

BINOCULAR ALIGNMENT AND VERGENCE  
ERRORS IN FREE SPACE

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*“It would, therefore, seem to be true that in voluntary divergence the optical axes are not brought into a position of direct fixation upon the point, but the eyes are so adjusted that the points to be fused fall approximately at the centres of vision, though in reality somewhat at the side. This confirms . . . . that there is no definite centre of fixation, but a somewhat extended area which is entirely satisfactory to the subject.”*

*Judd CH, Photographic records of convergence and divergence. Psychol Monog, 1907. 6:370-435*

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## INTRODUCTION

The human, along with other primates, has forward placed eyes, and an area of acute vision (the fovea) on each retina. The overlap of the visual fields and the hemi-decussation of the visual pathways at the optic chiasm provide the basis for binocular vision, in particular stereopsis, the accurate perception of the position of objects in three dimensional space and an improved ability to perceive the form of solid objects. An intricate system of eye movements is needed to achieve and maintain stable foveal fixation on each eye in an environment where visual targets vary in direction and depth, where the visual environment may be moving, the eyes or the rest of the body is moving.

The purpose of this study is to evaluate the accuracy of binocular alignment for far and near fixations, under relatively natural conditions. To achieve binocular fixation, accurate vergence eye movements are required to align the eyes, and to maintain this alignment when a person changes fixation to objects situated at different distances from the eyes. 'Pure' vergence eye movements occur when these objects are situated along the mid sagittal plane, however, in natural conditions other eye movement systems are also involved.

To understand the contribution of different eye movement systems to binocular fixation at different distances, the accuracy of binocular alignment in subjects with normal binocular single vision was evaluated in subjects with normal binocular vision under the following conditions

- Fixation on targets along the mid sagittal plane (vergence eye movements only)
- Fixation on targets displaced to either side of the mid sagittal plane (combined vergence eye movements and saccades)
- Fixation on earth fixed targets situated straight ahead in space, but with the head tilted to either side (combined vergence eye movements, saccades and torsional eye movements).

The protocol for all experiments was approved by the Human Ethics Committee of the University of Sydney and followed the tenets of the Declaration of Helsinki.

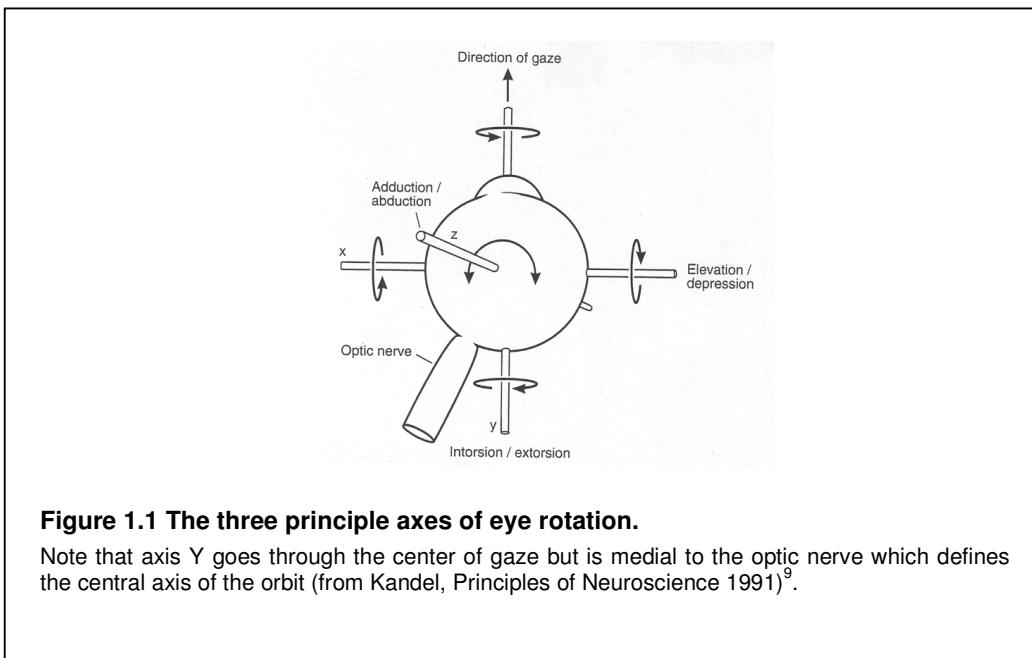
*Throughout this thesis the term 'binocular alignment' will be used to describe the position of each eye during or following a change in vergence. The term 'vergence error' will refer to situations where the angle of vergence alignment is different from that required, so that the image of the fixation target does not fall on the fovea of one or both eyes.*

