 DS	-0.75/-0.50x160
MD-H	f	21	-0.25 DS	-0.25/-0.50x170
GE	f	19	+0.25/-0.25x90	plano
KE	m	22	-0.25 DS	-0.25 DS
KF	m	20	-4.75 DS	-3.50/-0.75x100
SH	f	20	-0.75 DS	-0.50 DS
IH-T	m	20	+0.25 DS	+0.50/-0.25x90
JH	f	20	+0.75/-0.75x85	+0.75/0.75x80
KJ	f	24	0.00/-0.25x50	+0.25/-0.50x90
IL	m	20	0.00/-0.50x180	0.00/-0.25x180
HMcC	f	20	+4.75/-0.25x180	+6.00/-0.50x55
SMcC	m	20	-0.25/-0.25x180	-0.25/-0.25x25
MMcP	m	19	+0.50/-0.25x175	+0.50/-0.25x105
CM	f	19	-0.25/-0.25x5	+0.75/-0.25x5
EM	m	22	plano	plano
AM	m	21	+0.25/-0.50x95	-0.25/-0.50x95
MP	m	19	+0.50 DS	+0.50 DS
JS	f	19	+0.25 DS	-0.75 DS
SS	f	19	+1.50/-0.50x180	+0.75/-0.25x180
AS	m	20	-1.75/-0.25x155	-1.75/-0.25x180
BS	m	22	+0.50/+0.25x180	+0.25 DS
CT	f	19	plano	plano
MW	m	22	-0.25 DS	-0.25/-0.25x180

Table XVI.2 - Results of the effect on the TA (D) of 27 observers (O) of 15min sustained interaction with the visual task at 275cm (representing a stimulus of 0.36D). The figures in brackets following each post-TA value indicate the time (min) at which result recorded.

	PRE-TASK	POST-TASK					
O	TA	TA					
MB	2.51	1.75(3)	1.98(5)	2.00(9)	1.89(12)	1.90(14)	2.13(15)
RB	1.96	1.63(4)	1.59(8)	1.31(12)	1.22(15)		
SB	0.29	0.17(5)	0.16(8)	0.23(10)	0.21(12)	0.15(15)	
TC	2.37	1.85(2)	1.57(4)	1.48(6)	1.55(8)	1.28(13)	1.51(15)
MD	0.91	0.70(3)	0.61(5)	0.59(7)	0.44(10)	0.47(12)	0.52(15)
MD-H	2.04	1.98(2)	1.89(4)	1.78(8)	1.37(9)	1.24(11)	1.76(15)
GE	1.13	1.03(2)	0.62(5)	0.42(9)	0.37(11)	0.27(14)	0.27(15)
KE	3.59	2.70(2)	2.58(6)	2.40(9)	2.73(10)	3.03(13)	3.18(15)
KF	0.93	0.12(4)	-0.01(9)	0.16(13)	0.06(15)		
SH	1.10	0.61(2)	0.50(4)	0.41(6)	0.47(11)	0.52(13)	0.60(15)
IH-T	0.40	0.29(3)	0.24(6)	0.21(9)	0.28(15)		
JH	0.92	0.73(3)	0.88(5)	0.74(9)	0.74(11)	0.63(13)	0.63(15)
KJ	0.69	0.26(6)	0.11(7)	0.09(10)	0.15(15)		
IL	0.37	0.31(5)	0.41(8)	0.48(9)	0.25(12)	0.59(15)	
HMcC	1.48	0.82(4)	0.92(6)	0.91(9)	0.91(11)	1.00(15)	
SMcC	0.91	0.32(3)	0.50(6)	0.59(9)	0.60(12)	0.59(13)	0.52(15)
MMcP	0.07	0.17(1)	0.10(6)	0.04(8)	0.11(12)	0.21(13)	0.03(15)
CM	0.71	0.62(2)	0.68(6)	0.64(8)	0.55(11)	0.69(15)	
EM	0.53	0.69(3)	0.67(5)	0.55(9)	0.34(11)	0.40(15)	
AM	0.71	0.41(2)	0.58(4)	0.72(6)	0.47(9)	0.63(11)	0.40(15)
MP	2.86	2.82(4)	2.53(8)	1.46(11)	1.88(13)	2.24(15)	
JS	0.38	0.29(3)	0.21(7)	0.28(12)	0.28(15)		
SS	2.45	1.64(4)	1.72(7)	2.12(11)	2.12(13)	2.23(15)	
AS	0.83	0.25(3)	0.25(5)	0.38(9)	0.50(12)	0.37(15)	
BS	1.09	1.12(4)	0.71(8)	0.76(13)	0.64(15)		
CT	1.39	1.35(3)	1.02(6)	1.12(8)	1.28(10)	1.23(12)	1.23(15)
MW	0.59	0.61(5)	0.23(8)	0.31(11)	0.18(14)	0.28(15)	

Table XVI.3 - Results of the effect on the TA (D) of 27 observers (O) of 15min sustained interaction with the visual task at 100cm (theoretical stimulus of 1.00D). The figures in brackets following each post-TA value indicate the time (min) at which result recorded.

O	PRE-TASK TA	POST-TASK TA					
MB	2.18	1.65(3)	1.75(5)	1.89(8)	1.89(10)	2.01(13)	2.10(15)
RB	1.78	1.53(1)	1.60(5)	1.51(8)	1.53(11)	1.53(13)	1.53(15)
SB	0.35	0.42(1)	0.63(5)	0.50(9)	0.51(12)	0.19(15)	
TC	2.40	2.41(2)	2.31(5)	2.15(7)	1.97(11)	1.88(13)	2.02(15)
MD	0.61	0.63(3)	0.71(7)	0.66(9)	0.78(12)	0.78(15)	
MD-H	2.22	2.07(3)	2.01(7)	1.92(12)	2.02(13)	1.92(15)	
GE	1.25	1.10(4)	0.89(8)	1.01(12)	0.99(14)		
KE	3.50	3.02(3)	3.04(5)	3.02(6)	2.89(8)	2.91(12)	2.99(15)
KF	0.91	0.79(4)	0.76(7)	0.79(9)	0.79(13)	0.81(15)	
SH	1.35	1.39(3)	1.21(5)	1.30(9)	1.34(13)	1.38(15)	
IH-T	0.35	1.11(2)	1.07(5)	0.90(9)	0.99(12)	1.19(15)	
JH	1.06	0.97(3)	1.01(5)	0.95(7)	1.04(10)	1.37(12)	1.07(15)
KJ	0.93	1.12(3)	0.85(6)	0.83(8)	1.41(13)	0.97(15)	
IL	0.40	0.63(2)	0.77(5)	0.77(9)	0.59(11)	0.52(13)	0.40(15)
HMcC	1.55	1.26(1)	1.32(3)	1.24(6)	1.37(8)	1.48(11)	1.66(15)
SMcC	0.38	0.45(1)	0.59(7)	0.53(10)	0.46(12)	0.71(14)	0.61(15)
MMcP	0.32	0.56(1)	0.42(5)	0.25(7)	0.10(9)	0.22(15)	
CM	0.86	0.98(1)	1.03(5)	1.09(9)	1.09(11)	0.88(15)	
EM	0.68	0.81(3)	1.00(7)	0.87(11)	0.74(13)	0.72(15)	
AM	0.76	0.83(3)	0.83(6)	0.83(8)	0.85(10)	0.86(12)	0.86(15)
MP	3.63	2.94(3)	2.51(8)	2.94(13)	2.15(15)		
JS	0.59	0.47(3)	0.84(5)	0.65(10)	0.59(15)		
SS	1.16	1.30(3)	1.28(5)	0.96(10)	0.91(13)	1.09(15)	
AS	0.88	1.34(2)	0.95(4)	0.96(6)	0.96(10)	0.88(15)	
BS	0.97	1.15(2)	1.23(6)	1.06(10)	1.25(14)	1.17(16)	
CT	1.25	1.10(3)	1.10(5)	1.04(8)	1.00(11)	1.01(13)	1.10(15)
MW	0.44	0.64(2)	0.74(5)	0.61(8)	0.51(11)	0.48(15)	

Table XVI.4 - Results of the effect on the TA (D) of 27 observers (O) of 15min sustained interaction with the visual task at 33cm (theoretical stimulus of 3.00D). The figures in brackets following each post-TA value indicate the time (min) at which result recorded.

	PRE-TASK	POST-TASK					
O	TA	TA					
MB	2.18	2.22(1)	2.66(4)	2.69(6)	3.11(9)	2.55(12)	2.55(15)
RB	2.01	2.10(3)	2.30(8)	2.31(10)	2.31(15)		
SB	0.35	0.55(1)	0.57(5)	0.45(9)	0.45(12)	0.43(14)	0.40(15)
TC	2.34	2.42(5)	2.60(7)	2.44(10)	2.27(12)	2.48(15)	
MD	0.89	0.92(2)	1.11(5)	1.17(8)	1.25(10)	1.24(15)	
MD-H	1.61	2.01(5)	1.92(7)	1.89(10)	1.81(15)		
GE	0.68	0.95(3)	1.11(9)	1.07(13)	1.19(15)		
KE	3.59	3.12(4)	3.34(6)	3.65(8)	3.43(10)	3.33(13)	3.36(15)
KF	0.95	1.16(2)	1.16(6)	1.12(9)	1.16(12)	1.07(15)	
SH	0.53	1.00(2)	1.39(7)	0.98(9)	0.72(12)	0.75(14)	0.79(15)
IH-T	0.40	0.70(3)	1.10(6)	1.04(8)	1.38(8)	1.22(13)	1.29(15)
JH	1.36	1.65(3)	1.55(5)	2.18(7)	2.05(10)	1.55(14)	1.55(15)
KJ	1.11	1.55(2)	1.59(5)	1.72(8)	1.55(10)	1.47(12)	1.43(15)
IL	0.31	0.84(1)	0.84(5)	0.73(8)	0.73(10)	0.43(12)	0.35(15)
HMcC	1.68	2.10(2)	2.39(4)	2.39(7)	2.13(10)	2.15(12)	2.17(15)
SMcC	0.27	0.37(2)	0.45(4)	0.68(6)	0.93(9)	0.63(12)	0.43(15)
MMcP	0.31	0.77(3)	0.96(6)	1.02(9)	0.65(13)	0.65(14)	0.59(15)
CM	0.92	2.13(2)	1.83(8)	1.65(11)	1.39(15)		
EM	0.63	0.92(2)	1.01(5)	1.11(8)	0.68(11)	0.73(14)	0.77(15)
AM	0.87	1.07(3)	1.06(8)	1.77(12)	0.86(13)	0.86(15)	
MP	3.30	2.90(3)	2.96(6)	2.94(9)	3.11(12)	3.11(15)	
JS	0.85	1.55(6)	1.49(9)	1.23(11)	1.28(15)		
SS	1.75	1.97(2)	2.38(10)	2.18(12)	2.31(15)		
AS	0.88	2.40(6)	2.19(9)	1.70(11)	1.31(15)		
BS	3.29	3.01(6)	3.04(10)	3.04(15)			
CT	1.43	2.46(4)	1.97(6)	1.88(8)	1.98(10)	2.03(13)	2.23(15)
MW	0.46	0.52(3)	0.58(6)	0.43(9)	0.55(12)	0.58(14)	0.61(15)

Table XVI.5 - Results of the effect on the TV (deg) of 27 observers (O) of 15min sustained interaction with the visual task at 275cm (theoretical stimulus of 0.68deg). The figures in brackets following each post-TV value indicate the time (min) at which result recorded.

	PRE-TASK			POST-TASK			
O	TV			TV			
MB	1.94	1.93(1)	1.74(4)	1.28(7)	1.05(11)	1.19(13)	1.15(15)
RB	2.68	1.96(1)	2.03(5)	2.17(9)	2.20(13)	2.27(15)	
SB	1.31	1.28(1)	1.60(3)	1.35(7)	1.32(11)	1.19(13)	1.10(15)
TC	1.57	1.26(2)	1.36(4)	1.36(6)	1.21(8)	1.15(13)	1.15(15)
MD	1.53	0.96(3)	0.98(5)	1.03(7)	1.03(10)	1.07(14)	1.13(15)
MD-H	2.69	2.19(1)	2.09(3)	2.12(6)	2.16(9)	1.98(12)	2.85(15)
GE	1.42	0.89(1)	0.67(3)	0.73(6)	0.73(9)	0.73(11)	0.85(15)
KE	2.21	1.06(2)	1.23(4)	1.74(6)	1.29(8)	1.35(13)	1.46(15)
KF	1.58	1.10(1)	1.28(6)	1.22(10)	1.25(15)		
SH	1.74	1.29(1)	1.35(4)	1.57(5)	1.57(8)	1.64(12)	1.74(15)
IH-T	1.86	1.64(5)	1.50(8)	1.68(10)	1.68(15)		
JH	1.50	1.30(1)	1.26(4)	1.39(7)	1.56(10)	1.50(11)	1.59(15)
KJ	1.86	1.58(1)	1.58(6)	1.61(8)	1.59(12)	1.41(15)	
IL	0.92	0.62(1)	0.65(6)	0.67(8)	0.65(10)	0.57(13)	0.65(15)
HMcC	2.55	1.22(2)	1.09(4)	1.40(6)	1.22(9)	1.75(11)	1.94(15)
SMcC	1.82	1.28(1)	1.32(3)	1.79(6)	1.68(10)	1.68(13)	1.62(15)
MMcP	1.58	1.65(1)	1.58(6)	1.42(12)	1.38(15)		
CM	1.80	1.50(1)	1.33(5)	1.36(7)	1.76(10)	1.85(12)	1.85(15)
EM	1.88	1.51(1)	1.51(4)	1.65(8)	1.63(10)	1.75(13)	
AM	1.85	0.73(2)	0.99(4)	0.85(6)	0.87(11)	0.93(13)	0.93(15)
MP	3.74	3.63(1)	3.01(6)	2.95(9)	2.92(15)		
JS	2.55	2.20(5)	2.36(5)	2.36(8)	2.24(13)	2.24(15)	
SS	2.30	2.19(1)	1.90(6)	1.84(8)	1.32(12)	1.32(13)	1.32(15)
AS	1.60	0.56(3)	0.56(5)	0.65(9)	0.82(13)	0.88(15)	
BS	1.82	1.85(1)	1.56(6)	1.48(11)	1.70(14)	1.70(15)	
CT	2.05	0.99(3)	1.73(6)	1.73(8)	1.73(12)	1.73(15)	
MW	1.30	0.99(1)	1.07(6)	1.13(9)	0.87(13)	0.99(15)	

Table XVI.6 - Results of the effect on the TV (deg) of 27 observers (O) of 15min sustained interaction with the visual task at 100cm (theoretical stimulus of 1.87deg). The figures in brackets following each post-TV value indicate the time (min) at which result recorded.

O	PRE-TASK TV	POST-TASK TV					
MB	2.44	2.04(1)	2.03(2)	1.89(4)	1.95(9)	2.36(11)	2.52(15)
RB	2.30	2.02(2)	1.99(6)	2.06(9)	2.03(12)	2.16(13)	2.16(15)
SB	1.13	1.03(3)	0.79(7)	0.70(10)	0.73(15)		
TC	1.54	1.86(2)	1.65(5)	1.70(7)	1.67(11)	1.67(13)	1.67(15)
MD	1.01	1.04(3)	1.10(7)	1.34(9)	1.44(12)	1.44(15)	
MD-H	2.65	2.41(4)	2.41(10)	2.26(13)	2.55(14)	2.54(15)	
GE	2.08	1.96(1)	1.95(7)	1.91(10)	1.88(12)	1.82(15)	
KE	2.14	2.02(3)	1.90(5)	2.02(8)	2.02(9)	2.08(12)	2.08(15)
KF	1.69	1.90(1)	2.02(5)	2.01(8)	1.70(10)	1.82(14)	1.82(15)
SH	2.06	2.06(3)	1.77(5)	1.81(9)	1.85(13)	1.85(15)	
IH-T	1.48	1.48(2)	1.63(5)	1.55(9)	1.58(12)	1.58(13)	1.58(15)
JH	1.93	1.93(1)	1.96(4)	1.73(6)	1.69(8)	1.89(13)	1.89(15)
KJ	1.52	1.15(1)	1.69(4)	1.69(7)	1.61(8)	1.67(15)	
IL	0.73	0.82(3)	0.73(6)	0.82(9)	0.85(10)	0.85(12)	0.90(15)
HMcC	1.93	1.69(1)	1.88(4)	1.93(6)	1.99(9)	1.99(12)	0.96(15)
SMcC	2.56	1.84(1)	2.27(5)	2.27(8)	2.27(10)	2.34(13)	2.32(15)
MMcP	1.98	1.82(1)	2.16(6)	2.14(8)	1.75(10)	1.95(14)	
CM	2.05	2.05(2)	1.82(7)	1.79(10)	1.82(12)	1.82(15)	
EM	2.11	2.11(1)	2.05(4)	1.88(9)	1.88(12)	1.88(15)	
AM	1.30	1.59(1)	1.62(4)	1.62(8)	1.62(10)	1.62(12)	1.62(15)
MP	3.21	3.15(1)	2.75(3)	2.20(9)	2.49(15)		
JS	3.25	2.60(4)	2.99(4)	2.99(10)	2.95(12)	2.88(15)	
SS	1.82	1.85(1)	1.74(4)	1.65(8)	1.65(12)	1.85(14)	
AS	1.99	1.90(1)	1.85(4)	1.63(7)	1.71(13)	1.97(15)	
BS	3.50	3.50(6)	2.56(10)	2.41(14)	2.19(15)		
CT	2.49	1.90(3)	2.05(5)	2.31(8)	2.31(11)	2.35(13)	2.33(15)
MW	1.62	1.80(1)	1.76(7)	1.75(11)	1.65(15)		

Table XVI.7 - Results of the effect on the TV (deg) of 27 observers (O) of 15min sustained interaction with the visual task at 33cm (theoretical stimulus of 5.57deg). The figures in brackets following each post-TV value indicate the time (min) at which result recorded.

	PRE-TASK			POST-TASK			
O	TV			TV			
MB	1.94	1.94(1)	2.00(5)	2.21(7)	2.22(10)	2.30(12)	2.30(15)
RB	1.94	3.24(6)	3.51(9)	3.51(12)	3.51(15)		
SB	1.30	0.71(7)	0.96(11)	1.04(13)	1.62(15)		
TC	1.65	1.88(2)	1.97(6)	1.80(8)	1.91(11)	1.82(13)	1.82(15)
MD	1.13	0.84(1)	1.18(3)	1.18(6)	1.30(9)	1.18(13)	1.10(15)
MD-H	2.20	2.94(1)	2.94(5)	2.76(7)	2.34(12)	2.66(15)	
GE	0.90	1.88(1)	1.96(6)	1.85(11)	1.59(13)	1.53(15)	
KE	2.53	2.80(1)	2.70(5)	2.80(7)	2.70(9)	2.56(11)	2.47(15)
KF	1.96	1.93(1)	1.93(4)	2.08(7)	1.92(10)	1.95(15)	
SH	1.86	1.72(1)	2.23(5)	1.72(8)	1.69(10)	1.69(13)	1.86(15)
IH-T	1.86	1.98(1)	1.98(5)	1.83(7)	1.79(10)	1.89(11)	1.89(15)
JH	1.93	1.93(1)	1.93(4)	1.93(6)	2.13(8)	2.01(11)	2.01(15)
KJ	2.09	1.92(1)	1.92(4)	1.98(6)	1.98(9)	1.97(13)	1.97(15)
IL	0.59	0.83(1)	0.81(4)	0.85(6)	0.74(9)	0.74(10)	0.75(15)
HMcC	2.42	2.14(1)	3.19(7)	3.29(8)	3.08(11)	3.19(13)	3.21(15)
SMcC	1.90	1.99(1)	1.99(2)	1.99(4)	1.99(7)	1.93(10)	1.99(15)
MMcP	1.83	2.01(3)	1.92(7)	1.84(10)	1.84(14)	1.84(15)	
CM	1.87	1.97(1)	2.23(5)	2.25(9)	2.12(11)	1.83(15)	
EM	1.86	1.96(1)	1.96(6)	1.93(9)	1.86(12)	1.93(13)	1.89(15)
AM	1.37	1.64(1)	1.55(4)	1.53(7)	1.23(9)	0.89(13)	0.89(15)
MP	3.97	3.89(5)	3.89(7)	3.91(10)	3.91(13)	3.91(15)	
JS	1.98	3.19(2)	3.18(7)	2.72(13)	2.65(15)		
SS	1.90	1.90(1)	1.90(6)	2.11(12)	2.11(15)		
AS	1.60	1.60(2)	1.99(7)	1.97(10)	1.74(12)	1.65(15)	
BS	3.66	3.60(1)	3.60(6)	3.62(11)	3.59(15)		
CT	2.79	2.68(4)	3.09(6)	3.09(8)	3.09(10)	3.01(13)	3.01(15)
MW	1.47	1.47(1)	1.57(4)	1.60(7)	1.60(10)	1.52(12)	1.56(15)

Table XVI.8 - The induced change in the TA (D) of 27 observers (O) following 15min sustained interaction with the visual task at 275cm. A negative change indicates a hyperopic shift in TA, whilst a positive change indicates a myopic shift in TA. The figures in brackets following each post-task TA value indicate the time (min) at which result recorded.

O	PRE-TASK TA	CHANGE IN TA						MEAN TA CHANGE
MB	2.51	-0.77(3)	-0.54(5)	-0.51(9)	-0.62(12)	-6.11(14)	-0.38(15)	-0.57
RB	1.96	-0.32(4)	-0.37(8)	-0.65(12)	-0.74(15)			-0.51
SB	0.29	-0.12(5)	-0.13(8)	-0.06(10)	-0.08(12)	-0.14(15)		-0.11
TC	2.37	-0.52(2)	-0.80(4)	-0.89(6)	-0.82(8)	-1.09(13)	-0.86(15)	-0.83
MD	0.91	-0.21(3)	-0.29(5)	-0.31(7)	-0.47(10)	-0.43(12)	-0.39(15)	-0.35
MD-H	2.04	-0.06(2)	-0.16(4)	-0.27(8)	-0.67(9)	-0.80(11)	-0.28(15)	-0.39
GE	1.13	-0.11(2)	-0.51(5)	-0.71(9)	-0.76(11)	-0.86(14)	-0.86(15)	-0.64
KE	3.59	-0.89(2)	-1.01(6)	-1.19(9)	-0.86(10)	-0.56(13)	-0.41(15)	-0.86
KF	0.93	-0.91(4)	-0.94(9)	-0.77(13)	-0.87(15)			-0.87
SH	1.10	-0.49(2)	-0.61(4)	-0.69(6)	-0.64(11)	-0.58(13)	-0.50(15)	-0.60
IH-T	0.40	-0.11(3)	-0.15(6)	-0.19(9)	-0.12(15)			-0.14
JH	0.92	-0.20(3)	-0.04(5)	-0.19(9)	-0.19(11)	-0.19(13)	-0.29(15)	-0.17
KJ	0.69	-0.43(6)	-0.58(7)	-0.60(10)	-0.54(15)			-0.54
IL	0.37	-0.07(5)	+0.03(8)	+0.11(9)	-0.13(12)	+0.20(15)		+0.03
HMcC	1.48	-0.66(4)	-0.55(6)	-0.57(9)	-0.56(11)	-0.48(15)		-0.43
SMcC	0.91	-0.59(3)	-0.41(6)	-0.32(9)	-0.31(12)	-0.32(13)	-0.40(15)	-0.39
MMcP	0.07	+0.10(1)	+0.03(6)	-0.03(8)	+0.04(12)	+0.14(13)	-0.04(15)	+0.04
CM	0.71	-0.09(2)	-0.02(6)	-0.07(8)	-0.16(11)	-0.02(15)		-0.07
EM	0.53	+0.16(3)	+0.14(5)	+0.02(9)	-0.19(11)	-0.13(15)		0.00
AM	0.71	-0.30(2)	-0.12(4)	+0.01(6)	-0.24(9)	-0.08(11)	-0.30(15)	-0.19
MP	2.86	-0.04(4)	-0.33(8)	-1.41(11)	-0.98(13)	-0.26(15)		-0.69
JS	0.38	-0.08(3)	-0.17(7)	-0.10(12)	-0.10(15)			-0.11
SS	2.45	-0.81(4)	-0.73(7)	-0.33(11)	-0.33(13)	-0.17(15)		-0.47
AS	0.83	-0.58(3)	-0.58(5)	-0.45(9)	-0.33(12)	-0.46(15)		-0.48
BS	1.09	+0.04(4)	-0.38(8)	-0.32(13)	-0.44(15)			-0.28
CT	1.39	-0.05(3)	-0.37(6)	-0.27(8)	-0.11(10)	-0.16(12)	-0.16(15)	-0.19
MW	0.59	+0.02(5)	-0.35(8)	-0.28(11)	-0.41(14)	-0.31(15)		-0.27

Table XVI.9 - The induced change in the TA (D) of 27 observers (O) following 15min sustained interaction with the visual task at 100cm. A negative change indicates a hyperopic shift in TA, whilst a positive change indicates a myopic shift in TA. The figures in brackets following each post-task TA value indicate the time (min) at which result recorded.

O	PRE-TASK TA	CHANGE IN TA						MEAN TA CHANGE
MB	2.18	-0.53(3)	-0.43(5)	-0.29(8)	-0.28(10)	-0.17(13)	-0.08(15)	-0.30
RB	1.78	-0.26(1)	-0.19(5)	-0.28(8)	-0.26(11)	-0.26(13)	-0.26(15)	-0.25
SB	0.35	+0.07(1)	+0.28(5)	+0.15(9)	+0.16(12)	-0.16(15)		+0.10
TC	2.40	-0.09(5)	-0.25(7)	-0.43(11)	-0.52(13)	-0.38(15)		-0.34
MD	0.61	+0.02(3)	+0.10(7)	+0.04(9)	+0.17(12)	+0.17(15)		+0.10
MD-H	2.22	-0.16(3)	-0.22(7)	-0.31(12)	-0.20(13)	-0.31(15)		-0.20
GE	1.25	-0.15(4)	-0.36(8)	-0.24(12)	-0.26(15)			-0.26
KE	3.50	-0.48(3)	-0.46(5)	-0.48(6)	-0.61(8)	-0.58(12)	-0.51(15)	-0.49
KF	0.91	-0.14(4)	-0.15(7)	-0.12(9)	-0.12(13)	-0.10(15)		-0.12
SH	1.35	-0.04(3)	-0.14(5)	-0.04(9)	-0.01(13)	+0.03(15)		-0.02
IH-T	0.35	+0.76(2)	+0.73(5)	+0.55(9)	+0.64(12)	+0.85(15)		+0.71
JH	1.06	-0.09(3)	-0.05(5)	-0.11(7)	-0.02(10)	-0.02(12)	+0.01(15)	-0.05
KJ	0.93	+0.19(3)	-0.08(6)	-0.10(8)	+0.48(13)	+0.04(15)		+0.11
IL	0.40	+0.23(2)	+0.37(5)	+0.38(9)	+0.19(11)	+0.13(13)	+0.01(15)	+0.24
HMcC	1.55	-0.29(1)	-0.23(3)	-0.31(6)	-0.18(8)	-0.19(11)	+0.11(15)	-0.23
SMcC	0.38	+0.07(1)	+0.21(7)	+0.15(10)	+0.08(12)	+0.33(14)	+0.23(15)	+0.18
MMcP	0.32	+0.25(1)	+0.10(5)	-0.06(7)	-0.22(9)	-0.22(13)	-0.09(15)	-0.03
CM	0.86	+0.12(1)	+0.17(5)	+0.23(9)	+0.23(11)	+0.02(15)		+0.15
EM	0.68	+0.14(3)	+0.33(7)	+0.20(11)	+0.07(13)	+0.04(15)		+0.15
AM	0.76	+0.07(3)	+0.07(6)	+0.07(8)	+0.09(10)	+0.10(12)	+0.10(15)	+0.08
MP	3.63	-0.68(3)	-1.12(8)	-0.69(13)	-1.48(15)			-0.99
JS	0.59	-0.12(3)	+0.25(5)	+0.05(10)	-0.11(15)			+0.02
SS	1.16	+0.14(3)	+0.12(5)	-0.20(10)	-0.25(13)	-0.07(15)		-0.05
AS	0.88	+0.46(3)	+0.07(5)	+0.08(10)	+0.08(15)			+0.14
BS	1.00	+0.18(2)	+0.26(6)	+0.09(10)	+0.29(14)	+0.20(15)		+0.20
CT	1.25	-0.15(3)	-0.14(5)	-0.21(8)	-0.25(11)	-0.23(13)	-0.15(15)	-0.19
MW	0.44	+0.20(2)	+0.30(5)	+0.17(8)	+0.07(11)	+0.04(15)		+0.15

Table XVI.10 - The induced change in the TA (D) of 27 observers (O) following 15min sustained interaction with the visual task at 33cm. A negative change indicates a hyperopic shift in TA, whilst a positive change indicates a myopic shift in TA. The figures in brackets following each post-task TA value indicate the time (min) at which result recorded.

O	PRE-TASK TA	CHANGE IN TA						MEAN TA CHANGE
MB	2.18	+0.04(1)	+0.48(4)	+0.52(6)	+0.94(9)	+0.37(12)	+0.38(15)	+0.45
RB	2.01	+0.10(3)	+0.29(8)	+0.30(10)	+0.30(15)			+0.25
SB	0.35	+0.19(1)	+0.22(5)	+0.10(9)	+0.10(12)	+0.07(14)	+0.05(15)	+0.12
TC	2.34	+0.07(5)	+0.26(7)	+0.12(10)	-0.07(12)	+0.13(15)		+0.10
MD	0.89	+0.03(2)	+0.22(5)	+0.28(8)	+0.36(10)	+0.35(15)		+0.25
MD-H	1.61	+0.40(5)	+0.30(7)	+0.27(10)	+0.19(15)			+0.29
GE	0.68	+0.28(3)	+0.43(9)	+0.39(13)	+0.52(15)			+0.36
KE	3.60	-0.48(4)	-0.22(6)	+0.05(8)	-0.16(10)	-0.27(13)	-0.23(15)	-0.22
KF	0.95	+0.22(2)	+0.21(6)	+0.07(9)	+0.21(12)	+0.13(15)		+0.17
SH	0.53	+0.47(2)	+0.86(7)	+0.44(9)	+0.19(12)	+0.21(14)	+0.26(15)	+0.40
IH-T	0.40	+0.29(3)	+0.70(6)	+0.64(8)	+0.98(10)	+0.82(13)	+0.89(15)	+0.72
JH	1.36	+0.29(3)	+0.19(5)	+0.82(7)	+0.69(10)	+0.19(14)	+0.19(15)	+0.40
KJ	1.11	+0.44(2)	+0.48(5)	+0.61(8)	+0.44(10)	+0.36(12)	+0.32(15)	+0.44
IL	0.31	+0.53(1)	+0.54(5)	+0.42(8)	+0.42(10)	+0.13(12)	-0.34(15)	+0.29
HMcC	1.68	+0.43(2)	+0.71(4)	+0.71(7)	+0.45(10)	+0.47(12)	+0.39(15)	+0.51
SMcC	0.27	+0.10(2)	+0.18(4)	+0.41(6)	+0.66(9)	+0.36(12)	+0.16(15)	+0.31
MMcP	0.31	+0.46(3)	+0.66(6)	+0.71(9)	+0.35(13)	+0.35(14)	+0.29(15)	+0.47
CM	0.92	+1.21(2)	+0.92(8)	+0.73(11)	+0.47(15)			+0.83
EM	0.63	+0.29(2)	+0.38(5)	+0.48(8)	+0.05(11)	+0.10(14)	+0.14(15)	+0.24
AM	0.87	+0.23(3)	+0.19(8)	+0.90(12)	-0.01(13)	-0.01(15)		+0.26
MP	3.30	-0.40(3)	-0.34(6)	-0.35(9)	-0.19(12)	-0.19(14)		-0.30
JS	0.85	+0.70(6)	+0.63(9)	+0.38(11)	+0.43(15)			+0.54
SS	1.75	+0.23(2)	+0.63(10)	+0.43(12)	+0.57(15)			+0.47
AS	0.88	+1.52(6)	+1.21(9)	+0.82(11)	+0.43(15)			+0.99
BS	3.29	-0.29(6)	-0.25(10)	-0.25(12)	-0.25(15)			-0.25
CT	1.43	+1.03(2)	+0.53(6)	+0.44(8)	+0.54(10)	+0.59(13)	+0.59(15)	+0.62
MW	0.46	+0.06(3)	+0.12(6)	-0.03(9)	+0.09(12)	+0.12(14)	+0.14(15)	+0.08

Table XVI.11 - The induced change in the TV (D) of 27 observers (O) following 15min sustained interaction with the visual task at 275cm. A negative TV value indicates a divergent shift in the resting visual axes, whilst a positive value indicates a convergent shift. The figures in brackets following each post-task TV value indicate the time (min) at which result recorded.

O	PRE-TASK TV	CHANGE IN TV						MEAN TV CHANGE
MB	1.94	-0.01(1)	-0.20(4)	-0.66(7)	-0.89(11)	-0.75(13)	-0.79(15)	-0.55
RB	2.68	-0.71(1)	-0.64(5)	-0.51(9)	-0.47(13)	-0.41(15)		-0.55
SB	1.31	-0.05(1)	+0.29(3)	+0.04(7)	+0.09(11)	-0.12(13)	-0.21(15)	0.00
TC	1.57	-0.31(2)	-0.22(4)	-0.22(6)	-0.22(8)	-0.37(13)	-0.42(15)	-0.29
MD	1.53	-0.57(3)	-0.50(5)	-0.50(7)	-0.50(10)	-0.40(14)	-0.42(15)	-0.49
MD-H	2.69	-0.50(1)	-0.60(3)	-0.57(6)	-0.53(9)	-0.72(12)	+0.15(15)	-0.50
GE	1.42	-0.53(1)	-0.75(3)	-0.69(6)	-0.69(9)	-0.69(11)	-0.57(15)	-0.64
KE	2.21	-1.15(2)	-0.97(4)	-1.03(6)	-0.92(8)	-0.86(13)	-0.74(15)	-0.95
KF	1.57	-0.47(1)	-0.30(6)	-0.35(10)	-0.33(15)			-0.36
SH	1.74	-0.45(1)	-0.40(4)	-0.17(5)	-0.17(8)	-0.10(12)	0.00(15)	-0.28
IH-T	1.86	-0.22(1)	-0.34(5)	-0.36(8)	-0.18(10)	-0.18(15)		-0.26
JH	1.50	-0.20(1)	-0.25(4)	-0.12(7)	+0.06(10)	0.00(11)	+0.09(15)	-0.11
KJ	1.86	-0.29(1)	-0.29(6)	-0.25(8)	-0.29(12)	-0.49(15)		-0.31
IL	0.92	-0.30(1)	-0.27(6)	-0.24(8)	-0.27(10)	-0.34(13)	-0.27(15)	-0.29
HMcC	2.55	-1.33(2)	-1.46(4)	-1.15(6)	-1.33(9)	-0.80(11)	-0.60(15)	-1.02
SMcC	1.82	-0.54(1)	-0.50(3)	-0.03(6)	-0.14(10)	-0.14(13)	-0.20(15)	-0.24
MMcP	1.58	+0.07(1)	+0.01(6)	-0.16(12)	-0.20(15)			-0.07
CM	1.80	-0.30(1)	-0.47(5)	-0.44(7)	-0.04(10)	-0.04(12)	-0.04(15)	-0.20
EM	1.88	-0.37(1)	-0.37(4)	-0.23(8)	-0.24(10)	-0.13(15)		-0.27
AM	1.85	-1.12(2)	-0.86(4)	-1.00(6)	-0.97(11)	-0.91(13)	-0.92(15)	-0.97
MP	3.74	-0.10(1)	-0.73(6)	-0.79(9)	-0.82(15)			-0.61
JS	2.55	-0.35(1)	-0.35(5)	-0.20(8)	-0.31(13)	-0.31(15)		-0.30
SS	2.30	-0.11(1)	-0.40(6)	-0.46(8)	-0.98(12)	-0.98(13)	-0.98(15)	-0.65
AS	1.60	-1.04(3)	-1.04(5)	-0.95(9)	-0.78(13)	-0.72(15)		-0.91
BS	1.82	+0.03(1)	-0.26(6)	-0.34(11)	-0.12(14)	-0.12(15)		-0.16
CT	2.05	-1.06(3)	-0.31(6)	-0.31(8)	-0.31(10)	-0.31(12)	-0.31(15)	-0.44
MW	1.30	-0.32(1)	-0.23(6)	-0.17(9)	-0.43(13)	-0.31(15)		-0.29

Table XVI.12 - The induced change in the TV (D) of 27 observers (O) following 15min sustained interaction with the visual task at 100cm. A negative TV value indicates a divergent shift in the resting visual axes, whilst a positive value indicates a convergent shift. The figures in brackets following each post-task TV value indicate the time (min) at which result recorded.

O	PRE-TASK TV			CHANGE IN TV				MEAN TV CHANGE
MB	2.44	-0.40(1)	-0.60(2)	-0.60(4)	-0.50(9)	+0.19(11)	+0.19(15)	-0.31
RB	2.30	-0.28(2)	-0.31(6)	-0.25(9)	-0.27(12)	-0.15(13)	-0.15(15)	-0.23
SB	1.13	-0.09(3)	-0.34(7)	-0.43(10)	-0.40(15)			-0.32
TC	1.54	+0.32(2)	+0.11(5)	+0.16(7)	+0.13(11)	-0.13(13)	+0.13(15)	+0.16
MD	1.01	+0.03(3)	+0.09(7)	+0.31(9)	+0.43(12)	+0.43(15)		+0.26
MD-H	2.65	-0.34(4)	-0.24(10)	-0.39(13)	-0.10(14)	-0.11(15)		-0.24
GE	2.08	-0.11(1)	-0.13(7)	-0.17(10)	-0.20(12)	-0.26(15)		-0.17
KE	2.14	-0.12(3)	-0.24(5)	-0.12(8)	-0.12(9)	-0.06(12)	-0.06(15)	-0.12
KF	1.69	+0.21(1)	+0.33(5)	+0.32(8)	+0.01(10)	+0.13(14)	+0.13(15)	+0.19
SH	2.06	0.00(3)	-0.28(5)	-0.24(9)	-0.20(13)	-0.20(15)		-0.19
IH-T	1.48	0.00(2)	+0.15(5)	+0.08(9)	+0.11(12)	+0.11(13)	+0.11(15)	+0.09
JH	1.93	0.00(1)	+0.03(4)	-0.12(6)	-0.24(8)	-0.04(13)	-0.04(15)	-0.11
KJ	1.52	-0.37(1)	+0.18(4)	+0.18(7)	+0.09(8)	+0.16(15)		-0.11
IL	0.73	+0.09(3)	0.00(6)	+0.09(9)	+0.12(10)	+0.12(12)	+0.17(15)	+0.07
HMcC	1.93	-0.23(1)	-0.04(4)	0.00(6)	+0.06(9)	+0.03(15)		-0.05
SMcC	2.56	-0.72(1)	-0.29(5)	-0.29(8)	-0.29(10)	-0.22(13)	-0.25(15)	-0.33
MMcP	1.98	-0.16(1)	+0.17(6)	+0.16(8)	-0.23(10)	-0.03(15)		-0.02
CM	2.05	0.00(2)	-0.23(7)	-0.26(10)	-0.23(12)	-0.23(15)		-0.19
EM	2.11	0.00(1)	-0.06(4)	-0.23(9)	-0.23(12)	-0.23(15)		-0.15
AM	1.30	+0.29(1)	+0.32(4)	+0.32(8)	+0.32(10)	+0.32(12)	+0.32(15)	+0.31
MP	3.21	-0.06(1)	-0.46(3)	-1.01(9)	-0.71(15)			-0.56
JS	3.25	-0.65(1)	-0.26(4)	-0.26(10)	-0.30(12)	-0.37(15)		-0.37
SS	1.82	-0.03(1)	-0.09(4)	-0.18(8)	-0.18(12)	-0.03(15)		-0.09
AS	1.99	-0.08(1)	-0.14(4)	-0.46(7)	-0.28(13)	-0.02(15)		-0.20
BS	3.50	0.00(6)	-0.94(10)	-1.10(14)	-1.31(15)			-0.84
CT	2.49	-0.58(3)	-0.44(5)	-0.18(8)	-0.18(11)	-0.14(13)	-0.16(15)	-0.28
MW	1.62	+0.19(1)	+0.14(7)	+0.13(11)	+0.03(15)			+0.12

Table XVI.13 - The induced change in the TV (D) of 27 observers (O) following 15min sustained interaction with the visual task at 33cm. A negative TV value indicates a divergent shift in the resting visual axes, whilst a positive value indicates a convergent shift. The figures in brackets following each post-task TV value indicate the time (min) at which result recorded.

O	PRE-TASK TV	CHANGE IN TV						MEAN TV CHANGE
MB	1.94	0.00(1)	+0.06(5)	+0.27(7)	+0.28(10)	+0.36(12)	+0.36(15)	+0.22
RB	1.94	+1.30(6)	+1.56(9)	+1.56(12)	+1.56(15)			+0.95
SB	1.30	-0.59(2)	-0.34(7)	-0.26(11)	-0.26(13)	-0.31(15)		-0.12
TC	1.65	+0.23(2)	-0.31(6)	+0.15(8)	+0.25(11)	+0.17(13)	+0.17(15)	+0.21
MD	1.13	-0.29(1)	+0.06(3)	+0.06(6)	+0.17(9)	+0.06(13)	-0.03(15)	0.00
MD-H	2.20	+0.74(1)	+0.74(5)	+0.55(7)	+0.14(12)	+0.46(15)		+0.53
GE	0.90	+0.97(1)	+1.06(6)	+0.95(11)	+0.69(13)	+0.63(15)		+0.67
KE	2.53	+0.28(1)	+0.17(5)	+0.28(7)	+0.17(9)	+0.03(11)	-0.05(15)	+0.15
KF	1.96	-0.03(1)	-0.03(4)	+0.11(7)	-0.04(10)	-0.02(15)		0.00
SH	1.86	-0.14(1)	+0.37(5)	-0.14(8)	-0.17(10)	-0.17(13)	0.00(15)	-0.04
IH-T	1.86	+0.12(1)	+0.12(5)	-0.03(7)	-0.07(9)	+0.03(11)	+0.03(15)	+0.03
JH	1.93	0.00(1)	0.00(4)	0.00(6)	+0.20(8)	+0.08(11)	+0.08(15)	+0.06
KJ	2.09	-0.18(1)	-0.17(4)	-0.11(6)	-0.11(9)	-0.13(13)	-0.13(15)	-0.13
IL	0.59	+0.24(1)	+0.22(4)	+0.27(6)	+0.16(9)	+0.16(10)	+0.16(15)	+0.22
HMcC	2.43	-0.29(1)	+0.76(7)	+0.86(8)	+0.65(11)	+0.76(13)	+0.78(15)	+0.45
SMcC	1.90	+0.09(1)	+0.09(2)	+0.08(7)	+0.08(9)	+0.03(10)	+0.08(15)	+0.07
MMcP	1.83	+0.18(3)	+0.09(7)	+0.01(10)	+0.01(14)	+0.01(15)		+0.06
CM	1.87	+0.09(1)	+0.36(5)	+0.38(9)	+0.25(11)	-0.05(15)		+0.21
EM	1.86	+0.09(3)	+0.09(6)	+0.07(9)	0.00(12)	+0.07(13)	+0.03(15)	+0.06
AM	1.37	+0.27(1)	+0.18(4)	+0.16(7)	-0.14(9)	-0.49(13)	-0.49(15)	-0.09
MP	3.97	-0.08(5)	-0.08(7)	-0.06(10)	-0.06(13)	-0.06(15)		-0.07
JS	1.98	+1.21(2)	+1.20(7)	+0.74(13)	+0.67(15)			+0.95
SS	1.90	0.00(1)	0.00(6)	+0.20(12)	+0.20(15)			+0.10
AS	1.60	0.00(2)	+0.39(7)	+0.37(10)	+0.14(12)	+0.06(15)		+0.19
BS	3.66	-0.06(1)	-0.06(6)	-0.03(11)	-0.06(15)			-0.05
CT	2.69	-0.11(4)	+0.30(6)	+0.30(8)	+0.30(10)	+0.20(13)	+0.20(15)	+0.20
MW	1.47	0.00(1)	+0.10(4)	+0.13(7)	+0.13(10)	+0.05(12)	+0.09(15)	+0.08

Table XVI.14 - The means ($\bar{X}$) and standard deviations (sd) of the hysteretic changes in TA (D) for the three task locations (275, 100 and 33cm) over the 15min post-task measurement period (subdivided into 5 discrete time zones) for the 27 observers, divided on the basis of their mean pre-task TA levels, into three groups of 9 observers: the 'far', 'intermediate' and 'near' groups.

		TIME GROUPING					
TA GROUP AND TASK LOCATION		1 - 3	4 - 6	7 - 9	10 - 12	13 - 15	MEAN CHANGE AND sd
FAR - 275cm	$\bar{X}$	-0.12	-0.11	-0.16	-0.19	-0.19	-0.16
	sd	0.27	0.18	0.16	0.15	0.15	0.18
INT' - 275cm	$\bar{X}$	-0.24	-0.40	-0.46	-0.44	-0.45	-0.45
	sd	0.22	0.31	0.29	0.27	0.29	0.28
NEAR - 275cm	$\bar{X}$	-0.41	-0.47	-0.58	-0.75	-0.56	-0.55
	sd	0.46	0.37	0.26	0.34	0.28	0.34
FAR - 100cm	$\bar{X}$	+0.18	+0.34	+0.22	+0.20	+0.11	+0.21
	sd	0.25	0.21	0.21	0.19	0.32	0.24
INT' - 100cm	$\bar{X}$	+0.09	-0.04	-0.14	-0.02	+0.01	-0.02
	sd	0.20	0.12	0.13	0.20	0.21	0.17
NEAR - 100cm	$\bar{X}$	-0.26	-0.15	-0.41	-0.27	-0.23	-0.28
	sd	0.31	0.29	0.33	0.20	0.31	0.29
FAR - 33cm	$\bar{X}$	+0.23	+0.43	+0.43	+0.33	+0.24	+0.33
	sd	0.16	0.23	0.27	0.30	0.35	0.26
INT' - 33cm	$\bar{X}$	+0.52	+0.59	+0.59	+0.56	+0.32	+0.52
	sd	0.38	0.54	0.36	0.27	0.20	0.35
NEAR - 33cm	$\bar{X}$	+0.08	+0.10	+0.31	+0.13	+0.14	+0.15
	sd	0.31	0.44	0.42	0.29	0.31	0.35

Table XVI.15 - This table provides the mean and standard deviation hysteretic changes of TV (deg) for the three task locations (275, 100 and 33cm) over the 15min post-task measurement period (subdivided into 5 discrete time zones) for the 27 observers, having been formed into three groups of 9 observers (the "far", "intermediate" and "near" groups), on the basis of their mean pre-task TV levels.