# Chapter 1

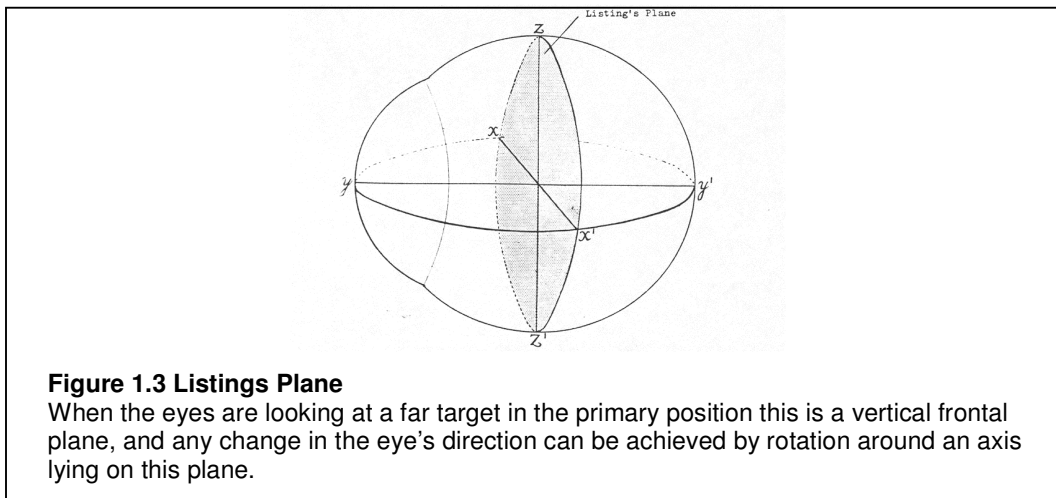
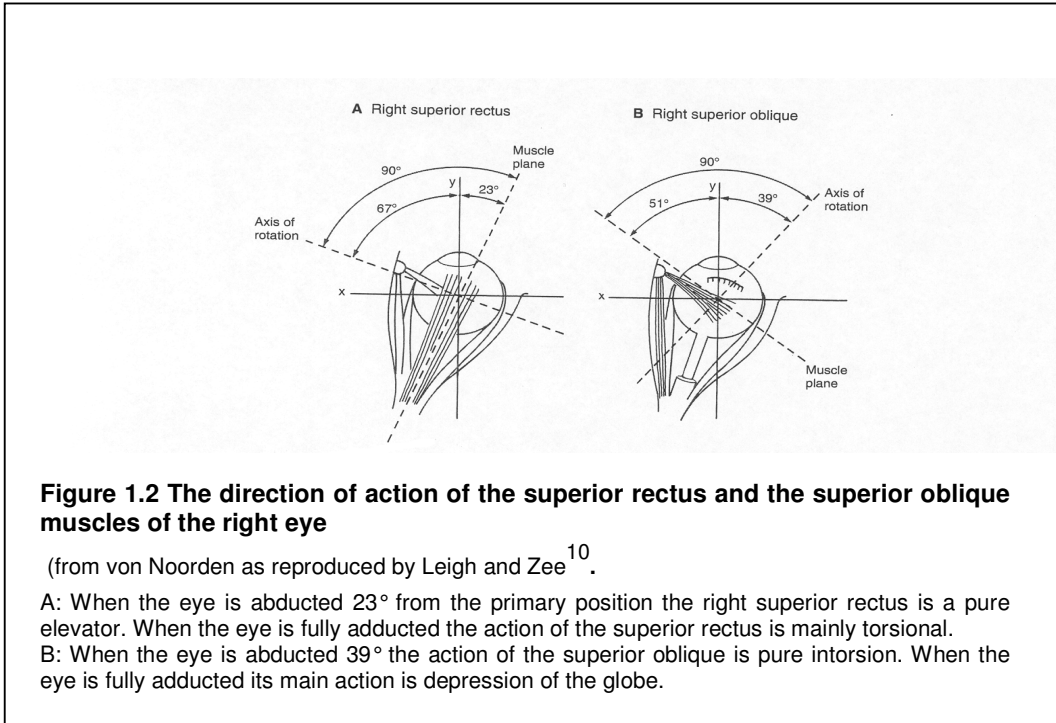
## Eye movements