TV GROUP AND		TIME GROUPING					MEAN CHANGE
TASK LOCATION		1 - 3	4 - 6	7 - 9	10 - 12	13 - 15	AND sd
FAR - 275cm	$\bar{X}$	-0.36	-0.35	-0.35	-0.34	-0.36	-0.35
	sd	0.36	0.27	0.33	0.32	0.23	0.30
INT' - 275cm	$\bar{X}$	-0.47	-0.41	-0.40	-0.21	-0.25	-0.35
	sd	0.25	0.30	0.28	0.24	0.29	0.27
NEAR - 275cm	$\bar{X}$	-0.55	-0.60	-0.69	-0.72	-0.50	-0.61
	sd	0.53	0.36	0.32	0.28	0.37	0.37
FAR - 100cm	$\bar{X}$	+0.09	+0.18	+0.12	+0.06	+0.10	+0.11
	sd	0.17	0.13	0.20	0.26	0.23	0.20
INT' - 100cm	$\bar{X}$	-0.22	-0.14	-0.21	-0.24	-0.16	-0.19
	sd	0.29	0.17	0.16	0.04	0.15	0.16
NEAR - 100cm	$\bar{X}$	-0.28	-0.24	-0.31	-0.21	-0.26	-0.26
	sd	0.20	0.20	0.34	0.33	0.43	0.30
FAR - 33cm	$\bar{X}$	+0.02	+0.14	+0.05	+0.03	-0.03	+0.04
	sd	0.28	0.12	0.16	0.16	0.21	0.19
INT' - 33cm	$\bar{X}$	+0.24	+0.29	+0.26	+0.16	+0.18	+0.23
	sd	0.50	0.43	0.43	0.35	0.32	0.41
NEAR - 33cm	$\bar{X}$	+0.11	+0.28	+0.51	+0.35	+0.38	+0.33
	sd	0.36	0.49	0.54	0.51	0.52	0.48

APPENDIX XVII

THE EFFECT OF TIMOLOL MALEATE ON TA AND TV - DATA.

This Appendix provides the data from the Timolol Maleate study of Chapter 6. Tables XVII.1 and XVII.2 illustrate the effects of Timolol and the control Saline respectively, on the TA measurements taken before and during the 40min post-drug measurement period, in total darkness. Tables XVII.3 and XVII.4 show the effects of Timolol and Saline respectively, on the TV measurements taken before and during the same post-drug period.

Table XVII.5 illustrates the effect that Timolol and Saline have on the pre- and post-drug measurement of TP. Table XVII.6 provides the results of Timolol and the saline control on IOP. Table XVII.7 shows the effect of Timolol and saline on pre- and post-drug measures of Rx, AA, AC/A, and the distance and near heterophorias.

Table XVII.1 - Measures of TA (at 632.8nm) before and during a 40min period after, instillation of Timolol to 10 observers (O). The figures in brackets following each post-drug TA measure indicates the time (in mins) that had elapsed since instillation of the drug.

	PRE-DRUG			POST-DRUG		
O	TA			TA		
BG	1.94	2.31(20)	2.27(25)	2.56(30)	2.88(36)	2.94(41)
SB	0.74	1.02(18)	1.05(24)	1.05(29)	1.10(34)	1.26(40)
SS	1.36	1.40(20)	1.60(26)	1.84(31)	2.00(38)	2.12(41)
MB	0.39	0.69(18)	0.73(27)	0.79(30)	0.82(36)	0.90(41)
JS	1.90	2.15(19)	2.90(24)	2.81(29)	3.02(36)	2.91(41)
MJ	1.03	1.31(17)	1.67(22)	1.61(29)	1.77(37)	1.79(42)
PM	1.47	1.58(14)	1.72(23)	1.82(30)	1.86(35)	2.00(41)
AD	1.53	1.67(20)	1.78(25)	2.30(29)	2.61(34)	2.76(40)
AH	0.71	0.76(20)	1.16(24)	1.27(27)	1.32(37)	1.40(42)
SR	2.02	2.88(17)	3.01(23)	3.06(31)	3.21(36)	3.20(41)

Table XVII.2 - Measures of TA (at 632.8nm) before and during a 40min period after, instillation of a Saline control, to 10 observers (O). The figures in brackets following each post-drug TA (D) measure indicates the time (in mins) that had elapsed since instillation of the Saline.

O	PRE-DRUG TA			POST-DRUG TA		
BG	2.11	2.28(19)	2.45(26)	2.15(29)	2.25(37)	2.19(43)
SB	0.59	0.57(17)	0.55(26)	0.59(29)	0.55(38)	0.47(42)
SS	1.46	1.55(17)	1.65(25)	1.41(33)	1.55(39)	1.55(43)
MB	0.35	0.23(20)	0.36(30)	0.39(33)	0.33(36)	0.30(41)
JS	2.04	2.00(21)	2.22(29)	2.07(33)	1.81(35)	2.04(40)
MJ	0.88	0.89(19)	0.89(26)	0.63(30)	0.79(38)	0.70(41)
PM	1.50	1.53(17)	1.43(23)	1.49(26)	1.46(32)	1.42(40)
AD	1.30	1.24(19)	1.03(23)	1.35(32)	1.30(38)	1.34(41)
AH	0.88	0.82(17)	0.88(23)	0.87(32)	0.86(38)	0.79(43)
SR	1.82	2.07(16)	1.74(26)	1.92(29)	1.81(34)	1.91(40)

Table XVII.3 - Measures of TV (deg) before and during a 40min period after, instillation of Timolol, to 10 observers (O). The figures in brackets following each post-drug TV measure indicates the time (in mins) that had elapsed since instillation of Timolol.

O	PRE-DRUG TV			POST-DRUG TV		
BG	1.74	1.74(20)	1.85(25)	1.79(30)	1.79(36)	1.79(42)
SB	1.89	1.78(18)	1.85(24)	1.85(29)	1.85(34)	1.85(40)
SS	2.27	2.27(17)	2.30(26)	2.30(31)	2.30(34)	2.23(41)
MB	2.00	2.00(18)	2.12(24)	1.93(30)	1.96(36)	1.96(41)
JS	3.16	3.03(19)	3.08(24)	3.12(29)	3.12(36)	3.12(41)
MJ	1.87	1.80(17)	1.65(22)	1.65(28)	1.61(36)	1.61(41)
PM	1.77	1.98(14)	2.05(23)	1.95(30)	1.95(35)	2.02(41)
AD	1.12	1.15(20)	1.15(25)	1.18(29)	1.09(34)	1.09(40)
AH	3.67	3.67(20)	3.67(26)	3.67(29)	3.67(34)	3.62(39)
SR	1.74	1.67(17)	1.78(23)	1.81(27)	1.81(33)	1.81(38)

Table XVII.4 - Measures of TV (deg) before and during a 40min period after, instillation of Saline to 10 observers (O). The figures in brackets following each post-drug TV measure indicates the time (in mins) that had elapsed since instillation of the drug.

O	PRE-DRUG TV			POST-DRUG TV		
BG	2.21	2.21(19)	2.31(25)	2.31(28)	2.31(33)	2.31(39)
SB	1.51	1.33(17)	1.44(26)	1.55(29)	1.55(33)	1.55(42)
SS	2.15	2.15(15)	2.15(23)	2.39(31)	2.11(37)	2.11(41)
MB	1.76	1.76(20)	1.79(30)	1.79(33)	1.84(36)	1.84(41)
JS	2.93	2.85(21)	2.89(28)	2.89(33)	2.89(35)	2.89(40)
MJ	1.43	1.43(15)	1.36(26)	1.36(30)	1.36(38)	1.36(41)
PM	1.84	1.87(17)	1.91(25)	2.06(28)	2.06(34)	1.98(42)
AD	0.75	0.65(19)	0.65(23)	0.59(27)	0.59(32)	0.69(41)
AH	3.54	3.54(17)	3.57(23)	3.57(27)	3.61(36)	3.61(41)
SR	1.53	1.60(16)	1.57(26)	1.64(29)	1.64(34)	1.64(40)

Table XVII.5 - The effect of Timolol and a Saline control on measures of horizontal pupil diameter (mm) taken from 10 observers (O) in total darkness over a 40min period. Each reading is the mean of two recordings.

	TIMOLOL MALEATE		SALINE CONTROL	
O	Pre-	40min	Pre-	40min
BG	6.7	6.5	6.6	6.6
SB	7.7	7.7	7.6	7.7
SS	7.1	7.0	7.2	7.1
MB	7.3	7.4	7.3	7.2
JS	7.0	6.7	6.9	7.0
MJ	7.5	7.4	7.5	7.5
PM	7.4	7.0	7.4	7.4
AD	7.1	6.6	6.7	6.8
AH	6.6	6.5	6.4	6.5
SR	6.9	6.9	6.8	6.9

Table XVII.6 - The effect of Timolol and a Saline control on measures of IOP (mmHg) taken from the right (R) and left (L) eyes of 10 observers (O) over a 40min period.

	TIMOLOL				SALINE CONTROL			
	Pre-		40min		Pre-		40min	
O	R	L	R	L	R	L	R	L
BG	16	15	13	13	15	16	15	16
SB	15	15	13	13	13	13	14	14
SS	16	17	14	14	17	17	16	17
MB	14	14	11	11	16	16	15	15
JS	14	15	11	11	14	14	14	14
MJ	15	15	13	13	13	13	13	13
PM	16	15	13	12	14	14	15	15
AD	14	14	11	12	14	14	14	14
AH	14	14	11	12	13	13	13	13
SR	13	13	10	11	13	13	13	13

Table XVII.7 - The left-eye best-sphere distance refractive error (Rx), the left-eye amplitude of accommodation (AA - mean of 5 measurements), AC/A ratio, and the heterophoria at 6m and 33cm, of 10 observers (O), before (pre-) and after (40min) instillation of Timolol.

							HETEROPHORIA			
	Rx (D)		AA (D)		AC/A		6m		33cm	
O	Pre	40min	Pre-	40min	Pre-	40min	Pre-	40min	Pre-	40min
BG	-4.75	-5.00	5.00	5.25	3.00	3.00	ortho	ortho	1Sop	2Sop
SB	+0.13	-0.13	7.40	7.15	2.00	2.33	ortho	ortho	2Xop	2Xop
SS	+0.75	+0.75	6.25	6.50	2.67	2.33	1Xop	1Xop	7Xop	7Xop
MB	-0.25	-0.50	9.80	9.85	2.33	2.67	2Sop	2Sop	2Sop	2Sop
JS	+0.50	+0.50	8.50	8.50	1.67	1.67	ortho	ortho	ortho	ortho
MJ	plano	-0.13	7.95	7.90	1.00	2.00	ortho	ortho	3Xop	2Xop
PM	+1.63	+1.38	7.25	6.75	2.33	3.00	1Sop	1Sop	2Xop	2Xop
AD	-3.88	-3.63	10.10	10.85	3.33	3.33	0.5Xop	0.5Xop	1Xop	ortho
AH	-3.13	-3.25	6.60	6.05	2.00	2.00	1Sop	2Sop	1Xop	1Sop
SR	+0.63	+0.63	7.00	7.00	1.33	1.00	ortho	ortho	8Xop	7Xop

APPENDIX XVIII

PREPARATION OF ISOPRENALINE SULPHATE (3%) AND CONTROL.

The 3% solution of Isoprenaline Sulphate and its Control were specially manufactured by Dr. Lee Wan Po, in the Department of Pharmaceutical Sciences, Aston University. The constituents used are listed below:

Table XVIII.1 - The preparation of a 3% solution of Isoprenaline and its control

	3% Solution	Control
ISOPRENALINE SULPHATE	750 mg	-
SODIUM METABISULPHATE BP	25 mg	25 mg
SODIUM CHLORIDE BP	230 mg	418 mg
DOUBLE-DISTILLED WATER	to 25 ml	to 25 ml

Both solutions were dispensed into 25ml 'ribbed' brown-glass bottles, labelled accordingly and autoclaved at 115-116°C (10 lbs/in^2) for 30 min.

APPENDIX XIX

THE EFFECT OF ISOPRENALINE SULPHATE (3%) ON TA AND TV - DATA.

This Appendix provides the data resulting from the Isoprenaline studies of Chapter 6.

Table XIX.1 - Measures of TA (at 632.8nm) before and during a 40min period after, instillation of 50microlitres Isoprenaline to 10 observers (O). The figures in brackets following each post-drug TA (D) measure indicates the time (in mins) that had elapsed since instillation of the drug.

O	PRE-DRUG TA	POST-DRUG TA					
BG	2.30	2.20(17)	2.10(19)	1.92(21)	1.70(24)	2.02(30)	2.09(32)
RH	1.21	0.88(15)	0.68(19)	0.50(23)	0.58(25)	0.68(33)	0.83(36)
MDH	1.55	1.25(16)	1.22(19)	1.24(21)	0.98(25)	0.80(33)	0.98(36)
SS	2.44	2.51(15)	2.03(18)	2.19(20)	2.01(22)	1.97(24)	2.03(28)
SMcC	0.19	0.09(15)	-0.02(18)	-0.13(21)	-0.22(23)	-0.17(31)	0.07(33)
MP	2.75	2.83(15)	2.73(18)	2.42(21)	2.18(24)	2.25(30)	2.55(36)
KJ	0.45	0.59(17)	0.35(18)	0.13(23)	-0.11(24)	-0.11(25)	-0.08(28)
IL	0.53	0.61(17)	0.53(19)	0.45(20)	0.56(27)	0.43(28)	0.43(37)
AS	1.45	1.43(18)	1.06(21)	0.84(25)	0.74(29)	0.76(31)	1.02(35)
KF	0.27	0.05(16)	-0.20(19)	-0.65(24)	-0.80(26)	-0.71(31)	-0.32(35)

Table XIX.2 - Measures of TA (at 632,8nm) before and during a 40min period after, instillation of the Control, to 10 observers (O). The figures in brackets following each post-drug TA (D) measure indicates the time (in mins) that had elapsed since instillation of the Control.

O	PRE-DRUG TA	POST-DRUG TA					
BG	2.63	2.60(16)	2.83(19)	2.73(22)	2.70(24)	2.88(28)	2.63(32)
RH	0.92	0.88(16)	0.83(19)	0.78(21)	0.82(25)	0.76(28)	0.91(31)
MDH	1.49	1.47(15)	1.53(18)	1.60(23)	1.49(27)	1.56(31)	1.47(34)
SS	2.32	2.46(17)	2.39(19)	2.30(22)	2.40(25)	2.42(29)	2.27(33)
SMcC	0.31	0.28(16)	0.42(19)	0.28(22)	0.30(25)	0.40(27)	0.28(31)
MP	2.99	2.80(17)	2.88(19)	3.11(22)	3.02(24)	2.71(28)	2.88(32)
KJ	0.45	0.39(17)	0.48(19)	0.28(22)	0.46(27)	0.47(29)	0.38(31)
IL	0.37	0.52(15)	0.42(19)	0.50(23)	0.36(27)	0.41(29)	0.37(32)
AS	1.71	1.81(16)	1.68(21)	1.77(23)	1.72(26)	1.67(28)	1.74(33)
KF	0.32	0.40(15)	0.33(17)	0.41(22)	0.30(26)	0.30(29)	0.37(33)

Table XIX.3 - Measures of TV (deg) before and during a 40min period after, instillation of Isoprenaline (3%), to 10 observers (O). The figures in brackets following each post-drug TV measure indicates the time (in mins) that had elapsed since instillation of Isoprenaline.

O	PRE-DRUG TV	POST-DRUG TV					
BG	1.94	1.57(17)	1.55(19)	1.67(21)	1.67(24)	1.67(30)	1.64(32)
RH	1.06	1.06(15)	1.06(17)	0.90(21)	0.90(24)	0.85(27)	0.85(32)
MDH	1.69	1.81(17)	1.81(20)	1.89(23)	1.80(27)	1.80(28)	1.71(31)
SS	3.09	3.09(15)	2.94(18)	2.59(20)	2.27(22)	2.09(24)	2.09(28)
SMcC	1.70	1.65(15)	1.82(18)	1.59(21)	1.59(23)	1.62(28)	1.62(31)
MP	2.96	2.46(15)	2.38(18)	2.21(21)	2.33(24)	2.33(30)	2.46(33)
KJ	1.68	1.59(15)	1.70(17)	1.45(20)	1.45(23)	1.42(25)	1.33(28)
IL	0.36	0.53(17)	0.22(19)	0.22(20)	0.39(23)	0.44(28)	0.44(32)
AS	1.18	0.93(17)	0.80(18)	0.80(21)	0.86(26)	0.87(29)	0.93(35)
KF	1.76	1.62(16)	1.56(19)	1.56(21)	1.53(26)	1.53(31)	1.53(35)

Table XIX.4 - Measures of TV (deg) before and during a 40min period after, instillation of Control solution to 10 observers (O). The figures in brackets following each post-drug TV measure indicates the time (in mins) that had elapsed since instillation of the control.

O	PRE-DRUG TV	POST-DRUG TV					
BG	1.92	1.92(16)	1.92(19)	1.92(20)	1.92(25)	1.92(28)	1.92(33)
RH	1.10	1.10(16)	1.10(19)	1.18(20)	1.10(22)	1.10(28)	1.10(33)
MDH	2.65	2.31(15)	2.41(19)	2.64(22)	2.55(26)	2.54(30)	2.31(33)
SS	2.30	2.30(17)	2.27(19)	2.27(21)	2.23(25)	2.23(29)	2.23(32)
SMcC	2.71	2.45(16)	2.66(19)	2.62(22)	2.42(26)	2.62(30)	2.77(32)
MP	3.97	3.87(15)	3.89(17)	3.91(19)	3.91(22)	3.91(24)	3.97(29)
KJ	1.52	1.52(16)	1.54(19)	1.61(20)	1.53(23)	1.53(28)	1.53(31)
IL	0.65	0.62(16)	0.65(18)	0.67(20)	0.65(24)	0.57(27)	0.65(31)
AS	0.87	0.87(17)	0.87(21)	0.88(22)	0.93(26)	0.87(31)	0.80(33)
KF	1.59	1.59(15)	1.62(19)	1.53(20)	1.56(24)	1.62(29)	1.62(32)

Table XIX.5 - The effect of Isoprenaline and control solution on pre- and post-drug measures of right-eye horizontal pupil diameter (mm) taken from 10 observers (O) in total darkness. Each reading is the mean of two recordings.

	ISOPRENALINE SULPHATE		CONTROL SOLUTION	
O	Pre-	Post-	Pre-	Post-
BG	6.45	6.5	6.5	6.5
RH	8.4	8.4	8.35	8.35
MDH	8.4	8.5	8.5	8.5
SS	7.05	7.15	7.1	7.1
SMcC	6.35	6.35	6.4	6.4
MP	6.05	5.7	6.0	6.0
KJ	7.4	7.4	7.3	7.35
IL	7.3	7.5	7.4	7.4
AS	7.6	7.6	7.6	7.6
KF	8.2	8.1	8.1	8.1

Table XIX.6 - The effect of Isoprenaline and a control solution on the mean of three pre- and post-drug measures of IOP (mmHg), taken from the left eye of 10 observers (O).

	ISOPRENALINE		CONTROL	
O	Pre	Post	Pre	Post
BG	17.3	17.0	17.0	17.0
RH	16.3	16.3	16.0	16.0
MDH	17.7	17.7	17.5	17.5
SS	22.0	18.0	20.3	20.3
SMcC	15.0	15.5	15.0	15.0
MP	11.0	11.5	12.7	12.5
KJ	15.5	13.0	14.0	14.3
IL	17.7	15.7	16.0	16.0
AS	15.5	15.0	15.7	15.5
KF	16.7	16.5	15.7	15.5

Table XIX.7 - The best-sphere distance refractive error (Rx) and amplitude of accommodation from the left-eye of 10 observers (O) before (pre-) and after (40min) instillation of Isoprenaline (3%).

	Rx (D)		AA (D)	
O	Pre	Post	Pre	Post
BG	-4.50	-4.75	6.0	5.0
RH	-3.50	-3.50	8.5	8.0
MDH	-6.50	-6.75	13.0	12.0
SS	+0.50	+0.50	7.0	7.0
SMcC	-0.25	-0.25	9.5	9.0
MP	+0.50	+0.50	10.0	10.0
KJ	0.00	0.00	8.5	8.0
IL	0.00	0.00	7.5	7.5
AS	0.00	0.00	7.5	7.5
KF	-3.75	-3.75	12.5	12.5

Table XIX.8 - The effect of Isoprenaline (3%) and a control solution on pre- and post-drug measures of the heart rate (pulse) and blood pressure (BP) of 10 observers.

	PULSE (No. per min)				BP (mmHg)			
	ISOPRENALINE		CONTROL		ISOPRENALINE		CONTROL	
O	Pre	Post	Pre	Post	Pre	Post	Pre	Post
BG	65	110	70	70	110/75	125/70	115/75	110/75
RH	52	96	55	56	110/65	115/60	115/65	115/65
MDH	68	105	65	63	120/90	170/90	115/90	120/90
SS	68	108	66	65	140/80	160/70	140/75	140/70
SMcC	72	92	70	70	120/85	125/80	120/80	120/80
MP	84	120	82	81	120/50	120/50	110/60	110/60
KJ	68	120	67	64	120/65	160/75	110/70	110/70
IL	64	100	65	66	160/70	160/65	155/70	155/70
AS	62	94	60	61	160/80	165/75	155/70	160/70
KF	80	120	80	80	160/100	155/60	150/70	150/75

APPENDIX XX

THE EFFECT OF TROPICAMIDE ON TA AND TV - DATA.

This Appendix provides the data resulting from the Tropicamide studies of Chapter 6. Tables XX.1 and XX.2 illustrate the effects of Tropicamide and a Saline control, respectively, on the TA measurements taken in total darkness before and during the post-drug measurement period. Tables XX.3 and XX.4 show the effects of Tropicamide and the Saline control respectively, on the TV measurements taken before and during the same post-drug period. Table XX.5 illustrates the effect that Tropicamide and its Saline control have on the pre- and post-drug measurement of TP, whilst Table XX.6 shows the effect of Tropicamide and a Saline control on pre- and post-drug measures of distance spherical refractive error and the amplitude of accommodation.

Table XX.1 - Measures of TA (at 632.8nm) before and during a 40min period after, instillation of 50microlitres of Tropicamide to 10 observers (O). The figures in brackets after each post-drug TA (D) measure indicates the time (in mins) that had elapsed since instillation of the drug.

O	PRE-DRUG TA	POST-DRUG TA				
SS	2.32	0.05(16)	-0.57(20)	-0.40(22)	-0.46(24)	-0.51(26)
KJ	0.39	-0.17(15)	-0.11(19)	-0.14(22)	-0.13(24)	-0.14(27)
IL	0.11	-0.26(15)	-0.37(17)	-0.41(18)	-0.41(20)	-0.39(24)
MD	1.32	-0.11(16)	-0.34(18)	-0.49(20)	-0.49(22)	-0.49(25)
KF	0.10	-0.25(16)	-0.37(18)	-0.44(20)	-0.52(22)	-0.46(23)
SB	0.28	-0.06(16)	-0.10(19)	-0.14(23)	-0.20(24)	-0.25(26)
JS	0.71	0.02(17)	-0.13(20)	-0.28(23)	-0.31(25)	-0.27(27)
MDH	0.64	0.28(16)	0.13(19)	-0.20(22)	-0.20(23)	-0.17(26)
BG	2.51	1.23(16)	0.69(23)	0.04(26)	-0.08(27)	-0.47(30)
RH	0.93	-0.32(18)	-0.49(24)	-0.28(26)	-0.33(27)	-0.38(29)

Table XX.2 - Measures of TA (at 632.8nm) before and during a 40min period after, instillation of the Saline control, to 10 observers (O). The figures in brackets following each post-drug TA (D) measure indicates the time (in mins) that had elapsed since instillation of the Saline.