### INTRODUCTION

The eye's orientation can be defined by three axes of rotation – horizontal, vertical and torsional. Horizontal movements (abduction and adduction) occur around the Z axis, vertical movements (elevation and depression) occur around the X axis and torsional movements (intorsion and extorsion) occur around the Y axis. (Figure 1.1). Listing's Plane is a vertical frontal plane that is defined by these axes of rotation. When the eyes are looking at a far target in the primary position this is a vertical frontal plane, (Figure 1.2), and any change in the eye's direction can be achieved by rotation around an axis lying on this plane. There is evidence that Listing's plane rotates when the eyes are converged to a near target that is situated above or below the midline<sup>1-8</sup>.



Eye movements are achieved by coordinated contraction and relaxation of the extraocular muscles (six in each eye). Horizontal rotations around the Z axis are primarily brought about by the medial and lateral rectus muscles. Vertical rotations occur around the X axis and torsional rotations occur around the Y axis. The cyclo vertical muscles (the superior and inferior rectus muscles and the superior and inferior oblique muscles) bring about both vertical and torsional movements as their muscle planes are not coincident with the visual axis when the eye is in the primary position (see Figure 1.3). Another consequence of this is that contraction of the cyclo-vertical muscles brings about different rotations depending on the position of the eye in the orbit.



The following summarises principal actions of the cyclo-vertical muscles in abduction (the eye is moved towards the temple and adduction (the eye is moved towards the nose), however torsional movements are primarily brought about by the oblique muscles and vertical rotations are primarily brought about by the vertical recti. The primary action of the muscle is shown as bold.

<u>Muscle</u>	<u>Abduction</u>	<u>Adduction</u>
Superior rectus	<b>Elevation</b>	Intorsion
Superior oblique	<b>Intorsion</b>	Depression
Inferior rectus	Depression	<b>Extorsion</b>
Inferior oblique	Extorsion	<b>Elevation</b>

## **Classification of eye movements**

In the following discussion, emphasis is placed on vestibular and vergence eye movements, and, to a lesser extent, saccadic eye movements, as these form the primary framework for the experiments reported in Chapters 3-7.

### **Conjugate eye movements (versions)**

Conjugate eye movements are those in which each eye moves in the same direction, for example, up and to the right. These movements have been classified depending on their characteristics.

### **Saccadic movements**

Saccades are fast eye movements that allow the eye to change foveal fixation from one image to another. Leigh & Zee<sup>10</sup>(p19) classify saccades as:

1. Volitional: Saccades that are made as part of purposeful behavior, that include predictive or anticipatory saccades, memory guided saccades, antisaccades (saccades generated when directed to look in the opposite direction to a sudden appearance of a target).
2. Reflexive: Saccades generated to a novel stimulus in the environment.
3. Express: Short latency saccades that can be elicited when a novel stimulus is introduced after the fixation stimulus has disappeared
4. Spontaneous: Seemingly random saccades to no particular stimulus
5. The quick phases of optokinetic or vestibular nystagmus.

Saccades show a consistent relationship between their peak velocity and their amplitude, This relationship is sometimes referred to as the 'main sequence'. Large saccades can have a peak velocity of over 700 deg/sec. The duration of a saccade is linearly related to its amplitude, with a 30° saccade lasting about 100msec. The latency of the movement is around 200 msec<sup>10</sup>.

Saccades occur when there is a high frequency burst of activity in an agonist muscle (the saccadic pulse) followed by a level of tonic innervation (the saccadic step) that maintains the eye in its new position. The antagonist muscle is inhibited during the saccadic pulse, and assumes a low level of tonic innervation at the end of the saccade<sup>10</sup>.