	PRE-DRUG	POST-DRUG				
O	TA	TA				
SS	2.22	2.19(15)	2.25(18)	2.20(22)	2.17(25)	2.22(27)
KJ	0.50	0.47(16)	0.44(19)	0.47(23)	0.51(25)	0.45(26)
IL	0.15	0.17(16)	0.20(18)	0.14(21)	0.17(24)	0.14(26)
MD	1.32	1.28(15)	1.33(18)	1.35(21)	1.27(24)	1.31(26)
KF	0.17	0.15(16)	0.20(19)	0.14(23)	0.20(25)	0.21(28)
SB	0.35	0.32(15)	0.29(20)	0.33(23)	0.41(26)	0.37(26)
JS	0.67	0.71(17)	0.75(19)	0.71(22)	0.68(24)	0.68(26)
MDH	0.65	0.70(16)	0.67(20)	0.59(23)	0.64(25)	0.67(27)
BG	2.43	2.40(17)	2.53(21)	2.39(24)	2.50(27)	2.46(29)
RH	1.03	0.98(16)	1.12(20)	0.99(23)	1.06(26)	1.03(28)

Table XX.3 - Measures of TV (deg) before and during a 40min period after, instillation of Tropicamide, to 10 observers (O). The figures in brackets following each post-drug TV measure indicates the time (in mins) that had elapsed since the initial instillation of the drug.

	PRE-DRUG	POST-DRUG				
O	TV	TV				
SS	2.74	2.74(16)	2.68(20)	2.68(23)	2.77(24)	2.74(26)
KJ	1.83	1.77(15)	1.91(19)	1.91(22)	1.92(24)	1.92(27)
IL	0.53	0.39(15)	0.56(18)	0.56(20)	0.56(23)	0.53(25)
MD	1.95	1.87(16)	1.98(18)	1.98(20)	1.90(22)	1.85(25)
KF	1.39	1.45(16)	1.45(18)	1.39(20)	1.47(23)	1.39(26)
SB	1.13	1.02(16)	0.79(19)	1.07(23)	1.02(26)	1.02(28)
JS	2.16	2.31(15)	2.29(18)	2.20(21)	2.16(24)	2.29(27)
MDH	1.66	1.49(16)	1.55(18)	1.55(21)	1.78(25)	1.78(28)
BG	1.81	1.60(14)	1.59(20)	1.51(22)	1.58(25)	1.64(27)
RH	0.92	1.08(14)	0.92(20)	0.87(24)	1.08(26)	1.08(30)

Table XX.4 - Measures of TV (deg) before and during a 40min period after, instillation of a Saline control to 10 observers (O). The figures in brackets following each post-drug TV measure indicates the time (in mins) that had elapsed since instillation of the drug control.

	PRE-DRUG	POST-DRUG				
O	TV	TV				
SS	2.68	2.68(16)	2.74(19)	2.80(22)	2.69(23)	2.69(26)
KJ	1.91	1.83(15)	1.96(18)	1.87(22)	1.91(24)	1.96(27)
IL	0.54	0.39(14)	0.53(19)	0.44(23)	0.54(25)	0.42(26)
MD	2.03	2.03(16)	2.03(20)	1.96(22)	2.01(24)	2.07(27)
KF	1.45	1.39(16)	1.44(19)	1.39(23)	1.45(25)	1.39(28)
SB	1.05	0.96(15)	1.12(18)	1.00(21)	0.93(25)	1.02(26)
JS	2.25	2.16(16)	2.22(19)	2.30(22)	2.21(24)	2.22(27)
MDH	1.59	1.61(17)	1.48(19)	1.60(23)	1.53(25)	1.59(28)
BG	1.71	1.71(15)	1.69(18)	1.73(22)	1.75(25)	1.65(27)
RH	1.02	0.97(14)	1.10(17)	1.04(22)	0.89(24)	1.02(27)

Table XX.5 - The effect of Tropicamide and a Saline control on pre- and post-drug measures of right-eye horizontal pupil diameter (mm) taken in total darkness from 10 observers (O). Each reading is the mean of two recordings.

	TROPICAMIDE		SALINE CONTROL	
O	Pre-	Post-	Pre-	Post-
SS	7.20	8.65	7.15	7.10
KJ	7.40	8.05	7.40	7.35
IL	7.30	8.05	7.35	7.40
MD	6.60	7.55	6.70	6.70
KF	7.80	9.20	7.75	7.80
SB	6.95	8.30	7.05	7.00
JS	6.70	8.80	7.40	7.40
MDH	8.25	9.10	8.40	8.45
BG	7.15	8.00	6.50	6.45
RH	7.40	8.50	7.60	7.65

Table XX.6 - The best-sphere distance refractive error (Rx) and amplitude of accommodation from the left-eye of 10 observers (O) before and after instillation of Tropicamide.

	Rx (D)		AA (D)	
O	Pre	Post	Pre	Post
SS	+0.75	+1.75	10.50	0.50
KJ	-0.50	plano	8.50	1.75
IL	plano	+0.25	8.50	0.50
MD	-0.75	-0.50	10.25	0.75
KF	-3.75	-3.50	10.50	1.00
SB	-0.25	+0.25	7.50	0.75
JS	-0.50	-0.25	9.50	1.00
MDH	-6.75	-6.25	11.00	0.50
BG	-4.75	-4.25	5.50	0.75
RH	-3.50	-3.00	8.00	0.50

APPENDIX XXI

PUBLISHED SUPPORTING PAPERS

XXI.1 - Hogan, R. E. and Gilmartin, B (1984a): Aspects of tonic levels of accommodation, vergence and pupil. Paper presented to the Society of Experimental Optometry, University of Aston, July 25 - 26, 1983. Abstracted in Ophthalmic and Physiological Optics. 4: 187.

XXI.2 - Gilmartin, B. and Hogan, R. E. (1984a): The effect of timolol maleate (0.5%) on tonic accommodation and tonic vergence. Paper presented to the Society of Experimental Optometry, University of Aston, July 25 - 26, 1983. Abstracted in Ophthalmic and Physiological Optics. 4: 188.

XXI.3 - Gilmartin, B. and Hogan, R. E. (1984b): The effect of a non-selective Beta adrenoceptor antagonist on tonic accommodation and tonic vergence. Paper published in Transactions of the First International Congress, B.C.O.O., London, April 11 - 14, 1984. 1: 140 - 147.

XXI.4 - Gilmartin, B., Hogan, R. E. and Thompson, S. M. (1984): The effect of timolol maleate on tonic accommodation, tonic vergence, and pupil diameter. Investigative Ophthalmology and Visual Science. 25: 763 - 770.

XXI.5 - Hogan, R. E. and Gilmartin, B. (1984b): The choice of laser speckle exposure duration in the measurement of tonic accommodation. Ophthalmic and Physiological Optics. 4: 365 - 368.

XXI.6 - Hogan, R. E. and Gilmartin, B. (1985a): The relationship between tonic vergence and oculomotor stress induced by ethanol. Ophthalmic and Physiological Optics. 5: 43 - 51.

XXI.7 - Gilmartin, B. and Hogan, R. E. (1985a): The role of the sympathetic nervous system in ocular accommodation and ametropia. Ophthalmic and Physiological Optics. 5: 91 - 93.

XXI.8 - Gilmartin, B. and Hogan, R. E. (1985b): The effect of a muscarinic receptor antagonist on tonic accommodation. Ophthalmic and Physiological Optics. 5: 234.

XXI.9 - Hogan, R. E. and Gilmartin, B. (1985b): The effect of sustained visual tasks on tonic accommodation and tonic vergence. Ophthalmic and Physiological Optics. 5: 234.

XXI.10 - Gilmartin, B. and Hogan, R. E. (1985c): The relationship between tonic accommodation and ciliary muscle innervation. Investigative Ophthalmology and Visual Science. 26: 1024 - 1028.

XXI.11 - Gilmartin, B. and Hogan, R. E. (1985d): The magnitude of longitudinal chromatic aberration of the human eye between 458nm and 633nm. Vision Research. Accepted for publication (proofs provided in appendix XXI.11).

REFERENCES

Abraham, S. V. (1964): The basic position of rest - convergence and divergence. Journal of Paediatric Ophthalmology. 1: 9 - 24.

Adams, A. J. (1977): The acute effects of alcohol and marijuana on vision. In: Frontiers in Visual Science, pp. 93 - 105. Edited by Cool, S. J. and Smith, E. L., Springer, New York.

Adler, F. H. (1945): Effect of anoxia on heterophoria and its analogy with convergent concomitant squint. Archives of Ophthalmology. 35: 227 - 232.

Adler, F. H. (1953): Pathological physiology of strabismus. Archives of Ophthalmology. 34: 227 - 232.

Ahlquist, R. P. (1948): A study of the adrenotropic receptors. American Journal of Physiology. 153: 586 - 600.

Allen, M. J. (1953): An investigation of the time characteristics of accommodation and convergence of the eyes. American Journal of Optometry & A. A. A. O.. 30: 393 - 402.

Allen, M. J. (1955): The stimulus to accommodation. American Journal of Optometry & A. A. A. O. 32: 422 - 431.

Allen, M. J. and Knoll, H. A. (1950): A method for the objective measurement of accommodation speed of the human eye. American Journal of Optometry & A. A. A. O. 27: 163 - 170.

Alpern, M. (1946): The after-effect of lateral duction testing on subsequent phoria measurements. American Journal of Optometry & A. A. A. O. 23: 442 - 447.

Alpern, M. (1950): The zone of clear single vision at the upper levels of accommodation and convergence. American Journal of Optometry & A. A. A. O. 27: 491 - 513.

Alpern, M. (1955): Testing distance effect on phoria measurement at various accommodation levels. Archives of Ophthalmology. 54: 906 - 915.

Alpern, M. (1958a): Variability of accommodation during steady fixation at various levels of illuminance. Journal of the Optical Society of America. 48: 193 - 197.

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

Alpern, M. (1962): Anatomical aspects. Chapter 4, in: The Eye. Vol. 3 (1st Edition). Ed. Davson, H. Academic Press, London.

Alpern, M. (1969a): Types of Movement. Chapter 5, in The Eye. Vol. 3 (2nd Edition), Ed. Davson, H. Academic Press, London.

Alpern, M. (1969b): 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. Industrial Medicine. 27: 551 - 555.

Alpern, M. and Larson, B. F. (1960): Vergence and accommodation: IV. Effect of luminance quantity on the AC/A. American Journal of Ophthalmology. 49: 1140 - 1149.

Alpern, M., Mason, G. L. and Jardinico, R. E. (1961): Vergence and accommodation v. pupil size changes associated with changes in accommodative vergence. American Journal of Ophthalmology. 52: 762.

Alpern, M. and Wolter, J. R. (1956): The relation of horizontal saccadic and vergence eye movements. Archives of Ophthalmology. 56: 685 - 690.

Alvarado, J. A. and Van Horn, C. (1975): Muscle cell types of the cat inferior oblique. In Basic Mechanisms of Ocular Motility. pp. 15 - 45. Eds. Lennerstrand, G. and Bach-y-Rita, P. Pergamon Press, Oxford.

Ames, A., Gliddon, G. H. and Ogle, K. N. (1932): Size and shape of ocular images. I. Methods of determination and physiological significance. Archives of Ophthalmology. 1: 576 - 597.

Amos, C. S. (1976): The effect of a nitrous-oxide mixture on the lateral heterophoria. American Journal of Optometry and Physiological Optics. 53: 182 - 186.

Angle, J. and Wissmann, D. A. (1980): The epidemiology of myopia. American Journal of Epidemiology. 111: 220 - 228.

Anisman, H. (1975): Time-dependent variations in aversively motivated behaviours: nonassociative effects of cholinergic and catecholaminergic activity. Psychological Review. 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, Plenum Press, New York.

Anisman, H. and Kokkinidis, L. (1974): Effects of central and peripheral adrenergic and cholinergic modification on time dependent processes in avoidance performance. Behavioural Biology. 10: 161 - 171.

Aslin, R. N. (1977): Development of binocular fixation in human infants. Journal of Experimental Child Psychology. 23: 133 - 150.

Aslin, R. N. (1981): Oculomotor constraints on binocular vision in infants. Paper presented to the Society for Research in Child Development, April 1981, Boston. (Source, Owens and Leibowitz, 1983).

Aslin, R. N. and Dobson, V. (1983): Dark vergence and dark accommodation in human infants. Vision Research. 23: 1671 - 1678.

Aslin, R. N., Dobson, V. and Jackson, R. W. (1982): Dark vergence and dark focus in human infants. Paper presented to the Association for Research in Vision and Ophthalmology, May 1982, Sarasota. Abstract in Investigative Ophthalmology and Visual Science. 22: 105.

Aslin, R. N. and Jackson, R. W. (1979): Accommodative-convergence in young infants: development of a synergistic sensory-motor system. Canadian Journal of Psychology. 33: 222 - 231.

Aslin, R. N. and Jackson, R. W. (1981): Dark vergence in human infants. Paper Presented to A.R.V.O. 1981, Sarasota, Florida. Abstracted in Supplement to Investigative Ophthalmology and Visual Science. 20: 47.

Bahuguna, R. D. and Malacara, D. (1983): Stationarity of speckle in laser refraction. Journal of the Optical Society of America. 73: 1213 - 1215.

Baker, J. R. (1966): Experiments on the function of the eye in light microscopy. Journal of the Royal Microscopic Society. 85: 231 - 254.

Baker, R., Brown, B. and Garner, L. (1983): Time course and variability of dark focus. Investigative Ophthalmology and Visual Science. 24: 1528 - 1531.

Baldwin, W. R. and Stover, W. B. (1968): Observation of laser standing wave patterns to determine refrative status. American Journal of Optometry & A. A. A. O. 45: 143 - 150.

Ball, G. V. (1951): Twilight myopia. In: Transactions of the International Optical Congress. pp. 92 - 103. British Optical Association, London.

Balsam, M. H. and Fry, G. A. (1959): Convergence-accommodation. American Journal of Optometry & A. A. A. O. 36: 567 - 575.

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

Barlow, H. B., Blakemore, C. and Pettigrew, J. D. (1967): The neural mechanism of binocular depth discrimination. Journal of Physiology (London). 193: 327 - 342.

Barris, M. C., Dawson, W. W. and Theis, C. L. (1980): The visual sensitivity of women during the menstrual cycle. Documenta Ophthalmologica. 49: 293 - 301.

Bedford, R. E. and Wyszecki, G. (1957): Axial chromatic aberration of the human eye. Journal of the Optical Society of America. 47: 564 - 565.

Behr, C. (1924): Die lehre v. der pupillenbewegungen. In Graefe-Saemisch Handbuch der Gesamten Augenheilkunde. 3rd Edition, Berlin. (Source, Duke-Elder, 1971).

Benel, R. A. (1980): Eyes and glass curtains: visual accommodation, the mandelbaum effect, and apparent size. Proceedings of the Human Factors Society - 24th annual meeting. Human Factors. 22: 616 - 620.

Benevento, L. A., Rezak, M. and Santos-Anderson, R. (1977): An autoradiographic study of the projections of the pretectum in the rhesus monkey (Macaca mulatta): Evidence for sensorimotor links to the thalamus and oculomotor nuclei. Brain Research. 127: 197 - 218.

Berens, C. and Sells, S. B. (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. Archives of Ophthalmology. 31: 148 - 159.

Berens, C. and Sells, S. B. (1950): Experimental studies of fatigue of accommodation: II. Archives of Ophthalmology. 33: 47 - 58.

Berens, C. and Stark, E. K. (1932): Studies in ocular fatigue: IV. Fatigue of accommodation, experimental and clinical observations. American Journal of Ophthalmology. 15: 527 - 542.

Berger, C. and Mahneke, A. (1954): Fatigue in two simple visual tasks. American Journal of Psychology. 67: 509 - 512.

Bergin, D. A. (1952): Relation of refractive findings to menses. American Journal of Optometry & A. A. A. O. 29: 129 - 133.

Bernard, C. (1878): La Science Experimentale. p. 155. Bailliere, Paris. (Source, Duke-Elder, 1961).

Berry, G. A. (1885): Letter to the Editor. *Nature (London).* 31: 387 - 388. (Source, Levene, 1977).

Biessels, W. J. (1954): An explanation of twilight myopia ?. *British Journal of Physiological Optics.* 11: 176 - 180.

Bietti, G. B. and Giardini, A. (1949): The influence of anoxia on ocular movements. 2. A comparison between the actions of anoxia and alcohol on the ocular muscle balance. *Riv. Med. Aeronaut. Spaz.* 12: 198 - 207.

Biggs, R. D., Alpern, M. and Bennett, D. R. (1959): The effect of sympathomimetic drugs upon the amplitude of accommodation. *American Journal of Ophthalmology*, 48: 169 - 171.

Bill, A. (1962): Autonomic nervous control of uveal blood flow. *Acta Physiologica Scandinavica.* 56: 70 - 81.

Billings, E. L., Billings, J. J., Brown, J. B. and Burger, H. G. (1972): Symptoms and hormonal changes accompanying ovulation. *Lancet.* 1: 282 - 4.

Bjork, A. (1952): Electrical activity of human extrinsic eye muscles. *Experientia.* 8: 226 - 227.

Blakemore, C. and Campbell, F. W. (1969): On the existence in the human visual system of neurons selectively sensitive to the orientation and size of retinal images. *Journal of Physiology (London).* 203: 237 - 260.

Boberg-Ans, J. (1955): Experience in clinical examination of corneal sensitivity. *British Journal of Ophthalmology.* 39: 705 - 726.

Boeke, J. (1926): Die beziehungen der nervenfasern zu den bindegewebselementen und tastzellen. *Zeitschrift fur Zellforschung und Mikroskopiche Anatomie.* 4: 448 - 509. (Source, Alpern, 1962).

Bohman, C. E. and Saladin, J. J. (1980): The relation between night myopia and accommodative convergence. *American Journal of Optometry and Physiological Optics.* 57: 551 - 558.

Bondareff, W. and Gorgon, B. (1966): Submicroscopic localization of norepinephrine in sympathetic nerves of rat pineal. *Journal of Pharmacology and Experimental Therapeutics.* 153: 42 - 47.

Borish, I. M. (1970): *Clinical Refraction.* 3rd Ed. Professional Press Inc. Illinois.

Bour, L. J. (1981): The influence of the spatial distribution of a target on the dynamic response and fluctuations of the accommodation of the human eye. *Vision Research.* 21: 1287 - 1296.

Bowman, W. C. and Rand, M. J. (1980): *Texbook of Pharmacology.* Blackwell, Oxford.

Braddick, O., Atkinson, J., French, J. and Howland, H. C. (1979): A photorefractive study of infant accommodation. *Vision Research.* 19: 1319 - 1330.

Braddick, O., Ayling, L., Sawyer, R. and Atkinson, J. (1981): A photorefractive study of dark focus and refraction. *Vision Research.* 21: 1761 - 1764.

Brecher, G. A., Hartman, A. P. and Leonard, D. D. (1955): The effect of alcohol on binocular vision. *American Journal of Ophthalmology.* 39: 44 - 51.

Breinin, G. M. (1957a): The nature of vergence revealed by electromyography: II. Accommodative and fusional vergence. *Archives of Ophthalmology*. 58: 623 - 631.

Breinin, G. M. (1957b): Electrophysiological insight in ocular motility. *American Orthoptic Journal*. 7: 5 - 19.

Breinin, G. M. and Moldaver, J. (1955): Electromyography of the human extraocular muscles: I. Normal kinesiology: divergence mechanism. *Archives of Ophthalmology*. 54: 200 - 210.

Breinin, G. M. (1959): Contributions of electromyography to strabismus. *Proceedings of the Institute of Medicine of Chicago*. 22: 303 - 310.

Brodkey, J. and Stark, L. (1967): Accommodative convergence: an adaptive nonlinear control system. *I.E.E.E. Transactions on Systems Science and Cybernetics*. SSC-3: 121 - 131.

Brown, J. L. (1974): LED's: A new source of light for visual experiments. *Proceedings of the Canadian Medical and Biological Engineering Society*. 5th Conference, Montreal. 5.4 a, b.

Brown, N. (1973a): The change in shape and external form of the lens of the eye on accommodation. *Experimental Eye Research*. 15: 441 - 459.

Brown, N. (1973b): In *The Human Lens - In Relation to Cataract*. C.I.B.A. Foundation Symposium 19, pp. 65 - 78. Elsevier, Amsterdam.

Brown, R. H. (1957): 'Empty-field' myopia and visibility of distant objects at high altitudes. *American Journal of Psychology*. 70: 376 - 385.

Bullimore, M. A., Gilmartin, B. and Hogan, R. E. (1985): Objective and subjective measurement of tonic accommodation. *Ophthalmic and Physiological Optics*. (In press).

Burow, C. A. (1841): *Beitrage zur physiologie und physik des menschlichen auges*. p.212, Berlin. (Source, Duke-Elder, 1970).

Burian, H. M. and von Noorden, G. K. (1974): *Binocular vision and ocular motility*. C. V. Mosby, St. Louis.

Buttner-Ennever, J. A. and Akert, K. (1981): Medial rectus subgroups of the oculomotor nucleus and their abducens internuclear input in the monkey. *Journal of Comparative Neurology*. 197: 17 - 27.

Campbell, F. W. (1953): Twilight myopia *Journal of the Optical Society of America*. 43: 925 - 926.

Campbell, F. W. (1954): The minimum quantity of light required to elicit the accommodation reflex in man. *Journal of Physiology (London)*. 123: 357 - 366.

Campbell, F. W. (1957): The depth of field of the human eye. *Optica Acta*. 4: 157 - 164.

Campbell, F. W. (1960): Correlation of accommodation between the two eyes. *Journal of the Optical Society of America*. 50: 738.

Campbell, F. W. and Durden, K. (1983): The visual display terminal issue: a consideration of its physiological, psychological and clinical background. *Ophthalmic and Physiological Optics*. 3: 175 - 192.

Campbell, F. W. and Primrose, J. A. E. (1953): The state of accommodation of the human eye in darkness. Transactions of the Ophthalmological Societies of the United Kingdom. LXXIII: 353 - 361.

Campbell, F. W. and Westheimer, G. (1959): Factors influencing accommodation responses of the human eye. Journal of the Optical Society of America. 49: 568 - 571.

Campbell, F. W. and Westheimer, G. (1960):Dynamics of accommodation responses of the human eye. Journal of Physiology (London). 151: 285 - 295.

Campbell, F. W., Robson, J. G. and Westheimer, G. (1959): Fluctuations of accommodation under steady viewing conditions. Journal of Physiology (London). 145: 579 - 594.

Cannon, W. B. and de la Paz, D. (1911): Emotional stimulation of adrenal secretion. American Journal of Physiology. 28: 64 - 70.

Cannon, W. B., Shohl, A. T. and Wright, W. S. (1911): Emotional glycosuria. American Journal of Physiology. 29: 280 - 287.

Cannon, W. B. (1914): The emergency function of the adrenal medulla in pain and the major emotions. American Journal of Physiology. 33: 356 - 372.

Carpenter, M. B. and Batton, R. R. (1980): Abducens internuclear neurons and their role in conjugate horizontal gaze. Journal of Comparative Neurology. 189: 191 - 209.

Carpenter, M. B. and Strominger, N. L. (1965): The medial longitudinal fasciculus and disturbances of conjugate horizontal eye movements in the monkey. Journal of Comparative Neurology. 125: 41 - 66.

Carpenter, R. H. S. (1977): The Movements of the Eyes. Pion, London.

Carreras, M. (1951): La myopia nocturna e influencia sobre la misma de la amplitud de acomodacion. Archivos de la Sociedad Americana de Oftalmologia Optometria. 11: 1443 - 1489. (Sources: Mellerio, 1966; Charman, 1982).

Carter, D. B. (1957): Studies of fixation disparity - historical review. American Journal of Optometry & A. A. A. O. 34: 320 - 329.

Carter, D. B. (1963): Effects of prolonged wearing of prisms. American Journal of Optometry & A. A. A. O. 40: 265 - 273.

Carter, D. B. (1965): Fixation disparity and heterophoria following prolonged wearing of prisms. American Journal of Optometry & A. A. A. O. 42: 141 - 152.

Carter, J. H. (1962): A servoanalysis of the human accommodative mechanism. Archivos de la Sociedad Americana de Oftalmologia Y Optometria. 4: 137 - 168.

Caspers, H. (1958): The effect of alcohol on the ascending reticular formation. Z. Ges. Exp. Med. 129: 582 - 600.

Charman, W. N. (1974): On the position of the plane of stationarity in laser refraction. American Journal of Optometry and Physiological Optics. 51: 832 - 837.

Charman, W. N. (1979): Speckle movement in laser refraction. 1. Theory. American Journal of Optometry and Physiological Optics. 56: 219 - 227.

Charman, W. N. (1982): The accommodative resting point and refractive error. Ophthalmic Optician. 22: 469 -473.

Charman, W. N. (1983): The retinal image in the human eye. Progress in Retinal Research. 2: 1 - 50.

Charman, W. N. and Chapman, D. (1980): Laser refraction and speckle movement. Ophthalmic Optician. Jan. 19th, 41 - 51.

Charman, W. N. and Heron, G. (1979): Spatial frequency and the dynamics of the accommodation response. Optica Acta. 26: 217 - 228.

Charman, W. N. and Jennings, J. A. M. (1976): Objective measurements of the longitudinal chromatic aberration of the human eye. Vision Research. 16: 999 - 1005.

Charman, W. N, Jennings, J. A. M. and Whitefoot, H. (1978): The refraction of the eye in relation to spherical aberration and pupil size. British Journal of Physiological Optics. 32: 78 - 93.

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

Charman, W. N. and Tucker, J. (1978a): Accommodation as a function of object form. American Journal of Optometry and Physiological Optics. 55: 84 - 92.

Charman, W. N. and Tucker, J. (1978b): Accommodation and color. Journal of the Optical Society of America. 68: 459 - 471.

Charman, W. N. and Whitefoot, H. (1977): Pupil diameter and the depth of field of the human eye as measured by laser speckle. Optica Acta. 24: 1211 - 1216.

Chiarandini, D. J. and Davidowitz, J. (1979): Structure and function of extraocular muscle fibres. In: Current Topics in Eye Research. Vol. 1, pp. 91 -142. Eds. Zadunaisky, J. A. and Davson, H. Academic Press, New York.

Chin, N. B. and Horn, R. E. (1956): Infra-red skiascope measurements of refractive changes in dim light and darkness. Journal of the Optical Society of America. 46: 60 - 66.

Chin, N. B., Ishikawa, S. and Lappin, H. (1968): Accommodation in monkeys induced by midbrain stimulation. Investigative Ophthalmology. 7: 386 - 396.

Churnside, J. H. (1982): Speckle from a rotating diffuse object. Journal of the Optical Society of America. 72: 1464 - 1469.

Ciuffreda, K. J. and Kenyon, R. V. (1983): Accommodative vergence and accommodation in normals, amblyopes, and strabismics. In Vergence Eye Movements: Basic and Clinical Aspects. Eds. Schor, C. M. and Ciuffreda, K. J. pp. 101 - 173. Butterworths, Boston.

Clarke-Jones, R. (1939): The Kormetron. Journal of the Optical Society of America. 29: 531 - 534.

Coakes, R. L. (1980): The role of fluorophotometry in glaucoma research. Res. Clin. Forums. 2: 101.

Cogan, D. G. (1937): Accommodation and the autonomic nervous system. Archives of Ophthalmology. 18: 739 - 766.

Cogan, D. G. (1956): Neurology of Ocular Muscles. 2nd Ed. Charles C. Thomas, Springfield, Illinois.

Cohen, M. M. and Alpern, M. (1969): Vergence and Accommodation: VI. The influence of ethanol on the AC/A ratio. American Journal of Ophthalmology. 81: 518 - 525.

Coleman, D. J. (1970): Unified model for accommodative mechanism. American Journal of Ophthalmology. 69: 1063 - 1079.

Collins C. C. (1975): The human oculomotor control system. In: Basic Mechanisms of Ocular Motility. pp. 283 - 325. Eds. Lennerstrand, G. and Bach-y-Rita, P. Pergamon Press, Oxford.

Colson, Z. W. (1940): The effect of alcohol on vision. Journal of the American Medical Association. 115: 1525 - 1527.

Committee of Vice-Chancellors and Principals of the Universities of the United Kingdom. (1978): Safety in Universities: Notes of Guidance. Part2: 1, Lasers. The Association of Commonwealth Universities, London.

Cooper, S. and Daniel, P. M. (1949): Muscle spindles in human extrinsic muscles. Brain. 72: 1 - 24.

Cooper, S. and Fillenz, M. (1955): Afferent discharges in response to stretch from the extraocular muscles of the cat and monkey and the innervation of these muscles. Journal of Physiology (London). 127: 400 - 413.

Cornsweet, T. N. (1956): Determination of the stimuli for involuntary drifts and saccadic eye movements. Journal of the Optical Society of America. 46: 987 - 993.

Cornsweet, T. N. and Crane, H. D. (1970): Servo-controlled infra-red optometer. Journal of the Optical Society of America. 60: 548 - 554.

Costa, E. and Groppetti, A. (1970): Biosynthesis and storage of catecholamines in tissues of rats injected with various doses of d-amphetamine. In: Amphetamines and Related Compounds, Eds. Costa, E. and Garattinni, S. Raven Press, New York.

Costello, M. (1974): The effect of stress and relaxation on autonomic function as measured by the resting point of accommodation. Unpublished Honours thesis. Pennsylvania State University, University Park, P. A.

Cramer. (1851): Tijdschrift der maatschappij vor geneeskunde. Nederlandsch Lancet. (Ser.2), 1: 529. (Source, Helmholtz, 1909).

Craske, B. and Crawshaw, M. (1974): Adaptive changes of opposite sign in thew oculomotor systems of the two eyes. Quarterly Journal of Experimental Psychology. 26: 106 - 113.

Crone, R. A. and Harjowijoto, I. (1979): What is normal binocular vision?: Documenta Ophthmologica. 47: 163 - 199.

Dalton, K. (1967): Influence of menstruation on glaucoma. British Journal of Ophthalmology. 51: 692 - 695.

Dalton, K. (1969): The Menstrual Cycle. Pantheon, New York.

Dalton, K. (1977): The Premenstrual Syndrome and Progesterone Therapy. Heinemann, London.

Dan, A., Graham, E. and Beecher, C. (1981): The Menstrual Cycle: An Interdisciplinary Synthesis. Springer, New York.

Davson, H. (1980): Physiology of the eye. 4th edition. Churchill Livingstone, London.

DeMarchi, G. W. and Tong, J. E. (1972): Menstrual, diurnal and activation effects on the resolution of temporally paired flashes. Psychophysiology. 9: 362 - 367.

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

Descartes. (1677): *Traite de l'homme*. Paris. (Source, Helmholtz, 1909).

Diamond, M., Diamond, A. L. and Mast, M. (1972): Visual sensitivity and sexual arousal levels during the menstrual cycle. *Journal of Nervous and Mental Diseases*. 155: 170 - 176.

Dietert, S. E. (1965): The demonstration of different types of muscle fibres in human extraocular muscles by electron microscopy and cholinesterase staining. *Investigative Ophthalmology*. 4: 51 - 63.

Ditchburn, R. W. (1980): Focussing of instruments. *Optica Acta*. 27: 713 - 715.

Donders, F. C. (1864): *On the Anomalies of Accommodation and Refraction of the eye*. Trans. by Moore, W. D. The New Sydenham Society, London.

Duane, A. (1909): The accommodation and Donder's curve and the need of revising our ideas regarding them. *Journal of the American Medical Association*. 52: 1992 - 1996.

Duane, A. (1912): Normal values of the accommodation at all ages. *Journal of the American Medical Association*. 59: 1010 - 1013.

Duane, A. (1922): Discussion of paper on "Presbyopia" given by E. Fuchs. *Archives of Ophthalmology*. 51: 63 - 66.

Duke-Elder, S. (1961): Anatomy of the visual system. Vol. II of the *System of Ophthalmology*. Henry Kimpton, 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.

Duke-Elder, S. (1973): Ocular Motility and Strabismus. Vol. VI of *System of Ophthalmology*. Henry Kimpton, London.

Duke-Elder, W. S. and Duke-Elder, P. M. (1930): The contraction of the extrinsic muscles of the eye by choline and nicotine. *Proceedings of the Royal Society*. B-107: 332 - 34.

Duncalf, D. and Jampel, R. S. (1961): The action of d-Tubocurarine on the extraocular muscles in strabismus. *American Journal of Ophthalmology*. 65: 366 - 368.

Dunn, A. J. and Kramarcy, N. R. (1984): Neurochemical responses in stress: Relationships between the hypothalamic - pituitary - adrenal and catecholamine systems. Chapt. 8, in *Handbook of Psychopharmacology. Volume 18, Drugs, Neurotransmitters and Behaviour*. Eds. Iverson, L. L., Iverson, S. D. and Snyder, S. H. pp. 455 - 515, Plenum Press, New York.

Dunn, J. S. and Brubaker, R. F. (1973): Perkins applanation tonometer, clinical and laboratory evaluation. *Archives of Ophthalmology*. 89: 149 - 151.

Duran, M. (1943): Los valores umbrales de la miopia nocturna. *Anales de Fisica y Quimica*. 39: 579 - 584.

Duwaer, A. L., Van Den Brink, G., Van Antwerpen, G. and Keemink, C. J. (1982): Comparison of subjective and objective measurement of ocular alignment in the vertical direction. Vision Research. 22: 983 - 989.

Dwyer, W. O., Kent, P., Powell, J., McElvain, R. and Redmond, J. (1972): Reliability of laser refraction for different refractive groups. American Journal of Optometry & A. A. A. O. 49: 929 - 931.

Dwyer, W. O., Granata, D., Bossin, R. and Andreas, S. R. (1973): Validity of laser refraction technique in determining spherical error for different refractive groups. American Journal of Optometry & A. A. A. O. 50: 222 - 225.

Ebenholtz, S. M. (1981): Hysteresis effects in the vergence control system: perceptual implications. Chapter 11.2 in Eye Movements: Visual Perception and Cognition. Edited by Fisher, D. F., Monty, R. A. and Senders, J. W. Erhlbaum Associates, Hillsdale, New Jersey.

Ebenholtz, S. M. (1983): Accommodative hysteresis: A precursor for induced myopia. Investigative Ophthalmology and Visual Science. 24:513 - 515.

Ebenholtz, S. M. (1985): Hysteresis magnitude and decay rate as a function of fixation distance from the dark focus. Paper presented at ARVO '85, May 2-7, Sarasota, USA. Abstracted in Supplement to Investigative Ophthalmology and Visual Science. 26: 269.

Ebenholtz, S. M. and Fisher, S. K. (1982): Distance adaptation depends upon plasticity in the oculomotor control system. Perception and Psychophysics. 31: 551 - 560.

Ehinger, B. (1966a): Ocular and orbital vegitative nerves. Acta Physiologica Scandinavica. 67: suppl. 268.

Ehinger, B. (1966b): Adrenergic nerves to the eye and to related structures in man and in the cynomolgous monkey (Macaca irus). Investigative Ophthalmology. 5: 42 - 52.

Ehinger, B. (1966c): Distribution of adrenergic nerves in the eye and some related structures in the cat. Acta Physiologica Scandinavica. 66: 123 - 128.

Ehinger, B. (1971): A comparative study of the adrenergic nerves to the anterior segment of some primates. Zeitschrift fur Zellforschung und Mikroskopiche Anatomie 116: 157 - 177.

Ellerbrock, V. J. (1950): Tonicity induced by fusional movements. American Journal of Optometry & A. A. A. O. 27: 8 - 20.

Emsley, H. H. (1953): Visual Optics. Vol. 1, 5th edition, Butterworths, London.

Epstein, D. (1983): Accommodation as the primary cause of low-luminance myopia. Acta Ophthalmologica. 61: 424 - 430.

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

Eskridge, J. B. (1971): An investigation of voluntary vergence. American Journal of Optometry & A. A. A. O. 48: 741 - 746.

Fecher, A. F. and Sprongl, H. (1975): Automatic measurement of vertex refraction with coherent light. Optica Acta. 22: 799 - 806.

Feldman, F., Bain, J. and Matuk, A. R. (1978): Daily assessment of ocular and hormonal variables throughout the menstrual cycle. Archives of Ophthalmology. 98: 1835 - 1838.

Fender, D. and Julesz, B. (1967): Extension of Panum's fusional area in binocularly stabilized vision. Journal of the Optical Society of America. 57: 819 - 830.

Ferree, C. E. (1913): Tests for the efficiency of the eye under different systems of illumination and a preliminary study of the causes of discomfort. Transactions of the Illumination and Engineering Society (New York). 8: 40 - 60.

Ferree, C. E. (1914): The efficiency of the eye under different systems of lighting. Opthalmology. 10: 622 - 636.

Ferree, C. E. and Rand, G. (1933): The effect on intensity of illumination on the near point of vision and a comparison of the effect for presbyopic and non-presbyopic eyes. *Transactions of the Illumination and Engineering Society (New York)*. XXVIII: 590 - 611.

Fincham, E. F. (1937): The mechanism of accommodation. British Journal of Ophthalmology. Monograph supplement No. VIII. Pulman, London.

Fincham, E. F. (1951): The accommodation reflex and its stimulus. British Journal of Ophthalmology. 35: 381 - 393.

Fincham, E. F. (1953): Defects of the colour-sense mechanism as indicated by the accommodation reflex. Journal of Physiology (London). 121: 570 - 580.

Fincham, E. F. (1955): The proportion of ciliary muscular force required for accommodation. Journal of Physiology (London). 128: 99 - 112.

Fincham, E. F. (1962): Accommodation and convergence in the absence of retinal images. Vision Research. 1: 425 - 440.

Fincham, E. F. and Walton, J. (1957): The reciprocal actions of accommodation and vergence. Journal of Physiology (London). 137: 488 - 508.

Fiorentini, A. and Ercoles, A. M. (1966): Involuntary eye movements during attempted monocular fixation. Atti Fondazione Giorgio Ronchi. 21: 199 - 217. (Source, Matin et al., 1970; Skavenski and Steinman, 1970).

Fisher, R. A. and Yates, F. (1974): Statistical Tables for Biological, Agricultural and Medical Research, 6th Edition, Longman, London.

Fisher, R. F. (1969a): The elastic constants of the human lens capsule. Journal of Physiology (London). 201: 1 - 20.

Fisher, R. F. (1969b): The significance of the shape of the lens and capsular energy changes in accommodation. Journal of Physiology (London). 201: 21 - 47.

Fisher, R. F. (1971): The elastic constants of the human lens. Journal of Physiology (London). 212: 147 - 180.

Fisher, R. F. (1973): presbyopia and its changes with age in the human crystalline lens. Journal of Physiology (London). 228: 765 - 779.

Fisher, R. F. (1977): The force of contraction of the human ciliary muscle during accommodation. Journal of Physiology (London). 270: 51 - 74.

Fisher, R. F. (1982): The vitreous and lens in accommodation. Transactions of the Ophthalmological Societies of the United Kingdom. 102: 328 - 322.

Fisher, R. F. and Wakely, J. (1976): The elastic constants and ultrastructural organization of a basement membrane (lens capsule). Proceedings of the Royal Society. 193: 335 - 358.

Fitzpatrick, J. P. and Hansen, D. W. (1973): The relationship between classroom visual fatigue and academic achievement in elementary school children. Journal of the American Optometric Association. 44: 812 - 823.

Fleming, D. G. (1957): The role of sympathomimetics in visual accommodation. American Journal of Ophthalmology. 43: 789.

Fleming, D. G. and Hall, J. L. (1959): Autonomic innervation of the ciliary body. American Journal of Ophthalmology. 48 (pt 2): 287 - 293.

Flom, M. C. and Takahashi, E. (1962): The AC/A ratio and undercorrected myopia. American Journal of Optometry & A. A. A. O. 39: 305 - 312.

Foley, J. M. (1980): Binocular distance perception. Psychological Review. 87: 411 - 434.

Francis, E. L. and Owens, D. A. *(1983): The accuracy of binocular vergence for peripheral* stimuli. Vision Research. 23: 13 - 19.

Frisby, J. and Mayhew, J. (1979): The role of spatial frequency tuned channels in vergence control. Vision Research. 20: 727 - 732.

Garner, L. F. (1983): Mechanisms of accommodation and refractive error. Ophthalmic and Physiological Optics. 3: 287 - 293.

Garner, L. F., Brown, B., Baker, R. and Colgan, M. (1983): The effect of phenylephrine on the resting point of accommodation. Investigative Ophthalmology and Visual Science. 24: 393 - 398.

Geacintov, T. and Peavler, W. S. (1974): Pupillography in industrial fatigue assessment. Journal of Applied Psychology. 59: 213 - 216.

Gellhorn, E. (1953): Physiological Foundations of Neurology and Psychiatry. pp. 337 - 338. University of Minnesota Press, Minneapolis.

Gilmartin, B. and Hogan, R. E. (1984a): The effect of timolol maleate (0.5%) on tonic accommodation and tonic vergence. Paper presented to the Society of Experimental Optometry, University of Aston, July 25 - 26, 1983. Abstracted in Ophthalmic and Physiological Optics. 4: 188.

Gilmartin, B. and Hogan, R. E. (1984b): The effect of a non-selective Beta adrenoceptor antagonist on tonic accommodation and tonic vergence. Paper published in Transactions of the First International Congress, B.C.O.O., London, April 11 - 14, 1984. 1: 140 - 147.

Gilmartin, B., Hogan, R. E. and Thompson, S. M. (1984): The effect of timolol maleate on tonic accommodation, tonic vergence, and pupil diameter. Investigative Ophthalmology and Visual Science. 25: 763 - 770.

Gilmartin, B. and Hogan, R. E. (1985a): The role of the sympathetic nervous system in ocular accommodation and ametropia. Ophthalmic and Physiological Optics. 5: 91 - 93.

Gilmartin, B. and Hogan, R. E. (1985b): The effect of a muscarinic receptor antagonist on tonic accommodation. Ophthalmic and Physiological Optics. 5: 234.

Gilmartin, B. and Hogan, R. E. (1985c): The relationship between tonic accommodation and ciliary muscle innervation. *Investigative Ophthalmology and Visual Science*. 26: 1024 - 1028.

Gilmartin, B. and Hogan, R. E. (1985d): The magnitude of longitudinal chromatic aberration of the human eye between 458nm and 633nm. *Vision Research*. Accepted for publication.

Gogel, W. C. (1969): The sensing of retinal size. *Vision Research*. 9:1079 - 1094.

Gogel, W. C. (1976): An indirect method of measuring perceived distance from familiar size. *Perception and Psychophysics*. 20: 419 - 429.

Gogel, W. C. (1977a): The metric of visual space. In: Epstein, W., ed. *Stability and Constancy in Visual Perception: Mechanisms and Processes*. Wiley, New York.

Gogel, W. C. (1977b): An indirect measure of perceived distance from oculomotor cues. *Perception and Psychophysics*. 21: 3 - 11.

Gogel, W. C. (1978): Size, distance, and depth perception. In: Carterette, E. C., Friedman, M. P., eds. *Perceptual Processing, Handbook of Perception*. Vol. 9, 299 - 333. Academic Press, New York.

Gogel, W. C. and Teitz, J. D. (1973): Absolute motion parallax and the specific distance tendency. *Perception and Psychophysics*. 13: 284 - 292.

Grant, V. W. (1942): Accommodation and convergence in visual space perception. *Journal of Experimental Psychology*. 31: 89 - 104.

Graves, B. (1925): The response of the lens capsules in the act of accommodation. *Transactions of the American Ophthalmological Society*. 23: 184 - 198.

Green, D. G. and Maaseidvaag, F. (1967): Closed circuit television pupillometer. *Journal of the Optical Society of America*. 57: 830 - 833.

Greenspan, S. B. (1981): Research studies of bifocals for myopia. *American Journal of Optometry and Physiological Optics*. 58: 536 - 540.

Gunnarsson, E. and Soderberg, I. (1983): Eye strain resulting from V.D.T. work at the Swedish Telecommunications Administration. *Applied Ergonomics*. 14: 61 - 69.

Haine, C., Long, W. and Reading, R. (1976): Laser meridional refractometry. *American Journal of Optometry and Physiological Optics*. 53: 194 - 204.

Hakerem, G. (1967): Pupillography, Chapt. 10, pp. 337 - 349, in *Manual of Physiological Methods*. Ed. Venables, P. H. and Martin, I., North Holland, Amsterdam.

Hamasaki, D., Ong, J. and Marg, E. (1956): The amplitude of accommodation in presbyopia. *American Journal of Optometry & A. A. A. O.* 33: 3 - 14.

Hampton, D. R. and Kertesz, A. E. (1983): Fusional vergence response to local peripheral stimulation. *Journal of the Optical Society of America*. 73: 7 - 10.

Harker, D. W. (1972): The structure and innervation of sheep superior rectus and levator palprebrae muscles. *Investigative Ophthalmology*. 11: 956 - 969.

Harting, J. K. (1977): Descending pathways from the superior colliculus: an autoradiographic analysis in the rhesus monkey. *Journal of Comparative Neurology*. 173: 583 - 612.

Haynes, H. M., White, B. L. and Held, R. (1965): Visual accommodation in human infants. Science. 148: 528 - 530.

Heath, G. G. (1956a): The influence of visual acuity on accommodative responses of the eye. American Journal of Optometry & A. A. A. O.,33: 513 - 524.

Heath, G. G. (1956b): Components of accommodation. American Journal of Optometry & A. A. A. O., 33: 569 - 579.

Heath, G. C. (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.

Heaton, J. M. (1966): The pain in eyestrain. American Journal of Ophthalmology. 61: 104 - 112.

Hebbard, F. W. (1962): Comparison of subjective and objective measurements of fixation disparity. Journal of the Optical Society of America. 52: 706 - 712.

Hedman, L. R. and Briem, V. (1984): Short-term changes in eyestrain of VDU users as a function of age. Human Factors. 26: 357 - 370.

Helmholtz, H. Von (1909): Handbuch der physiologischen optik. Vol 1. Translated and edited from the 3rd German edition by Southall, J. P. C. as Helmholtz's Treatise on Physiological Optics. Volume 1, Dover publications, New York, 1962.

Henke, W. (1860): Der mechanismus der accommodation fur nahe und ferne. Albrecht Von Graefes Archive fur Ophthalmologie. (pt. 2) 6: 53 - 72. (Source, Helmholtz, 1909).

Henn, V. and Cohen, B. (1976): Coding of information about rapid eye movements in the pontine reticular formation of alert monkeys. Brain Research. 8: 307 - 325.

Hennessy, R. T. (1975): Instrument myopia. Journal of the Optical Society of America. 65: 1114 - 1120.

Hennessy, R. T., Iida, T., Shiina, K. and Leibowitz, H. W. (1976): The effect of pupil size on accommodation. Vision Research. 16: 587 - 589.

Hennessy, R. T. and Leibowitz, H. W. (1970): Subjective measurement of accommodation with laser light. Journal of the Optical Society of America. 60: 1700 - 1701.

Hennessy, R. T. and Leibowitz, H. W. (1971): The effect of a peripheral stimulus on accommodation. Perception and Psychophysics. 10: 129 - 132.

Hennessy, R. T. and Leibowitz, H. W. (1972): Laser optometer incorporating the Badal principle. Behavioural Research Methods and Instrumentation. 4: 237 - 239.

Hensen, V. and Volckers, C. (1873): Albrecht Von Graefes Archive fur Ophthalmologie. 19: 156. (Source, Duke-Elder, 1970).

Henson, D. B. and North, R. (1980): Adaptation to prism induced heterophoria. American Journal of Optometry and Physiological Optics. 57: 129 - 137.

Heron, G. (1972): A study of accommodation using an infra-red optometer. MSc Thesis, University of Manchester.