The different characteristics of horizontal and vertical saccades are summarized in Table 1.1.

**Table 1.1 Characteristics of horizontal and vertical saccades**

Summarised from Collewijn et al<sup>11, 12</sup> and Leigh and Zee<sup>10</sup>.

	<b>Horizontal saccades</b>	<b>Vertical saccades</b>
Accuracy	Undershoot by approx 0.5°, independent of amplitude (range 10° to 70°)	Less accurate than horizontal saccades. Upward saccades undershoot by about 10%; downward saccades tend to overshoot.
Peak velocities	Approx 200 deg/s for 10° amplitude, to asymptotic level at 700 deg/s for 80° amplitude	Increase with amplitude to 513 deg/s. Distinct asymptotic level not apparent
Duration	Linearly related to amplitude up to 50°	
Symmetry	Abducting eye has larger size, peak velocity and shorter duration than adducting eye Centripetal saccades show peak velocities approx. 10% faster than centrifugal saccades.	Vertical movements symmetrical. Upward saccades associated with divergence and downward saccades associated with convergence.
Postsaccadic drift	Version and vergence component	Converging drift after upward saccades, diverging drift after downward saccades.
Factors influencing velocity	Slower in darkness (to remembered or auditory targets), to predictable targets or in the opposite direction to a stimulus (antisaccades). Faster when repetitive movements made at higher frequencies and in association with manual tasks,	



During a saccade, there is a rapid movement of the visual world across the retina. However, this does not result in blur or perception of movement of the visual field. This 'saccadic suppression' is considered to be related to suppression of the magnocellular pathways<sup>13 14-16</sup>. The neural pathways for saccadic eye movements are complex and the following presents a simplified model<sup>17</sup>.

Fibres pass from the frontal eye fields and the anterior limb of the internal capsule to the level of the rostral diencephalon where they separate into two bundles depending on the type of movement required.

1. Horizontal saccades: The more ventral bundle descends to the rostral pons where it decussates to synapse in the horizontal gaze center, the paramedian pontine reticular formation (PPRF). From here some fibres pass to the ipsilateral abducens nucleus, while others pass to the ascending contralateral medial longitudinal fasciculus (MLF) to terminate in the supraocular area close to the oculomotor nucleus. This provides coordinated innervation to the lateral rectus of one eye and the medial rectus of the other eye, the yoke muscles for horizontal gaze.
2. Vertical saccades: The more dorsal bundle passes through the thalamus to terminate in the pretectum, the superior colliculus and the periaqueductal grey matter. From here the prefrontal oculomotor bundle projects to oculomotor nucleus, the ipsilateral interstitial nucleus of the MLF and the interstitial nucleus of Cajal, all of which are involved in the coordination of vertical eye movements.

### **Smooth Pursuit movements**

Smooth pursuit eye movements allow for fixation and tracking of slowly moving objects, and therefore provide stable retinal images from moving objects. Smooth pursuit movements result from a negative feedback control system, with its input, (image motion across the retina driving eye velocity to match target velocity<sup>18, 19, 10, 20</sup>).

Smooth pursuit movements have a latency of about 100 msec and are relatively slow, the gain (peak eye velocity/peak target velocity) is around 0.8 to 1 for target motion of 30 deg/sec<sup>10</sup> but does not significantly deteriorate until target velocity exceeds 100 deg/sec<sup>21</sup>.

The neural pathways for pursuit eye movements are less well known. For voluntary movements the pathway probably originates in the parietal cortex and the adjacent superior temporal and anterior occipital lobes and descend in the interior capsule to the dorsolateral pontine nucleus (DLPN) that contains neurons that encode a variety of visual and oculomotor signals. A second descending pathway originates in the frontal eye fields that also passes to the DLPN<sup>10</sup>.

## **Vestibular Movements**

The function of vestibular eye movements is to maintain a steady image on the retina despite both angular (rotational) and linear translations of the head. These functions are controlled by the vestibular system of the inner ear and its close relationship with the cerebellum and other neural areas that control ocular motility.

### **Anatomy of the vestibular system**

#### **Labyrinths**

The peripheral sensory organs for vestibular eye movements are the two membranous labyrinths that lie within the temporal bone of each inner ear. Each labyrinth contains the three semicircular canals that sense head rotation, and the maculae of the utricle and saccule (otoliths) that sense linear motion and static changes in gravitational forces. The labyrinth also contains the cochlea, the primary auditory sensory organ.

#### **Semicircular canals**

There are three semicircular canals that are more or less orthogonal with respect to each other, and are continuous with the utricle and saccule. Each canal consists of a circular tube filled with viscous endolymphatic fluid. The horizontal canals are approximately horizontal when the head is held straight whilst the vertical canals are arranged in diagonal planes that subtend roughly 45° relative to the sagittal and frontal planes of the skull. Thus the anterior canal on one side is parallel to the posterior canal of the other.

The sensory receptors for rotational acceleration, the cristae, are located at the base of each semicircular canal in an enlarged area, the ampulla. Each crista consists of a gelatinous sail like structure (the cupula) in which are embedded the ampulla's hair cells. The cupula bends in response to movement of the endolymphatic fluid within the semicircular canals, which in turn exerts force on the cilia of hair cells. These hair cells contain many small processes (stereocilia) and one larger kinocilium. Bending of the cilia towards the kinocilium causes it to depolarise, increasing the firing of the afferent fibre, bending away from the kinocilium causes hyperpolarisation resulting in a decreased firing rate.

#### **Otoliths**

The maculae, the sensory receptors for linear acceleration and static changes in gravity with respect to the head are located in two vestibular sacs, the utricle and saccule. Each macula consists of a gelatinous mass, the otolith membrane in which crystals of calcium carbonate (otoconia) and the cilia of hair cell receptors (stereocilia and a kinocilium) are embedded. When the head is in the upright position, this tissue is located on the floor of the utricle and on the wall of the saccule. The utricle is therefore oriented to response to lateral or fore-aft tilts and side to side translations of the head, whilst the saccule responds best to up-down translations of the head<sup>10</sup>.

Motion or changes in gravity cause shearing movements of the otoconial layer that bend the hair cells, causing polarization and hyperpolarisation in a manner similar to that in the semicircular canals.

**Neural pathway for the vestibular-ocular response\_**

Afferents from the vestibular apparatus pass to Scarpa's ganglion, located within the internal auditory meatus and then as the vestibular nerve to synapse in the vestibular nuclei. Neurons in the vestibular nuclei project to the oculomotor nuclei in such a way that inputs from each canal excite and inhibit complementary muscles in each eye (See Table 1.2)

**Table 1.2** (from Kandel, Schwartz and Jessell)<sup>9</sup>  
Relationship between each semicircular canal and the extraocular muscles

<b>Canal</b>	<b>Excites</b>	<b>Inhibits</b>
Horizontal	ipsilateral medial rectus	ipsilateral lateral rectus
	contralateral lateral rectus	contralateral medial rectus
Posterior	ipsilateral superior oblique	ipsilateral inferior oblique
	contralateral inferior rectus	contralateral superior oblique
Anterior	ipsilateral superior rectus	ipsilateral eye inferior rectus
	contralateral inferior oblique	contralateral superior oblique.

**Characteristics of vestibular eye movements**

Vestibulo-ocular reflex (VOR)

The function of this reflex is to stabilise the image on the retina during rotations of the head. This reflex depends on the semicircular canals that detect head movements and initiate a rapid compensatory movement in the opposite direction with a latency of less than 16 msec. The VOR is more efficient in yaw (head rotates horizontally) and pitch (head rotates vertically) than in roll movements (ear to shoulder), as for these movements the image is not moved off the fovea <sup>10</sup>. Sustained rotations of the body produce vestibular nystagmus, with the fast phase beating in the same side as the direction of the head.

Translational movements of the head also initiate a compensatory horizontal or vertical eye movement if the object of regard is near to the subject, These movements are initiated by the otoliths system (translational VOR).