Heron, G., Smith, A. C. and Winn, B. (1981): The influence of method on the stability of dark focus position of accommodation. Ophthalmic and Physiological Optics. 1: 79 - 90.

Hess, A. (1961): The structure of slow and fast extrafusal muscle fibres in the extraocular muscles and their nerve endings in guinea pigs. Journal of Cellular and Comparative Physiology. 58: 63 - 79.

Hess, C. (1896): Arbeiten aus dem gebiete der accommodationslehre. Albrecht Von Graefes Archive fur Ophthalmologie. 47: 43. (Source, Fincham, 1937).

Hess, C. and Heine, L. (1898): Arbeiten aus dem gebiete der accommodationslehre. Albrecht Von Graefes Archive fur Ophthalmologie. 46: 243. (Source, Cogan, 1937).

Hess, E. H. (1965): Attitude and pupil-size. Scientific American. 212: 46 - 54.

Heuer, H. and Luschow, U. (1983): Aftereffects of sustained convergence: some implications of the eye muscle potentiation hypothesis. Perception. 12: 337 - 346.

Highstein, S. M. (1977): Abducens and oculomotor internuclear neurons: relation to gaze. In: Baker, R., Berthoz, A., eds. Control of Gaze by Brain Stem Neurons. pp. 153 - 162. Elsevier, New York.

Highstein, S. M. and Baker, R. (1978): Excitatory termination of abducens internuclear neurons on medial rectus motorneurons: relationship to syndrome of internuclear ophthalmoplegia. Journal of Neurophysiology. 41: 1647 - 1661.

Himwich, H. E. and Callison, D. A. (1972): The effects of alcohol on evoked potentials of various parts of the CNS of the cat. PP. 67 - 84. In Kissin, B. and Beglieter, H. (Eds) The Biology of Alcoholism. Vol. 2. Physiology and Behaviour, Plenum Press, New York.

Hirsch, M. J., Alpern, M. and Schultz, H. (1948): The variation of phoria with age. American Journal of Optometry & A. A. A. O. 25: 535 - 541.

Hitchings, F. W., Sloan, H. G. and Austin, J. B. (1913): Laboratory studies of the activity of the brain and the adrenal in response to specific stimuli. Cleveland Medical Journal. 12: 684 - 691. (Source, Dunn and Kramarcy, 1984).

Hoffmann, F. B. and Bielschowsky, A. (1900): Uber die der willkue entzogenen fusions-bewegungen der augen. Pflugers Archives Ges. Physiol. 80: 1 - 40. (Source: Schor, 1979a).

Hofstetter, H. W. (1942): The proximal factor in accommodation and convergence. American Journal of Optometry & A. A. A. O.. 19: 67 - 76.

Hofstetter, H. W. (1945): The zone of clear single binocular vision. American Journal of Optometry & A. A. A. O. 22: 301 - 333.

Hogan, M. J., Alvarado, J. A. and Weddell, J. E. (1971): Histology of the Human Eye. Saunders, Philadelphia, P. A.

Hogan, R. E. and Linfield, P. B. (1983): The effects of moderate doses of ethanol on heterophoria and other spects of binocular vision. Ophthalmic and Physiological Optics. 3: 21 - 31.

Hogan, R. E. and Gilmartin, B. (1984a) Aspects of tonic levels of accommodation, vergence and pupil. Paper presented to the Society for Experimental Optometry, July 1983, University of Aston in Birmingham. Abstract in Ophthalmic and Physiological Optics. 4: 187.

Hogan, R. E. and Gilmartin, B. (1984b): The choice of laser speckle exposure duration in the measurement of tonic accommodation. Ophthalmic and Physiological Optics. 4: 365 - 368.

Hogan, R. E. and Gilmartin, B. (1985a): The relationship between tonic vergence and oculomotor stress induced by ethanol. Ophthalmic and Physiological Optics. 5: 43 - 51.

Hogan, R. E. and Gilmartin, B. (1985b): The effect of sustained visual tasks on tonic accommodation and tonic vergence. *Ophthalmic and Physiological Optics*. *5: 234*.

Hokoda, S. C. and Ciuffreda, K. J. (1983): Theoretical and clinical importance of proximal vergence and accommodation. Chapter 4, in Vergence Eye Movements. Eds. Schor, C. M. and Ciuffreda, K. J. Butterworths, Boston.

Home, R. and Poole, J. (1977): Measurement of the preferred binocular dioptric settings at a high and low light level. Optica Acta. 24: 97 - 98.

Hosoba, M., Bando, T. and Tsukahara, N. (1978): The cerebellar control of accommodation of the eye of the cat. Brain Research. 153: 495 - 505.

Howcroft, M. J. and Parker, J. A. (1977): Aspheric curvatures for the human lens. Vision Research. 17: 1217 - 1223.

Howe, L. (1916): The fatigue of accommodation as registered by the ergograph. Journal of the American Medical Association. 67: 100 - 104.

Hubel, D. H. and Wiesel, T. N. (1974): Uniformity of monkey striate cortex: A parallel relationship between field size, scatter and magnification factor. Journal of Comparative Neurology. 158: 295 - 306.

Hughes, A. (1977): The topography of vision in mammals of contrasting lifestyle: comparative optics and retinal organization. In Handbook of Sensory Physiology, Vol. VII/5 The Visual System in evolution. A. Vertebrates. Edited by Crescitelli, F. pp. 613 - 756. Springer - Verlag.

Hung, G. K. and Ciuffreda, K. J. (1983): Supplementary glossary of control system terminology. In Vergence Eye Movements. Eds. Schor, C. M. and Ciuffreda, K. J., pp. 699 - 703. Butterworths, Boston.

Hung, G. K. and Semmlow, J. L. (1980): Static behaviour of accommodation and vergence: computer simulation of an interactive dual feedback. I.E.E.E. Transactions on Biomedical Engineering. BME-27: 439 - 447.

Hurwitz, B. S., Davidowitz, J., Chin, N. B. and Breinin, G. B. (1972a): The effects of the sympathetic nervous system on accommodation: I. Beta sympathetic nervous system. Archives of Ophthalmology. 87: 668 - 674.

Hurwitz, B. S., Davidowitz, J., Pachter, B. R. and Breinin, G. B. (1972b): The effects of the sympathetic nervous system on accommodation: II. Alpha sympathetic nervous system. Archives of Ophthalmology. 87: 675 - 678.

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

Irving, A. (1957): Ametropia at low illuminations. Unpublished M.Sc. Thesis, University of Manchester (Technology).

Ishikawa, T. (1962): Fine structure of the human ciliary muscle. Investigative Ophthalmology. 1: 587 - 608.

Ittelson, W. H. and Ames, A. A. (1950): Accommodation, convergence and their relation to apparent distance. Journal of Psychology. 30: 43 - 62.

Ivanoff, A. (1947a): Les aberrations de chromatisme et de sphericite de l'oeil; Leur role en vision nocturne. Revue D'Optique Theorique et Instrumentale. 26: 145. (Source, Koomen et al., 1949; Mellerio, 1966).

Ivanoff, A. (1947b): On the influence of accommodation on spherical aberration in the human eye, an attempt to interpret night myopia. Journal of the Optical Society of America. 37: 730 - 731.

Ivanoff, A. (1953): Les Aberrations de l'Oeil. Editions Revue d'Optique. Masson, Paris. (Source, Le Grand, 1967; Inglestam and Ragnarsson, 1972; Charman and Tucker, 1978b).

Ivanoff, A. (1955): Night binocular convergence and night myopia. Journal of the Optical Society of America. 45: 769 - 770.

Ivanoff, A. and Bourdy, C. (1954): Le comportement de la convergence en nocturne. Annales d'Optique Oculaire.3: 70 - 75.

Iwai, T., Takai, N. and Asakura, T. (1982): Dynamic statistical properties of laser speckle produced by a moving diffuse object under illumination of a gaussian beam. Journal of the Optical Society of America. 72: 460 - 467.

Jackson, (1888): Symmetrical aberration of the eye. Transactions of the American Ophthalmological Society. 5: 141 - 150. (Sources, Borish, 1970; Mellerio, 1966).

Jampel, R. S. (1959): Representation of the near-response on the cerebral cortex of the macaque. American Journal of Ophthalmology. 48: 573 - 581.

Jampel, R. S. (1960): Convergence, divergence, pupillary reactions and accommodation of the eyes from faradic stimulation of macaque brain. Journal of Comparative Neurology. 115: 371 - 400.

Jampel, R. S. (1967): Multiple motor systems in the extraocular muscles of man. Investigative Ophthalmology. 6: 288 - 293.

Jampel, R. S. and Mindel, J. (1967): The nucleus for accommodation in the midbrain of the macaque. Investigative Ophthalmology. 6: 40 - 50.

Jenkins, T. C. A. (1963): Aberrations of the eye and their effects on vision. British Journal of Physiological Optics. Parts 1 and 2, 20: 59 - 91 and 161 - 201.

Jennings, J. A. M. and Charman, W. N. (1973): A comparison of error in some subjective methods of refraction. Ophthalmic Optician. 13: 8 - 18.

Jennings, J. A. M. and Charman, W. N. (1981): Off-axis image quality in the human eye. Vision Research. 21: 445 - 455.

Jensen, B. K. (1982): Menstrual cycle effects on task performance examined in the context of stress research. Acta Psychologica. 50: 159 - 178.

Jessop, W. H. (1886): On the anatomy, histology and physiology of the intraocular muscles of mammals. Proceedings of the Royal Society. 40: 478 - 484.

Johnson, C. A. (1976): Effects of luminance and stimulus distance on accommodation, and visual resolution. Journal of the Optical Society of America. 66: 138 - 142.

Johnson, C. A., Post, R. B. and Tsuetaki, T. K. (1982): Dynamic properties of the resting focus od accommodation. Paper presented to A.R.V.O., Sarasota, Florida 1982. Abstracted in Supplement to Investigative Ophthalmology and Visual Science. 22: 84.

Johnson, C. A., Post, R. B. and Tsuetaki, T. K. (1984): Short-term variabilty of the resting focus of accommodation. Ophthalmic and Physiological Optics. 4: 319 - 326.

Jones, R. and Kerr, K. E. (1972): Vergence eye movements to pairs of disparity stimuli with shape selection cues. Vision Research. 12: 1425 - 1430.

Kasai, T., Unno, M., Fujii, K., Sekiguchi, M. and Shinohara, K. (1971): Dynamic characteristics of human eye accommodation system. Technical Report. Osaka University. 21 (1014) 569 - 586.

Kato, T. (1938): Uber histologische untersuchungen der augenmuskeln von menschen und saugetieren. Okajimas Folia Anatomicae Japonicae. 16: 131 - 145. (Source, Carpenter, 1977).

Keily, P. M., Carney, L. G. and Smith, G. (1983): Menstrual cycle variations of corneal topography and thickness. American Journal of Optometry and Physiological Optics. 60: 822 - 829.

Keller, E. L. (1973): Accommodative vergence in the alert monkey. Vision Research. 13: 1565 - 1575.

Keller, E. L. (1974): Participation of medial pontine reticular formation associated with eye movements. Journal of Neurophysiology. 37: 316 - 332.

Keller, E. L. and Robinson, D. A. (1972): Abducens unit behaviour in the monkey during vergence movements. Vision Research. 12: 369 - 382.

Kent, P. R. (1958): Convergence-accommodation. American Journal of Optometry & A. A. A. O. 35: 393 - 406.

Kenyon, R. V., Ciuffreda, K. J. and Stark, L. (1978): Binocular eye movements during accommodative vergence. Vision Research. 18: 545 - 555.

Kepler. (1611): Dioptrice. Propos. 26, Augsburg. (Source, Helmholtz, 1909).

Kern, R. (1968): Uber die adrenergischen receptoren der extraocularen muskeln des rhesusaffen. Albrecht Von Graefes Archive fur Klinische und Experimentelle Ophthalmologie. 174: 278 - 286.

Kern, R. (1970): Die adrenergischen receptoren der intraocularen muskeln des menschen. Albrecht Von Graefes Archive fur Klinische und Experimentelle Ophthalmologie. 180: 231 - 248.

Kersten, D. and Legge, G. E. (1983): Convergence accommodation. Journal of the Optical Society of America. 73: 332 - 338.

Kikkawa, Y. and Sato, T. (1963): Elastic properties of the lens. Experimental Eye Research. 2: 210 - 215.

Kintz, R. T. and Bowker, D. O. (1982): Accommodation response during a prolonged visual search task. Applied Ergonomics. 13: 55 - 59.

Kirchof, H. (1940): Eine methode zur objectiven messung der akkommodations geschwindigkeit des menschlichen auges. Zeitschrift fur Biologie. 100: 408 - 420. (Source, see translation by Allen and Knoll, 1950).

Kinney, J. A. S., Luria, S. M., Ryan, A. P., Schlichting, C. L. and Paulson, P. A. (1980): The vision of submariners and guardsmen: a longitudinal study. American Journal of Optometry and Physiological Optics. 57: 469 - 478.

Kitchener, W. (1824): Economy of the eyes...., p.101, Hurst Robinson, London. (Source, Levene, 1977).

Knoll, H. A. (1959): Proximal factors in convergence. American Journal of Optometry & A. A. A. O. 36: 378 - 381.

Knoll, H. A. (1966): Measuring ametropia with a gas laser: A preliminary report. American Journal of Optometry & A. A. A. O. 43: 415 - 418.

Komnenich, P., McSweeney, M. Noack, J. A. and Elder, S. N. (1981): The Menstrual Cycle. Volume II. *Research and Implications for Women's Health*. Springer, New York.

Koomen, M., Tousey, r. and Scolnik, R. (1949): The spherical aberration of the eye. Journal of the Optical Society of America. 39: 370 - 376.

Koomen, M., Scolnik, R. and Tousey, R. (1951): A study of night myopia. Journal of the Optical Society of America. 41: 80 - 90.

Koretz, J. F. and Handelman, G. H. (1982): Model of the accommodative mechanism in the human eye. Vision Research. 22: 917 - 927.

Koretz, J. F. and Handelman, G. H. (1983): A model for accommodation in the young human eye: The effects of lens elastic anisotropy on the mechanism. Vision Research. 23: 1679 - 1686.

Krishnan, V. V., Shirashi, D. and Stark, L. (1977): Dynamic measures of vergence accommodation. American Journal of Optometry and Physiological Optics. 54: 470 - 473.

Krishnan, V. V. and Stark, L. (1977): A heuristic model for the human vergence eye movement system. I. E. E. E. Transactions on Bio-Medical Engineering. BME-24: 44 - 49.

Kruger, P. (1929): Uber einen moglichen Zusammenhang zwischen struktur, funktion und chemischer beschaffenheit der muskeln. Biologisches Zentralblatt. 49: 616 - 622. (Source, Duke-Elder, 1973; Carpenter, 1977).

Kruger, P. B. (1980): The effect of cognitive demand on accommodation. American Journal of Optometry and Physiological Optics. 57: 440 - 445.

Kruger, P. B. and Pola, J. (1983): Size, blur and chromatic aberration are stimuli for accommodation. Paper presented at the Annual Meeting of the American Academy of Optometry, Houston, Texas 1983. Abstracted in American Journal of Optometry and Physiological Optics. 60: 92P.

Kruger, P. B. and Pola, J. (1984): Size is an effective stimulus for accommodation. Paper presented at A.R.V.O. 1984, Sarasota, Florida. Abstracted in Investigative Ophthalmology and Visual Science. 25: 73.

Kuffler, S. W. and Vaughan Williams, E. M. (1953a): small-nerve junctional potenetials: the distribution of small motor nerves to frog skeletal muscle, and membrane characteristics of the fibres they innervate. Journal of Physiology (London). 121: 289 - 317.

Kuffler, S. W. and Vaughan Williams, E. M. (1953b): Properties of the 'slow' skeletal muscle fibres of the frog. Journal of Physiology (London). 121: 318 - 340.

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

Kuntz, A., Richens, C. A. and Casey, C. A. (1946): Reflex control of the ciliary muscle. Journal of Neurophysiology, 9: 445.

Lancaster, W. B. and Williams, E. R. (1914): New light on the theory of accommodation with practical implications. Transactions of the American Academy of Ophthalmology and Oto-Laryngology. 19: 170.

Lands, A. M., Arnold, A., McAnliff, J. P., Luduena, F. P. and Brown, R. G.,Jr (1967): Differentiation of receptor system activated by sympathomimetic amines. Nature (London). 214: 697 - 598.

Langenbeck, M. (1849): Klinische Beitrage aus dem Gebiete der Chirurgie und Ophthmologie. Gottingen. (Source, Helmholtz, 1909).

Langer, S. Z. (1973): The regulation of transmitter release by nerve stimulation through presynaptic ffed-back mechanism. In: Frontiers in Catecholamine Research. pp. 543 - 549. Eds, Usdin, E. and Snyder, S. H. Pergamon, New York.

Langer, S. Z. and Dubocovich, M. L. (1978): Recent Advances in the Pharmacology of Adrenoceptors. pp. 181 - 189. 1st edition. Elsevier / North Holland Biomedical, New York.

Langley, J. H. and Anderson, H. K. (1892): On the mechanism of the movement of the iris. Journal of Physiology (London). 13: 554. (Source, Cogan, 1937).

Laties, A. and Jacobowitz, D. (1964): A histochemical study of the adrenergic and cholinergic innervation of the anterior segment of the rabbit eye. Investigative Ophthalmology. 3: 592 - 600.

Leach, N. E., Wallis, N. E., Lothringer, L. L. Olson, J. A. (1971): Corneal hydration changes during the normal menstrual cycle - a preliminary study. Journal of Reproductive Medicine. 6: 201 - 204.

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

Le Grand, Y. (1956): Optique Physiologique. III, p. 18, Editions de la Revue d'Optique, Paris. (Source, Ingelstam and Ragnarsson, 1972).

Le Grand, Y. (1967): Form and Space Vision. Translated by Millodot, M. and Heath, G. G. Indiana University Press, Bloomington.

Leibowitz, H. W. (1976): Visual perception and stress. In: Physical Work and Effort Ed. Borg, G. pp. 25 - 37 : Proceedings of the International Symposium, Wenner-Gren Centre, New York. Pergamon Press, New York.

Leibowitz, H. W., Hennessy, R. T. and Owens, D. A. (1975): The intermediate resting position of accommodation and some implications for space perception. Psychologica. 18: 162 - 170.

Leibowitz, H. W. and Owens, D. A. (1975a): Anomalous myopias and the intermediate dark-focus of accommodation. Science. 189: 646 - 648.

Leibowitz, H. W. and Owens, D. A. (1975b): Night myopia and the intermediate dark-focus of accommodation. Journal of the Optical Society of America. 65: 1121 - 1128.

Leibowitz, H. W. and Owens, D. A. (1978): New evidence for the intermediate position of relaxed accommodation. Documenta Ophthmologica. 46: 133 - 147.

Leigh, R. J. and Zee, D. S. (1983): The Neurology of Eye Movements. F. A. Davis Co., Philadelphia.

Levene, J. R. (1965): Nevil Maskelyne F.R.S. and the discovery of night myopia. Proceedings of the Royal Society (London). Notes and Reports 20: 100 - 108.

Levene, J. R. (1977): Clinical Refraction and Visual Science. Chapter 8: Night Myopia, pp. 190 - 199. Butterworths, London.

Levy, J. (1969): Physiological position of rest and phoria. American Journal of Ophthalmology. 68: 706 - 713.

Lockhart, R. D. and Brandt, W. (1938): Length of striated muscle fibres. Journal of Anatomy (London). 72: 470.

Loewy, A. D., Saper, C. B. and Yamodis, N. D. (1978): Re-evaluation of the efferent projections of the Edinger-Westphal nucleus in the cat. Brain Research. 141: 151.

Long, W. F. (1974): A mathematical analysis of multi-meridional refractometry. American Journal of Optometry *and Physiological Optics*. 51: 260 - 263.

Lovasik, J. V. and Beauchamp, R. (1982a): Ocular accommodation in the cat after electrical stimulation of mesencephalic reticular formation. American Journal of Optometry and Physiological Optics. 59: 726 - 734.

Lovasik, J. V. and Beauchamp, R. (1982b): Ocular accommodation neurones in brain stem of the alert cat. American Journal of Optometry and Physiological Optics. 59: 785 - 794.

Lowenstein, O. and Loewenfeld, I. E. (1958): Electronic pupillography. Archives of Ophthalmology. 59: 352 - 363.

Lowenstein, O. and Loewenfeld, I. E. (1969): The pupil. In The Eye, Vol. 3. Edited by Davson, H. Academic Press, New York.

Luckiesh, M. and Moss, F. K. (1940): Functional adaptation for near vision. Journal of Experimental Psychology. 26: 352 - 356.

Ludvigh, E., McKinnon, P. and Zartzeff, L. (1964): Temporal course of the relaxation of binocular duction (fusion) movements. Archives of Ophthalmology. 71: 389 - 399.

Lund, J. S., Lund, R. D. and Hendrickson, A. E. (1975): The origin of efferent pathways from the primary visual cortex, area 17, of the macaque monkey as shown by retrograde transport of horseradish peroxidase. Journal of Comparative Neurology. 164: 287 - 304.

Luria, S. M. (1980): Target size and correction for empty field myopia. Journal of the Optical Society of America. 70: 1153 - 1154.

Luschei, C. S. and Fuchs, A. F. (1972): Activity of brain stem neurones during eye movement of alert monkeys. Journal of Neurophysiology. 35: 455 - 461.

Lutjen, E. (1966): Histrometrische untersuchungen uber den ziliarmuskel der primaten. Albrecht Von Graefes Archive fur Klinische und Experimentelle Ophthalmologie. 171: 121. (Source, Rohen, 1969).

Maddock, R. J., Millodot, M., Leat, S. and Johnson, C. A. (1981): Accommodation responses and refractive error. Investigative Ophthalmology and Visual Science. 20: 387 - 391.

Maddox, E. E. (1893): The clinical use of prisms; and the decentring of lenses. 2nd ed. John Wright & Sons, Bristol, England.

Maickel, R. P., Matussek, N., Stern, D. N. and Brodie, B. B. (1967a): The sympathetic nervous system as a homeostatic mechanism. I. Absolute need for sympathetic nervous function in body temperature maintenance of cold exposed rats. Journal of Pharmacological and Experimental Therapeutics. 157: 103 - 110.

Maickel, R. P., Stern, D. N., Takabatuke, E. and Brodie, B. B. (1967b): The sympathetic nervous system as a homeostatic mechanism. II. Effect of adrenocortical hormones on body temperature maintenance of cold-exposed adrenalectomized rats. Journal of Pharmacological and Experimental Therapeutics. 157: 111 - 116.

Magoun, H. W. and Ranson, S. W. (1935): The central path of the light reflex. A study of the effect of lesions. Archives of Ophthalmology. 13: 791 - 811.

Malacara, D. (1974): Measurements of visual refractive defects with a gas laser. American Journal of Optometry and Physiological Optics. 51: 15 - 23.

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

Malmstrom, F. V. and Randle, R. J. (1976): Effects of visual imagery on the accommodation response. Perception and Psychophysics. 19: 450 - 453.

Malmstrom, F. V., Randle, R. J., Bendix, J. S. and Weber, R. J. (1980): The visual accommodation response during concurrent mental activity. Perception and Psychophysics. 28: 440 - 448.

Malmstrom, F. V., Randle, R. J., Murphy, M. R., Reed, L. E. and Weber, R. J. (1981): Visual fatigue: The need for an integrated model. Bulletin of the Psychonomic Society. 17: 183 - 186.

Mandelbaum, J. (1941): Dark adaptation. Archives of Ophthalmology. 26: 203 - 239.

Mandelman, T. and Sivak, J. G. (1983): Longitudinal chromatic aberration of the vertebrate eye. Vision Research. 12: 1555 - 1559.

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

Marg, E. (1951): An investigation of voluntary as distinguished from reflex accommodation. American Journal of Optometry & A. A. A. O. 28: 347 - 356.