#### Ocular counter-roll (OCR)

When the head makes a static tilt to the side, the eyes respond by making a static conjugate torsional movement with the 12 o'clock meridian rotating in the opposite direction to the tilt. This reflex is otolith induced. Although this reflex may have originated to maintain a horizontal horizon in vertebrates with laterally placed eyes, in humans it only compensates for approximately 10% of the tilt<sup>22</sup>.

#### Cervico-ocular reflex

A rotation of the torso about the Z axis, relative to a stationary head produces small amplitude horizontal nystagmus and a conjugate horizontal eye movement opposite to the movement of the torso. A forward inclination of the torso with respect to the head produces vertical eye movements. Ott<sup>23</sup> considers that a sideways tilt of the torso in the absence of utricular input does not induce eye torsion, although others<sup>24-28</sup> have suggested that there may be some effect of proprioception of the sterno-cleido-mastoid muscles on ocular counter-roll when otolith function is reduced or absent. This will be discussed further in Chapter 6 ( experiment 4).

#### Skew deviation

When animals with laterally directed eyes tilt the head to one side there is a compensatory movement whereby the lower eye moves up, and the higher eye moves down (skew deviation). In humans a similar response may occur following lesions of the midbrain where the eye on the same side as the head tilt moves up and the contralateral eye moves downward. There is evidence that very small skew deviations can occur on head tilt in normal subjects<sup>29-33</sup>.

### **1.1.2 Disconjugate eye movements (vergences)**

Disconjugate eye movements are those in which the eyes rotate in opposite directions to each other. They are also known as vergence eye movements and, although they are differentiated from conjugate movements in everyday situations eye movements are frequently a combination of vergence and versions, as changes in fixation (or movements of an object) rarely take place purely along the midline or the horopter.

## **Horizontal vergence**

The primary function of horizontal vergence movements is to allow binocular fixation (normally bifoveal fixation) to be maintained as the observer changes fixation to objects at nearer or more distant positions, or as the fixation object moves closer or further away. The classical view of horizontal vergence, as proposed by Maddox in 1893<sup>37</sup> is that convergence can be demonstrated as a synkinetic response to accommodation (accommodative convergence), a corrective response to retinal disparity (fusional convergence), a perceptual response to perceived distance (proximal convergence) or as a tonic response in alert individuals in the absence of any direct stimulus. (tonic convergence)\*. This classification is still influential. Voluntary convergence of the eyes can also be demonstrated in many normal subjects.

Accommodative convergence can be demonstrated in a non presbyopic subject by inducing accommodation (focussing) of the eye by means of a concave lens while the other eye is covered. The covered eye can be shown to make a convergent movement, even though there is no direct vergence stimulus to this eye. The amount of convergence stimulated in this way is expressed as the AC/A ratio, where AC refers to the convergence induced by accommodation (in prism diopters), and A refers to the amount of accommodation induced (in lens dipoters). The AC/A ratio is usually between 2-4 in subjects with normal binocular vision, and in young subjects is linear over a range of 0-5D.

This synkinesis between accommodation and convergence can also be demonstrated as accommodation being induced by a convergence movement. This relationship can be expressed as the CA/C ratio, where CA refers to the accommodation induced by convergence, and C refers to the convergence induced. There is evidence of cross-coupling between the often competing outputs of the AC/A the CA/C linkages<sup>38</sup>.

Under 'open loop' conditions (for example where the subject is looking through pin hole lenses that allow accommodation to occur without blur, or by occluding one eye), it can be shown that this is a fixed relationship, even a small amount of one function will stimulate the other. However, under 'closed loop' conditions, either of these functions can be induced over a small range without the other being evident. For example, a certain amount of convergence can be induced by base out prisms before the images blur, and non presbyopic subjects can accommodate through weak concave lenses without additional convergence. The range over which this apparent dissociation of these functions can occur is called 'relative fusion'.

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\* Although horizontal vergence eye movements consist of both convergent and divergent movements; most texts define them in terms of the convergence movement. However, the relevant term divergence could also be used in this context as appropriate.