Marg, E. (1954): Accommodative response of the eye to electrical stimulation of the ciliary ganglion in cats. American Journal of Optometry & A. A. A. O. 31: 127 - 136.

Marmolin, H. and Rendahl, I. (1975): Interindividual Differences in Mesopic Night Vision Ability Measured by the Mesoptometer. Report 177, Department of Psychology, University of Uppsala, Sweden.

Marshall, J., Beaconsfield, M. and Rothery, S. (1982): The anatomy and development of the human lens and zonules. Transactions of the Ophthalmological Societies of the United Kingdom. 102: 423 - 440.

Maskelyne, N. (1789): An attempt to explain a difficulty in the theory of vision. Philosophical Transactions of the Royal Society. 19: 258. (Source: Levene, 1977).

Mason, J. W. (1968): A review of psychoendocrine research on the sympathetic - adrenal medullary system. Psychomat. Med. 30: 631 - 653.

Mason, J. W. (1971): A re-evaluation of the concept of "non-specificity" in stress theory. Journal Psychiat. Res. 8: 323 - 333.

Masters, R. L. (1964): The effects of alcohol and hypoxia on the heterophorias. Aeromedical Review. 2: 64.

Matin, L., Matin, E. and Pearce, D. G. (1970): Eye movements in the dark during the attempt to maintain a prior fixation position. Vision Research. 10: 837 - 858.

Mays, L. E. (1982): Activity of pontine and midbrain neurons during vergence eye movements. Supplement to Investigative Ophthalmology and Visual Science. 22: 3.

Mays, L. E. (1983): Neurophysiological correlates of vergence eye movements. In: Schor, C. and Cuiffreda, K. (eds.). Vergence eye movements: basic and clinical aspects, Chapter 20, pp. 649 - 670. Butterworths, Boston.

Mays, L. E. (1984): Neural control of vergence eye movements: convergence and divergence neurons in midbrain. Journal of Neurophysiology. 51: 1091 - 1108.

Mays, L. E. and Porter, J. D. (1982): Activity of abducens and oculomotor neurons during symmetrical vergence eye movements. Society for Neuroscience - Symposia abstracts 8: 155.

McBrien, N. A. and Barnes, D. A. (1984): A review and evaluation of theories of refractive error development. Ophthalmic and Physiological Optics. 4: 201 - 213.

McKenzie, B. E. and Day, R. H. (1972): Object distance as a determinant of visual fixation in early infancy. Science. 178: 1108 - 1110.

McNamee, J. E., Piggins, D. and Tong, J. (1981): Confirmation of the influence of alcohol on heterophoria using a vision screener. American Journal of Optometry and Physiological Optics. 761 - 765.

Meesman, A. (1952): Experimentelle untersuchungen uber die antagonistiche innervation der ciliarmuskulatur. Albrecht Von Graefes Archives of Ophthalmology. 152: 335 - 356. (Source, Tornqvist, 1966).

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

Melton, C. E., Purnell, E. W. and Brecher, G. A. (1955): The effect of sympathetic nerve impulses on the ciliary muscle. American Journal of Ophthalmology. 40: 155 - 162.

Merrillees, N. C. R., Sutherland, S. and Hayhow, W. (1950): Neuromuscular spindles in the extraocular muscles of man. Anatomical Record. 108: 23 - 30.

Mershon, D. H. and Amershon, T. L. (1980): Stability of measures of the dark focus of accommodation. Investigative Ophthalmology and Visual Science. 19: 217 - 221.

Meyers, M. P. (1951): The position of the eyes under general anesthesia. American Journal of Ophthalmology. 34: 1749 - 1752.

Michaels, D. D. (1975): Visual Optics and Refraction. Mosby and Co., St. Louis, Illinois.

Miller, J. E. (1959): The electromyography of vergence eye movements. Archives of Ophthalmology. 62: 790 - 794.

Miller, R. J. (1978a): Temporal stability of the dark focus of accommodation. American Journal of Optometry and Physiological Optics. 55: 447 - 450.

Miller, R. J. (1978b): Mood changes and the Dark focus of accommodation. Perception and Psychophysics. 24: 437 - 443.

Miller, R. J. (1980): Ocular vergence-induced accommodation and its relation to dark focus. Perception and Psychophysics. 28: 125 - 132.

Miller, R. J. (1983): Accommodation fatigue and dark focus: The effects of accommodation-free visual work as assessed by two psychophysical methods. Perception and Psychophysics. 34: 532 - 540.

Miller, R. J. and LeBeau, R. C. (1982): Induced stress, situationally-specific trait anxiety, and dark focus. Psychophysiology. 19:260 - 265.

Miller, R. J., Pigion, R. G., Wesner, M. F. and Patterson, J. G. (1983): Accommodation fatigue and dark focus: The effects of accommodation-free visual work when assessed by two psychophysical methods. Perception and Psychophysics. 34: 532 - 540.

Miller, R. J., Wesner, M. F., Pigion, R. G. and Martin, K. D. (1984): Overaccommodation, underaccommodation and the clinical phoropter: A study of instrument myopia and related effects. American Journal of Optometry and Physiological Optics. 61: 293 - 303.

Millodot, M. (1968): Effet des microfluctuations de l'accommodation sur l'acuite visuelle. Vision Research. 8: 73 - 80.

Millodot, M. and Lamont, A. (1974): Influence of menstruation on corneal sensitivity. British Journal of Ophthalmology. 58: 752 - 756.

Millodot, M. and Sivak, J. (1973): Influence of accommodation on the chromatic aberration of the eye. British Journal of Physiological Optics. 28: 169 - 174.

Mitchell, A. M. and Ellerbrock, V. J. (1955): Fixation disparity and the maintenance of fusion in the horizontal meridian. American Journal of Optometry & A. A. A. O. 32: 520 - 534.

Mitchell, D. E. (1966a): A review of the concept of "Panum's fusional areas". American Journal of Optometry & A. A. A. O.. 43: 387 - 401.

Mitchell, D. E. (1966b): Retinal disparity and diplopia. Vision Research. 6: 441 - 451.

Mitchell, D. E. (1970): Properties of stimuli eliciting vergence eye movements and stereopsis. Vision Research. 10: 145 - 162.

Mitchell, D. E. and Blakemore, C. (1970): Binocular depth perception and the corpus callosum. Vision Research. 10: 49 - 54.

Mohindra, I. (1977a): Comparison of "near retinoscopy" and subjective refraction in adults. American Journal of Optometry and Physiological Optics. 54: 319 - 322.

Mohindra, I. (1977b): A non-cycloplegic refraction technique for infants and young children. Journal of the American Optometric Association. 48: 518 - 523.

Mohney, J. B., Morgan, M. W., Olmsted, J. M. D. and Wagman, I. H. (1942): The pathway of sympathetic nerves to the ciliary muscles in the eye. American Journal of Physiology. 135: 759 - 762.

Morat, J. P. and Doyon, M. (1891): Le grand sympathetique, nerf de l'accommodation pour la vision des objets eloignes. Annals d'oculaires. 106: 28 - 30. (Source, Alpern, 1969b).

Morgan, M. W. (1944a): The nervous control of accommodation. American Journal of Optometry & A. A. A. O., 21: 87 - 93.

Morgan, M. W. (1944b): Accommodation and its relationship to convergence. American Journal of Optometry & A. A. A. O., 21: 183 - 195.

Morgan, M. W. (1946): A new theory for the control of accommodation. American Journal of Physiology. 23: 99 - 110.

Morgan, M. W. (1947): The direction of visual lines when fusion is broken as in duction tests. American Journal of Optometry & A. A. A. O. 24: 8 - 12.

Morgan, M. W. (1954): The ciliary body in accommodation and accommodation convergence. American Journal of Optometry & A. A. A. O. 31: 219 - 229.

Morgan, M. W. (1957): The resting state of accommodation. American Journal of Optometry & A. A. A. O., 34: 347 - 353.

Morgan, M. W. (1962): Effect of perceived distance on accommodation and convergence. Transactions of the International Ophthalmic Optical Congress, New York. Hafner Publishing Co.

Morgan, M. W. (1968): Accommodation and vergence. American Journal of Optometry & A. A. A. O. 45: 417 - 454.

Morgan, M. W. (1980): The Maddox classification of vergence eye movements. American Journal of Optometry and Physiological Optics. 57: 537 - 539.

Morgan, M. W. (1983): The Maddox analysis of vergence. In: Schor, C. M. and Ciuffreda, K. J. (Eds.). Vergence Eye Movements: Basic and Clinical Aspects, Chapter 2, pp. 15 - 21, Butterworths, Boston.

Morgan, M. W. and Olmsted, J. M. D. (1939): Quantitative measures of relative accommodation and relative convergence. Proceedings of the Society of Experimental Biology and Medicine. 41: 303 - 307.

Morgan, M. W., Olmsted, J. M. D. and Watrous, W. G. (1940): Sympathetic action in accommodation for far vision. American Journal of Physiology. 128: 588 - 591.

Moskowitz, H., Sharma, S. and Shapero, M. (1972): A comparison of the effects of marijuana and alcohol on visual function. In: Lewis, M. F. (Ed.). Current Researches in Marijuana, pp. 129 - 150. Academic Press, New York.

Moss, F. K. (1932): A modified Brocca pupillometer. Journal of the Optical Society of America. 22: 735 - 738.

Mueller, J. (1843): Elements of Physiology. Vol. 2. Translated by Baly W. Taylor and Walton, London. (Source, Stark et al., 1980).

Nachmias, J. (1961): Determiners of drift of the eye during monocular fixation. Journal of the Optical Society of America. 51: 761 - 766.

Nakoa, S., Mine, K., Nishioka, K. and Kamiya, S. (1969a): The distribution of refractive indices in the human crystalline lens. Japanese Journal of Clinical Ophthalmology. 23: 41 - 44.

Nakoa, S., Ono, T., Nagata, R. and Iwata, K. (1969b): The distribution of refractive indices in the human crystalline lens. Japanese Journal of clinical Ophthalmology. 23: 903 - 906.

Namba, T., Nakamura, T. Takahashi, A. and Grob, D. (1968): Motor nerve endings in extraocular muscles. Journal of Comparative Neurology. 134: 385 - 396.

Newman, H. and Fletcher, E. (1941): The effect of alcohol on vision. American Journal of Medical Science. 202: 723 - 731.

North, R. and Henson, D. B. (1981): Adaptation to prism induced heterophoria in subjects with abnormal binocular vision or asthenopia. American Journal of Optometry and Physiological Optics. 58: 746 - 752.

Nutting, P. G. (1914): The axial chromatic aberration of the human eye. Proceedings of the Royal Society. Series A, 90: 440 - 443.

Nyberg, G. (1976): The influence of B-adrenoceptor antagonists on accommodation of the lens. Clinical and Experimental Pharmacology and Physiology. 3: 493 - 495.

Nygaard, R. W. and Frumkes, T. E. (1982): LED's: Convenient, inexpensive sources for visual experimentation. Vision Research. 22: 435 - 440.

Ogata, D. and Weymouth, F. W. (1918): Refraction differences in foveal and parafoveal vision. American Journal of Ophthalmology. 1: 630 - 644.

Ogle, K. N. (1968): Optics - An Introduction for Ophthalmologists. 2nd ed., C. Thomas, Illinois.

Ogle, K. N. and Martens, T. G. (1957): On the accommodative convergence and the proximal convergence. Archives of Ophthalmology. 57: 702 - 715.

Ogle, K. N., Martens, T. G. and Dyer, J. A. (1967): Oculomotor imbalance in binocular vision. Lea & Febiger, Philadelphia, P. A.

Ogle, K. N., Mussey, M. A. and Prangen, A. de H. (1949): Fixation disparity and the fusional processes in binocular single vision. American Journal of Ophthalmology. 32: 1069 - 1087.

Ogle, K. N. and Prangen, A. de H. (1949): Further considerations of fixation disparity and the binocular fusion processes. American Journal of Ophthalmology. 32: 57 - 75.

Ogle, K. N. and Prangen, A. de H. (1953): Observations on vertical divergences and hyperphorias. Archives of Ophthalmology. 49: 313 - 334.

Ogle, K. N. and Schwartz, J. T. (1959): Depth of focus of the human eye. Journal of the Optical Society of America. 49: 273 - 280.

Oliver, B. M. (1963): Sparkling spots and random diffraction. Proceedings of the Institution of Electrical and Electronic Engineers. 51: 220 - 221.

Olmstead, J. M. D. (1944): The role of the autonomic nervous system in accommodation for far and near vision. Journal of Nervous and Mental Disease. 99: 794 - 798.

Olmsted, J. M. D. and Morgan, M. W. (1939): Refraction of the rabbit's eye in the unexcited and excited state. American Journal of Physiology. 127: 602 - 604.

Olmsted, J. M. D. and Morgan, M. W. (1941): The influence of the cervical sympathetic nerve on the lens of the eye. American Journal of Physiology. 133: 720 - 723.

O'Neill, W. D. and Stark, L. (1968): Triple-function ocular monitor. Journal of the Optical Society of America. 58: 570 - 573.

Ong, J. and Fisher, M. (1973): *Effect of accommodative stimulation on galvanic skin response.* American Journal of Optometry A. A. A. O., 50: 395 - 398.

Ono, H. and Nakamizo, S. (1978): Changing fixation in the transverse plane at eye level and Hering's law of equal innervation. Vision Research. 18: 511 - 519.

Ostberg, O., Powell, J. and Blomkvist, A. (1980): Laser Optometry in Assessment of Visual Fatigue. Technical Report 1 T. Department of Human Work Sciences, University of Lulea, Sweden.

Otero, J. M. (1953): The measurement of accommodation in dim light and darkness by means of the purkinje images. Journal of the Optical Society of America. 43: 925.

Otero, J. M. and Duran, A. (1941): Rendimiento fotometrico de sistemas opticos a baja luminosidades. Anales de Fisica y Quimica 37: 459 - 477. (Source: Borish, 1970).

Otero, J. M. and Duran, A. (1942): Continuacion del estudio de la miopia nocturna. Anales de Fisica y Quimica 38: 236 - 248. (Source: Mellerio, 1966).

Otero, J. M. and Duran, A. (1943): Influencia del efecto de peukinje combinado con la aberracion cromatica del ojo, en la miopia nocturna. Anales de Fisica y Quimica 39: 567 - 578. (Source: Toates, 1972).

Otero, J. M., Plaza, L. and Rios, M. (1948): Influencia de la aberracion monocromatica de apertura en la miopia nocturna, Anales de Fisica y Quimica. 44: 293 - 304. (Source: Mellerio, 1966).

Otero, J. M., Vigon, M. T. and Galvez, D. (1950): Sobre la posicion natural de cristalino y la causa principal de las ametropias nocturnas. Anales de Fisica y Quimica. 46: 227 - 230. (Source: Mellerio, 1966).

Owens, D. A. (1979): The Mandelbaum effect: evidence for an accommodative bias toward intermediate viewing distance. Journal of the Optical Society of America. 69: 646 - 652.

Owens, D. A. (1980): A comparison of accommodative responsiveness and contrast sensitivity for sinusoidal gratings. Vision Research. 20: 159 - 167.

Owens, D. A. and Leibowitz, H. W. (1975): The fixation point as a stimulus for accommodation. Vision Research. 15: 1161 - 1163.

Owens, D. A. and Leibowitz, H. W. (1976a): Oculomotor adjustments in darkness and the specific distance tendency. Perception and Psychophysics. 20: 2 - 9.

Owens, D. A. and Leibowitz, H. W. (1976b): Night myopia: cause and a possible basis for amelioration. American Journal of Optometry and Physiological Optics. 53: 709 - 717.

Owens, D. A. and Leibowitz, H. W. (1980): Accommodation, convergence, and distance perception in low illumination. American Journal of Optometry and Physiological Optics. 57: 540 - 550.

Owens, D. A. and Leibowitz, H. W. (1983): Perceptual and motor consequences of tonic vergence. Chapter 3 in Vergence Eye Movements: Basic and Clinical Aspects. Editors Schor, C. M. and Ciuffreda, K. J. pp. 25 - 74. Butterworths, Boston.

Owens, D. A. and Wolf, K. S. (1984): Dissociation of the dark focus and tonic vergence by near work. Paper presented at *ARVO '84, April 30 - May 4*, Sarasota. Abstracted in Supplement to Investigative Ophthalmology and Visual Science. 25: 183.

Owens, R. L. and Higgins, K. E. (1983): Long-term stability of the dark focus of accommodation. American Journal of Optometry and Physiological Optics. 60: 32 - 38.

Paige, K. E. (1971): Effects of oral contraceptives on affective fluctuations associated with the menstrual cycle. Psychosomatic Medicine. 33: 515 - 538.

Parker, J. A. (1972): Aspheric optics of the human lens. Canadian Journal Ophthalmology. 7: 168 - 175.

Palmer, D. A. (1976): Speckle patterns in incoherent light and ocular refraction. Vision Research. 16: 436.

Panum, P. (1858): Physiologische Untersuchungen Uber das Sehen mit zwei Augen. Schaersche Burchandlung, Keil. (Source, Mitchell, 1966a).

Parlee, M. B. (1974): Stereoscopic beliefs about menstruation: a methodological note on the Moos Menstrual Distress Questionnaire and some new data. Psychosomatic Medicine. 36: 229 - 240.

Parlee, M. B. (1982): Menstrual rhythms in sensory processes: a review of fluctuations in vision, olfaction, audition, taste and touch. Psychological Bulletin. 3: 539 - 548.

Peachey, L. D. and Huxley, A. F. (1962): Structural identification of twitch and slow striated muscle fibres of the frog. Journal of Cellular Biology. 13: 177 - 180.

Peachey, L. D. (1971): The structure of the extraocular muscles fibres of mammals. In: Bach-y-Rita, P., Collins, C. C. and Hyde, J. E. (eds.) The Control of Eye Movements. pp 47 - 66. Academic Press, New York.

Perkins, E. S. (1965): Hand-held applanation tonometer. British Journal of Ophthalmology. 49: 591.

Perrine, M. W. (1974): Alcohol influences upon driving related behaviour: a critical review of laboratory studies of neurophysiological, neuromuscular and sensory activity. In Perrine, M. W. (Ed.) Alcohol, Drugs and Driving, p. 17. U. S. Department of Commerce, National Technical Information Service (No. PB-232 111).

Phillips, D. E., Sterling, W. and Dwyer, W. O. (1975): Validity of the laser refractive technique for determining cylindrical error. American Journal of Optometry and Physiological Optics. 52: 328 - 331.

Phillips, S. R. (1974): Ocular neurological control systems: accommodation and the near response triad. Unpublished PhD. thesis, Department of Mechanical Engineering, University of California, Berkeley. (Source, Ciuffreda and Kenyon, 1983).

Phillips, S. R., Shirachi, D. K. and Stark, L. (1972): Analysis of accommodation response times using histogram information. American Journal of Optometry & A. A. A. O. 49: 389 - 401.

Phillips, S. and Stark, L. (1977): Blur: A sufficient accommodative stimulus. Documenta Ophthmologica. 43: 65 - 89.

Pirchio, M, Spinelli, D., Fiorentini, A. and Maffei, L. (1978): Infant contrast sensitivity evaluated by evoked potentials. Brain Research. 141: 179 - 184.

Pitts, D. G. (1964): Ocular accommodation in the cat from electrical stimulation of the brain. Unpublished PhD thesis, Indiana University. (Source, Lovasik and Beauchamp, 1982a). .

Poggio, G. F. and Fischer, B. (1977): Binocular interaction and depth sensitivity in striate and prestriate cortex of behaving rhesus monkey. Journal of Neurophysiology. 40: 1392 - 1405.

Poos, F. (1928): Zur frage der sympathischen innervation des ziliarmuskels und ihrer bedeutung fur die akkommodation. Klinische Monatasbl. fur Augenheilk. 80: 749. (Source, Cogan, 1937).

Porges, S. W. (1976): Peripheral and neurochemical parallels of psychology: A psychophysical model relating autonomic imbalance to hyperactivity, psychology and autism. In: Advances in Child Development and Behaviour, pp. 36 - 65. Ed. Reese, H. W., Academic Press, New York.

Porterfield. (1759): Treatise on The Eye, The Manner and Phenomena of Vision. Vol. 1, p. 124. Edinburgh. (Source, Helmholtz, 1909; Leigh and Zee, 1983, p. 125).

Post, R. B., Johnson, C. A. and Tsuetaki, T. K. (1984): Comparison of laser and infrared techniques for measurement of the resting focus of accommodation: mean differences and long-term variability. Ophthalmic and Physiological Optics. 4: 327 - 332.

Powell, W. H. (1938): Ocular manifestations of alcohol and consideration of individual variations in seven case studies. Journal of Aviation Medicine. 9: 97 - 103.

Provines, W. F. (1971): The effects of aging on the amplitude of convergence. American Journal of Optometry & A. A. A. O.. 48: 479 - 483.

Ramazzani, B. (1700): De Morbis Artificum - Diseases of Workers. English Edition 1964. Hafner, New York. (Sorce, Campbell and Durden, 1983).

Ramsdale, C. (1978): A Study of Binocular and Monocular Accommodation. Unpublished M.Sc. Thesis, University of Manchester (Technology).

Ramsdale, C. (1979): Monocular and Binocular accommodation. Ophthalmic Optician. 19: 606 - 622.

Ramsdale, C. (1982): Studies Into Some Aspects of Accommodation and Convergence. Unpublished Ph.D thesis, Victoria University of Manchester.

Randle, R. J. (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.

Randle, R. J. and Murphy, M. R. (1974): The dynamic response pf visual accommodation over a seven-day period. American Journal of Optometry and Physiological Optics. 51: 530 - 544.

Rashbass, C. and Westheimer, G. (1961a): Disjunctive eye movements. Journal of Physiology (London). 159: 339 - 360.

Rashbass, C. and Westheimer, G. (1961b): Independence of conjunctive and disjunctive eye movements. Journal of Physiology (London). 159: 361 - 364.

Rayleigh, J. W. S., Lord (1883): On the visibility of small objects in bad light. Proceedings of the Cambridge Philosophical Society. 4: 324. (Source: Levene, 1977; Mellerio, 1966).

Rayleigh, J. W. S., Lord (1885): Civilization and eye-sight. Nature (London). 31: 407. (Source: Levene, 1977).

Raymond, J. E., Lindblad, I.M. and Leibowitz, H. W. (1984) The effect of contrast on sustained detection. Vision Research. 24: 183 - 188.

Richards, O. W. (1976): Instrument Myopia - Microscopy. American Journal of Optometry and Physiological Optics. 53: 658 - 663.

Richards, O. W., Mathews, S. M. and Shaffer, S. M. (1980): Focused apparent image position with convergent, parallel binocular and monocular microscopes. Journal of Microscopy. 122: 187 - 191.

Richardson, K. C. (1966): Electron microscopic identification of autonomic nerve endings. Nature (London). 210: 756.

Richler, A. A. and Bear, J. C. (1972): Refraction, near work and education. A population study in Newfoundland. Acta Ophthalmologica. 58: 468 - 478.

Rigden, J. D. and Gordon, E. I. (1962): The granularity of scattered optical maser light. Proceedings of the Institution of Radio Engineers. 50: 2367 - 2368.

Riggs, L. A. and Niehl, E. W. (1960): Eye movements recorded during convergence and divergence. Journal of the Optical Society of America. 50: 913 - 920.

Ripps, H., Breinin, G. M. and Baum, J. (1961): Accommodation in the cat. Transactions of the American Ophthalmological Society. 59: 176 - 191.

Ripps, H., Chin, N., Seigel, I. M. and Breinin, G. (1962a): The effect of pupil size on accommodation, convergence and the AC/A ratio. Investigative Ophthalmology. 1: 127 - 135.

Ripps, H., Seigel, I. M. and Getz, W. B. (1962b): Functional organization of ciliary muscle in the cat. American Journal of Physiology. 23: 857 - 859.