Disparity convergence (Maddox's fusional vergence, however Stark and co-workers<sup>39</sup> argue that disparity vergence is a more appropriate term) is a corrective response to retinal disparity when the eyes are imperfectly aligned on the object of regard. It can be demonstrated by placing a small horizontal prism in front of one eye. This eye will make a corrective vergence movement in the direction of the apex of the prism. Convergent movements to a base out prism can be induced to 40<sup>Δ</sup> or more in normal subjects, although responses to prisms greater than 20<sup>Δ</sup> are usually associated with voluntary effort. Divergence responses to base in prisms are limited by the physiological inability of the eyes to diverge more than approximately 4<sup>Δ</sup> from the parallel position; however if the eyes are already converged to a near target, relaxation of this convergence can be induced by an appropriate base in prism.

Vergence in response to perceptual awareness of near or distance is often called proximal convergence. It can be demonstrated by calculating the alignment of the eyes when inputs to disparity vergence and accommodative vergence are eliminated, for example by the use of appropriate convex lenses and by covering one eye. The contribution of proximal convergence varies depending on the methods used to measure it, however Wick<sup>40</sup>, Wick and Bedell<sup>41</sup> and Joubert and Bedell<sup>42</sup> have shown that it contributes between 22% to 39% to the total convergence response.

Tonic convergence is that which results from normal muscle tone in an awake, alert subject. It has been described as the difference between the anatomical position of rest the position of the eyes in deep sleep or under anaesthesia and as the physiological position of rest (the position of the eyes when all inputs to accommodative, disparity or proximal convergence have been eliminated). Tonic convergence is considered to be responsible for the resting level of convergence measured in the dark, where it is said to average around 3<sup>°</sup>, however, as Rosenfield has commented, this fails to include the magnitude of the anatomical position of rest. If this is considered then the true typical value of tonic vergence is approximately 23<sup>°</sup> to 43<sup>°</sup>. Tonic factors are also said to be responsible for the initial persistence of vergence that can demonstrated when the initial stimulus to convergence has been removed<sup>44</sup>.

### **Vertical vergence**

Vertical vergence in primates is limited, but small amounts are required when a person fixates an objects above or below the midline and situated to one side, or when the head is tilted when fixating on an objects straight ahead<sup>34, 35</sup>. In subjects with normal ocular muscle balance, a maximum of about 4<sup>Δ</sup> of vertical vergence can be induced by base up or base down prisms<sup>45-48</sup>.

## **Torsional vergence**

Small amounts of torsional vergence eye movements can be demonstrated on convergence above or below the midline, with each eye showing increasing intorsion as the eyes elevate, and extorsion as they depress<sup>1, 29, 36, 2-8</sup>. This will be discussed further in Chapter 7.

## **Neural Pathways for vergence eye movements**

(The following studies were conducted on monkeys, unless stated otherwise.)

### **Cortical areas**

Gamlin & Yoon<sup>49</sup> recently identified regions of the frontal cortex, immediately anterior to the frontal eye field region, in which cells were found that responded to both stepwise and continuous vergence eye movements. Of particular interest in this study is the confirmation that the arcuate region of the frontal cortex contains areas specialised for all classes of voluntary eye movements – saccades, smooth pursuit and vergence.

Gnadt and Mays<sup>50</sup> identified neurons on the lateral bank of the intraparietal sulcus that responded to vergence eye movements to target positions nearer, and further away, from the plane of fixation. For a particular neuron, its response increased when the target was positioned at a particular depth. This study therefore links stereoscopic perception to vergence eye movements.

Hasebe et al<sup>51</sup> used positron emission tomography to study the response of human cortical areas to vergence eye movements. Activation in relation to vergence eye movements was not detected in the frontal cortex, but this may have been due to spatial filtering that limited the area of activation that could be detected. However, activation was detected in the left inferior parietal lobule, in agreement with previous animal experiments, and in both temporo-occipital junctions, the human equivalent of the striate and extrastriate cortex in monkeys and cats, where binocular disparities are processed. Activation was also detected in the right fusiform gyrus, however, it was possible that this was related to the spatio-temporal processing of the complex stimulus or the attention required for the task, rather than the eye movements directly.