Robinson, D. A. (1964): The mechanics of human saccadic eye movements. Journal of Physiology (London). 174: 245 - 264.

Robinson, D. A. (1966): The mechanics of human vergence eye movements. Journal of Paediatric Ophthalmology. 3: 31 - 37.

Robinson, D. A. (1970): Oculomotor unit behaviour in the monkey. Journal of Neurophysiology. 33: 393 - 404.

Robinson, D. A. (1981): The use of control systems analysis in the neurophysiology of eye movements. Annual Review of Neuroscience. 4: 463 - 503.

Robinson, D. A. and Fuchs, A. F. (1969): Eye movements evoked by stimulation of frontal eye fields. Journal of Neurophysiology. 32: 637 - 648.

Rohen, J. W. (1979): Scanning electron microscopic studies of the zonular apparatus in human and monkey eyes. Investigative Ophthalmology and Visual Science. 18: 133 - 144.

Rohen, J. W. and Rentsch, F. J. (1969): Der konstruktive bau des zonulaapparates beim menschen und dessen funktionelle bedeutung. Albrecht Von Graefes Archive fur Klinische und Experimentelle Ophthalmologie. 178: 1 - 19.

Romaine, H. H. (1951): Fatigue of accommodation. The Eye, Ear, Nose and Throat Monthly. 30: 140 - 142.

Ronchi, V. (1947): La miopia notturna. Ricerca Scientifica e Ricostruzione. 17: 1417 - 1418. (Source, Mellerio, 1966).

Ronchi, V. (1948): Miopia notturna e accomodazione. Atti Fondazione Giorgio Ronchi. 3: 22 - 31. (Source: Mellerio, 1966).

Roth, C. D. and Richardson, K. C. (1969): Electron microscopical studies on axonal degeneration in the rat iris following ganglionectomy. American Journal of Anatomy. 124: 341 - 360.

Ruskell, G. L. (1967): Vasomotor axons of the lacrimal glands of monkeys and the ultrstructural identification of sympathetic terminals. Zeitschrift fur Zellforschung und Mikroskopiche Anatomie. 83: 321 - 333.

Ruskell, G. L. (1973): Sympathetic innervation of the ciliary muscle in monkeys. Experimental Eye Research. 16: 183 - 190.

Ruskell, G. L. (1975): The ciliary muscle - its structure, innervation and control. The Optician. 170: 9,13+16.

Ruskell, G. L. and Griffiths, T. (1979): Peripheral nerve pathway to the ciliary muscle. Experimental Eye Research. 28: 277 - 284.

Saito, M., Tanaka, T. and Oshima, M. (1981): Eyestrain in inspection and clerical workers. Ergonomics. 24: 161 - 173.

Salzmann, M. (1912): The anatomy and histology of the human eyeball in the normal state. Translated by Brown, E. V. L. Univeratity of Chicago Press, Chicago.

Scheiner, C. (1619): Oculus hoc est: fundamentum opticum. Oeniponti, lib.III, p. 163. (Source, Helmholtz, 1909).

Schiefferdecker. (1905): S. B. Nieder. Ges. Bonn. 14: 54. (Source, Duke-Elder, 1973).

Scher, D., Pionk, M. and Purcell, D. G. (1981): Visual sensitivity fluctuations during the menstrual cycle under dark and light adaptation. Bulletin of the Psychonomic Society. 18: 159 - 160.

Schiller, P. H. (1970): The discharge characteristics of single units in the oculomotor and abducens nuclei of the unanesthetized monkey. Experimental Brain Research. 10: 347 - 362.

Schober, H. A. W. (1947): Die Nachtmyopie und ihre ursachen. Albrecht Von Graefes Archive fur Ophthalmologie. 148: S. 171 - 186. (Source: Borish, 1970).

Schober, H. A. W. (1954): Uber die akkommodationsruhelage. Optik. 11: 282 - 290.

Schober, H. A. W., Dehler, H. and Kassel, R. (1970): Accommodation during observations with optical instruments. Journal of the Optical Society of America. 60: 103 - 107.

Schor, C. M. (1979a): The influence of rapid prism adaptation upon fixation disparity. Vision Research. 19: 757 - 765.

Schor, C. M. (1979b): The relationship between fusional vergence eye movements and fixation disparity. Vision Research. 19: 1359 - 1367.

Schor, C. M. (1980): Fixation disparity: a steady-state error of disparity-induced vergence. American Journal of Optometry and Physiological Optics. 57: 618 - 631.

Schor, C. M. (1983): Fixation and disparity: Chapter 14 in: Vergence Eye Movements. Eds. Schor, C. M. and Ciuffreda, K. J. pp. 465 - 516. Butterworths, Boston.

Schor, C. M. and Narayan, V. (1982): Graphical analysis of prism adaptation, convergence accommodation and accommodation convergence. American Journal of Optometry and Physiological Optics. 59: 774 - 784.

Schor, C. M., Johnson, C. A. and Post, R. B. (1984): Adaptation of tonic accommodation. Ophthalmic and Physiological Optics. 4: 133 - 137.

Sears, M. L. (1984): Autonomic nervous system: Adrenergic agonists. In: Sears, M. L. (Ed.). Pharmacology of the Eye, Chapter 5a, pp. 193 - 248.
Springer-Verlag Berlin, Heidelberg.

Seedorff, H. H. (1956): The effect of alcohol on the motor fusion reserves and stereopsis as well as the tendency of nystagmus. Acta Ophthalmologica. 34: 273 - 280.

Selye, H. (1936): Thymus and adrenals in the response of the organism to injuries and intoxications. British Journal of Experimental Pathology. 17: 234 - 248.

Semmlow, J. L. (1981): The ocular motor response. In: Zuber, B. ed. Models of Oculomotor Behavour. Chemical Rubber, New York.

Semmlow, J. L. and Heerema, D. (1979): The synkinetic interaction of convergence accommodation and accommodative convergence. Vision Research. 19: 1237 - 1242.

Semmlow, J. L. and Hung, G. K. (1979): Accommodative and fusional components of fixation disparity. Investigative Ophthalmology and Visual Science. 18: 1082 - 1086.

Semmlow, J. L. and Hung, G. K. (1981): Experimental evidence for separate mechanisms mediating accommodative vergence and vergence accommodation. Documenta Ophthmologica. 51: 209 - 224.

Semmlow, J. L. and Hung, G. K. (1983): The near response: theories of control.Chapter 6 in: Vergence Eye Movements. Eds. Schor, C. M. and Ciuffreda, K. J. pp. 175 - 195. Butterworths, Boston.

Semmlow, J. L. and Venkiteswaran, N. (1976): Dynamic accommodative vergence in binocular vision. Vision Research. 16: 403 - 411.

Semmlow, J. L. and Wetzel, P. (1979): Dynamic contributions of the components of binocular vergence. Journal of the Optical Society of America. 69: 639 - 645.

Shahnavaz, H. and Hedman, L. (1984): Visual accommodation changes in VDU-operators related to environmental lighting and screen quality. Ergonomics. 27: 1071 - 1082.

Sheard, C. (1920): Dynamic skiametry. Cleveland Press, Chicago.

Shigekazu, U. G. A. (1967): Electron microscopic studies of motor nerve endings in the ciliary muscle of human and monkey eyes. Japanese Journal of Ophthalmology. 11: 121 - 132.

Shirachi, D., Liu, J., Lee, M., Jang, J., Wong, J. and Stark, L. (1978): Accommodation dynamics 1. Range nonlinearity. American Journal of Optometry and Physiological Optics. 55: 631 - 641.

Siebeck, P. (1953): Akkommodationsimpuls und Akkommodationserfolg unter medikamentoesem einfluss. Albrecht Von Graefes Archives of Ophthalmology. 153: 438 - 450. (Source, Alpern, 1969a).

Simmerman, H. (1950): Visual Fatigue. American Journal of Optometry & A. A. A. O. 27: 554 - 561.

Simonelli, N. M. (1979): The dark focus of visual accommodation: its existence, its measurement, its effects. Air Force Office of Scientific Research. Technical Report Bel - 79 - 3/AFOSR - 79 - 7. Las Cruces, New Mexico State University, Department of Psychology, Behavioural Engineering Laboratory.

Simonelli, N. M. (1980a): Polarized Vernier Optometer. Behavioural Engineering Laboratory, Department of Psychology, New Mexico State University. Technical Report Bel - 79 - 4/AfOSR - 79 - 8.

Simonelli, N. M. (1980b): The effects of age and ametropia on the dark focus of visual accommodation. Paper presented to The human Factors Society, 24th Annual Meeting, 1980. Proceedings of the Human Factors Society. 22: 312 - 316.

Simonelli, N. M. (1983): The dark focus of the human eye and its relationship to age and visual defect. Human Factors. 25: 85 - 92.

Sinclair, D. C. (1965): Demonstration of chromatic aberration in the eye using coherent light. Journal of the Optical Society of America 55: 575 - 576.

Sivak, J. G. and Mandelman, T. (1982): Chromatic dispersion of the ocular media. Vision Research. 22: 997 - 1003.

Sivak, J. G. and Millodot, M. (1974): Axial chromatic aberration of the eye with an achromatizing lens. Journal of the Optical Society of America. 64: 1724 - 1725.

Skavenski, A. A. and Steinman, R. M. (1970): Control of eye position in the dark. Vision Research. 10: 193 - 203.

Slater, A. M. and Findlay, J. M. (1975): Binocular fixation in the newborn baby. Journal of Experimental Child Psychology. 20: 248 - 273.

Smith, G. (1983): The accommodative resting states, instrument accommodation and their measurement. Optica Acta. 30: 347 - 359.

Smith, J. L. and Cogan, D. G. (1959): Internuclear ophthalmoplegia. Archives of Ophthalmology. 61: 678 - 694.

Smith, M. A. (1983): personal communication to Keily et al. (1983).

Smith, W. J. (1979): A review of literature relating to visual fatigue. Proceedings of the Human Factors Society. 23rd Annual Meeting. 362 - 366.

Smithline, L. M. (1974): Accommodative response to blur. Journal of the Optical Society of America. 64: 1512 - 1516.

Sommer, B. (1973): The effect of menstruation on cognitive and perceptual-motor behaviour. Psychosomatic Medicine. 35: 515 - 534.

Soni, P. S. (1980): Effects of oral contaceptive steroids on the thickness of the human cornea. American Journal of Optometry and Physiological Optics. 57: 825 - 834.

Southall, J. (1933): Mirrors, Prisms and Lenses - A Textbook of Geometrical Optics. 3rd ed., pp. 422 - 423. Macmillan, New York.

Southam, A. L. and Gonzaga, F. P. (1965): Systematic changes during the menstrual cycle. American Journal of Obstetrics and Gynecology. 91: 142 - 165.

Stark, L., Kenyon, R. V., Krishnan, V. V. and Ciuffreda, K. J. (1980): Disparity vergence: a name proposed name for a dominanat component of binocular vergence eye movements. American Journal of Optometry and Physiological Optics. 57: 606 - 609.

Stark, L., Takahashi, Y. and Zames, G. (1965): Nonlinear servo-analysis of human lens accommodation. I.E.E.E. Transations on Sytems Science and Cybernetics. SSC-1: 75 - 83.

Sternbach, R. A. (1966): Principles of Psychology. pp. 57 - 78, Academic Press, New York.

Stewart, C. R. (1961): Jump vergence response. American Journal of Optometry & A. A. A. O.38: 57 - 86.

Stone, E. A. (1975): Stress and catecholamines. In: Friedhoff, A. J. (Ed.). Catecholamines and Behaviour, Volumes 2., Neuropsychopharmacology, pp. 31 - 72, Plenum Press, New York.

Streeten, B. W. and Licari, P. A. (1983): The zonules and the elastic microfibrillar system in the ciliary body. Investigative Ophthalmology and Visual Science. 24:667 - 681.

Stuart-Black Kelly, T., Chatfield, C. and Tustin, G. (1975): Clinical assessment of the arrest of myopia. British Journal of Ophthalmology. 59: 529 - 538.

Suzuki, R. (1983): Neuronal influence on the mechanical activity of the ciliary muscle. British Journal of Pharmacology. 78: 591 - 597.

Tait, E. F. (1951): Accommodative convergence. American Journal of Ophthalmology. 24: 1093 - 1107.

Tagawa, S., Fukae, K. and Nonaka, T. (1967): Response of ciliary muscle to adrenergic agents in regard to alpha and beta receptors. Japanese Journal of Ophthalmology. 11: 227 - 232.

Taylor,S. (1977): Techniques for measuring pupil size. Optician. 174: 19,20,29.

Thomas, J. V. and Epstein, D. L. (1981): Study of the additive effect of Timolol and Epinephrine in lowering intraocular pressure. British Journal of Ophthalmology. 65: 596.

Thorner, W. and Spanuth, H. (1932): The Variator. British Journal of Physiological Optics. 6: 25 - 28.

Toates, F. M. (1968): The control of the eye's intrinsic muscles. Measurement and Control. 1: T.129 - T.132.

Toates, F. M. (1970): A model of accommodation. Vision Research. 10: 1069 - 1076.

Toates, F. M. (1972): Accommodation function of the human eye. Physiological Reviews. 52:828 - 863.

Toates, F. M. (1974): Vergence eye movements. Documenta Ophthmologica. 37: 153 - 214.

Tornqvist, G. (1966): Effect of cervical sympathetic stimulation on accommodation in monkeys. Acta Physiologica Scandinavica. 67: 363 - 372.

Tornqvist, G. (1967): The relative importance of the parasympathetic and sympathetic nervous systems for accommodation in monkeys. Investigative Ophthalmolgy. 6: 612 - 617.

Tornqvist, G. (1970): Effect of cervical sympathetic stimulation on accommodation in guanethidine-treated monkeys. Investigative Ophthalmology and Visual Science. 9: 765 - 768.

Trope, G. E. and Clark, B. (1982): Beta adrenergic receptors in pigmented ciliary processes. British Journal of Ophthalmology. 66: 788.

Tscherning, M. (1898): Optique Physiologique. p.98 and 158. Carre et Naud, Paris. (Source, Koomen et al., 1949; Duke-Elder, 1970).

Tscherning, M. (1909): Hermann von Helmholtz et la Theorie de l'accommodation. Paris. (Source, Fincham, 1937).

Tucker, J. and Charman, W. N. (1975): The depth of focus of the human eye for snellen letters. American Journal of Optometry and Physiological Optics. 52: 3 - 21.

Tucker, J. and Charman, W. N. (1979): Reaction and response times for accommodation. American Journal of Optometry and Physiological Optics. 56: 490 - 503.

Tyler, C. W. (1983): Sensory processing of binocular disparity. Chapter 7 in Schor, C. M. and Ciuffreda, K. J., eds. Vergence Eye Movements: Basic and Clinical Aspects. 199 - 295. Butterworths, Boston.

Ukai, K., Ohzu, H. and Takata, T. (1978): Refractometer and optometer by aid of laser speckle pattern. In: International Symposium on Ophthalmological Optics. pp. 95 - 98, May 7-9, University of Tsukuba, Tokyo.

Vaegan and Pye, D. (1979): Independence of convergence and divergence: norms, age trends, and potentiation in mechanized prism vergence tests. American Journal of Optometry and Physiological Optics. 56: 143 - 152.

Van Alphen, G. W. H. M. (1961): On emmetropia and ametropia. Ophthalmologica (Suppl.) 142: 1 - 92.

Van Alphen, G. W. H. M., Kern, R. and Robinette, S. L. (1965): Adrenergic receptors of the intraocular muscles. Archives of Ophthalmology. 74: 253 - 259.

Van Alphen, G. W. H. M. (1976): The adrenergic receptors of the intraocular muscles of the human eye. Investigative Ophthalmolgy and Visual Science. 15: 502 - 505.

Velhagen, K. (1937): Heterophoria unter den bedingungen des hohenfluges. Luftahrmedizin. 1: 344.

Von Graefe. (1860): Albrecht Von Graefes Archive fur Ophthalmologie. 7: 150. (Source, Duke-Elder, 1970).

Von Hofsten, C. (1976): The role of convergence in visual space perception. Vision Research. 16: 193 - 198.

Wald, G. and Griffen, D. R. (1947): The change in refractive power of the human eye in dim and bright light. Journal of the Optical Society of America. 37: 321 - 336.

Walker, J. (1982): The speckle on a surface lit by laser light can be seen with other kinds og illumination. Scientific American. 246: 128 - 133.

Wallach, H., Frey, K. J. and Bode, K. A. (1972): The nature of adaptation in distance perception based on oculomotor cues. Perception and Psychophysics. 11: 110 - 116.

Wanko, T. and Gavin, M. A. (1958): The fine structure of the lens epithelium. Archives of Ophthalmology. 60: 868 - 879.

Ward, M. M., Stone, S. C. and Sandman, C. A. (1978): Visual perception in women during the menstrual cycle. Physiology and Behaviour. 20: 239 - 243.

Warlomont, E. (1875): Le muscle ciliare. Annals d'Oculaire. 73: 195. (Source, Cogan, 1937).

Warren, D. E., Tedford, W. H. Jr. and Flynn, W. E. (1979): Behavioural effects of cyclic changes in serotonin during the menstrual cycle. Medical Hypotheses. 5: 359 - 364.

Warwick, R. (1953): Representation of the extraocular muscles in the oculomotor nuclei of the monkey. Journal of Comparative Neurology. 98: 449 - 504.

Warwick, R. (1954): The ocular parasympathetic nerve supply and its mesencephalic sources. Journal of Anatomy (London). 88: 71 - 93.

Warwick, R. (1955): The so-called nucleus of convergence. Brain. 78: 92 - 114.

Warwick, R. (1956): Oculomotor organisation. Annals of the Royal College of Surgeons (England). 19: 36 - 52.

Warwick, R. (1964): Oculomotor organization. Chapter 7 in: Bender, M. B. (ed), The Oculomotor System. p. 173. Harper and Row, New York.

Wax, M. B. and Molinoff, P. B. (1984): Distribution and properties of beta-adrenergic receptors in human iris/ciliary body. Abstract in Supplement to Investigative Ophthalmology and Visual Science. 25: 305.

Weale, R. A. (1962): Presbyopia. British Journal of Ophthalmology. 46: 660 - 668.

Wenger, M. A., Jones, F. N. and Jones, M. H. (1956): Physiological Psychology. pp. 258 - 271. Henry Holt and Co. New York.

Westheimer, G. (1955): The relationship between accommodation and accommodative convergence. American Journal of Optometry & A. A. A. O. 52: 206 - 212.

Westheimer, G. (1957): Accommodation measurements in empty visual fields. Journal of the Optical Society of America, 47: 714 - 718.

Westheimer, G. (1963): Amphetamine, barbiturates and accommodation-convergence. Archives of Ophthalmology. 70: 830 - 836.

Westheimer, G. and Blair, S. M. (1973): The parasympathetic pathways to internal eye muscles. Investigative Ophthalmology. 12: 193 - 197.

Westheimer, G. and Mitchell, A. M. (1956): Eye movement responses to convergence stimuli. Archives of Ophthalmology. 55: 848 - 856.

Westheimer, G. and Mitchell, A. M. (1969): The sensory stimulus for disjunctive eye movements. Vision Research. 9: 749 - 755.

Weston, H. W. (1954): Visual Fatigue. Transactions of the Illumination and Engineering Society (New York). 49: 63 - 76.

White, A. D. and Rigden, J. D. (1962): Continuous gas maser operation in the visible. Proceedings of the Institution of Radio Engineers. 50: 1697.

Whitefoot, H. D. (1977): Laser Refraction. Unpublished M.Sc. Thesis, Victoria University of Manchester.

Whiteside, T. C. D. (1952): Accommodation of the human eye in a bright and empty visual field. Journal of Physiology (London). 118: 65P.

Whiteside, T. C. D. (1953): Accommodation of the human eye in an empty visual field. Flying Personnel Research Committee Report FPRC 821.

Wibaut, F. (1919): Refractitoeneming in schemerdonker. Nederlands Tijdschrift voor Geneeskunde 55: 1437 - 1441. (Source, Mellerio, 1966).

Wilmer, W. H. and Berens, C. (1918): The effect of altitude on ocular functions. Journal of the American Medical Association. 71: 1394 - 1398.

Wilson, D. C. (1972): Accommodation - accommodation vergence synkinesis in the human visual system. Unpublished Ph.D thesis, University of California.

Wilson, M. E. and Toyne, M. J. (1970): Retino-tectal and cortico-tectal projections in Macaca mulatta. Brain Research. 24: 395 - 406.

Wist, E.R., Hughes, F. W. and Forney, R. B. (1967): The effect of low blood levels of alcohol on stereoscopic acuity and fixation disparity. Perception and Motor Skills. 24: 83 - 87.

Wolf, K. S., Ciuffreda, K. J. and Jacobs, S. N. (1985): Time course and decay of induced changes in dark focus and dark vergence. Paper presented at ARVO '85, May 6-10, Sarasota, Florida. Abstracted in: Supplement to Investigative Ophthalmology and Visual Science. 26: 269.

Wolfe, D. E., Potter, L. T., Richardson, K. C. and Axelrod, J. (1962): Localizing tritiated norepinephrine in sympathetic axons by electron microscopic autoradiography Science (New York). 138: 440 - 442.

Wolfe, J. M. and Owens, D. A. (1981): Is accommodation colorblind? Focusing chromatic contours. Perception. 10: 53 - 62.

Wolffe, E. (1976): Anatomy of the Eye and Orbit. 7th edition. Lewis, London.

Wolter, J. R. (1954): The morphology of the nervous system of the striated muscles of the human eye. In Proceedings of the Seventeenth International congress of Ophthalmology. Sept. 10-17. Vol. III, pp. 1865 - 1873. University of Toronto Press, Toronto. (Source, Alpern, 1962).

Wolter, J. R. (1955): Morphology of the sensory nerve apparatus in the striated muscle of the human eye. Archives of Ophthalmology. 53: 201 - 217.

Yamaguchi, I. and Komatsu, S. I. (1977): Theory and applications of dynamic laser speckles due to in-plane object motion. Optica Acta. 24: 705 - 724.

Yamazaki, H. (1977): Clinical study on the resting state of accommodation. Report 2. The resting state of accommodation on the refraction-abnormal eyes. Acta Societatis Ophthalmologicae Japonicae. 81: 577 - 589.

Yoshide, T. and Watanabe, A. (1969): Analysis of interaction between accommodation and vergence feedback control systems of human eyes. Bulletin N.H.K. Broadcasting and Scientific Research Laboratories. 3: 72 - 80.

Young, T. (1801): On the mechanism of the eye. Philosophical Transactions of the Royal Society. 91: 23 - 88. (Source, Helmholtz, 1909; Koomen et al., 1949).

Zimmerman, A. A., Armstrong, E. L. and Scammon, R. E. (1933): The change in position of the eyeballs during fetal life. Anatomical Record. 59: 109 - 134.

Zimmerman, T. J. and Boger W. P. (1979): III - The beta-adgrenergic blocking agents and the treatment of glaucoma. Survey of Ophthalmology. 23: 347.

Zuber, B. L. and Stark, L. (1968): Dynamic characteristics of the fusional vergence system. I.E.E.E. Transactions on Systems Science and Cybernetics. SSC-4: 72 - 79.

Zulch, J. and Kreuger, H. (1978): Rechnergesteuertes tachistoskop zur messung der akkommodationszeit und ruhelage des menschlichen auges. Biomedizinsche Technik. Supplement 23, May-June.

Gilmartin, B. (1986): The role of sympathetic innervation of the ciliary muscle in ocular accommodation: a review. Ophthalmic and Physiological Optics. 6: 23 - 37.

Litsinger, G. G. (1981): Amplitude of accommodation. Optometric Weekly. 72: 42 - 44.

Westheimer, G. and Blair, S. M. (1973): Accommodation of the eye during sleep and anaesthesia. Vision Research. 13: 1035 - 1040.