### **The nucleus reticularis tegmenti pontis**

The nucleus reticularis tegmenti pontis (NTRP) is a precerebellar nucleus in the midbrain that has been identified by Gamlin and Clarke<sup>52</sup> to contain neurons that increase their firing rate during both near and far responses. In this experiment they found the same number of neurons that demonstrated transient and tonic firing rates in relation to convergence and divergence. Many of these cells responded to both convergence and accommodation – indicating that they are located after the cross-links that couple blur and disparity to vergence

and accommodation. Many cells were also found to be located close to cells related to saccadic activity – illustrating the close relationships in the motor pathways that are responsible for conjugate and disjugate movements.

### **Cerebellum**

The possible role of the deep cerebellar nuclei in the neural pathway for vergence eye movements has been identified by May et al<sup>53</sup> by using retrograde tracing from the known midbrain near-response region that is located in the supra-oculomotor area (SOA) of the midbrain. These labelled cells were concentrated in the ventro-lateral corner of the contralateral posterior interposed nucleus (IP) and in the contralateral and ipsilateral fastigial nuclei. Neurons in the IP projected to the SOA, whilst fastigial nucleus neurons projected to both the SOA and the Edinger Westphal nucleus (EW).

To date, the only detailed study on these nuclei reports the characteristics of neurons in the IP. The activity of these cells increases with *decreases* in vergence angle and accommodation, (both coupled, and tested 'open loop'), but none showed changes in activity during conjugate activity. These cells were called 'far response neurons'<sup>54</sup>.

In a review of related research to 1996, Gamlin<sup>55</sup> states: "*Our studies have provided evidence for a cerebro-ponto-cerebellar pathway involved in the neural control of vergence and ocular accommodation*". It is interesting that the neurons in the IP (where only far response cells were found) were identified by retrograde tracing from the midbrain SOA, close to the oculomotor nucleus and not the pons, as the lateral rectus muscles are implicated in divergence movements. Evidence of a pontine area directly linked to the abducens nuclei (the so called 'divergence centre') is yet to be found.

### **Midbrain**

The supra-oculomotor area (SOA) is found 2mm just dorsal and lateral to the oculomotor nucleus. Most neurons in this area respond only to convergent movements, however, there are others (far fewer in number) that fire for divergent movements<sup>56-58</sup>. While some neurons are related specifically to vergence or accommodation, the majority show activity that is related to both stimuli. This again confirms that the accommodation/vergence cross-links arise early in the neural pathways for vergence. Antidromic stimulation from the medial rectus subdivision of the oculomotor nucleus has identified near response cells within the SOA, but not far response cells<sup>59</sup>.

Convergence cells have also been located in a more dorsal midbrain region, rostral to the superior colliculus. Both of these areas also contain cells that encode the vergence angle<sup>60</sup>.



## Ocular Motor Nerves

The Oculomotor (3<sup>rd</sup>) cranial nerve carries fibres destined for the medial rectus – the muscle primarily responsible for convergence. Studies of the oculomotor nucleus indicate that most medial rectus neurons fire in response to conjugate as well as vergence movements suggesting that these signals are generated independently, and combined for the first time at the motoneurons<sup>57, 61, 62</sup>.

A very small number of 'divergence neurons' have been located in the oculomotor nucleus, as well as internuclear neurons that project to the abducens nuclei in the pons (ipsilateral, contralateral or both)<sup>63</sup>. This connection could be associated with the reciprocal relaxation of the lateral recti during convergence.

The abducens (6<sup>th</sup>) cranial nerve carries fibres destined for the lateral rectus muscle, the muscle primarily responsible for divergence. The abducens nucleus contains lateral rectus motoneurons and also internuclear neurons. These decussate and ascend in the medial longitudinal fasciculus (MLF) to innervate the medial rectus of the ipsilateral eye and produce conjugate horizontal movements. Mays and Porter<sup>60</sup> have shown that almost all abducens motoneurons carry signals for both divergence and conjugate movements, meaning that 'inappropriate' signals would be generated at the oculomotor nucleus during a divergence movements. This was confirmed in a later study<sup>64</sup> in which the behaviour of abducens internuclear neurons during vergence was compared to that of horizontal fibres in the MLF. The authors concluded *"this inappropriate MLF signal must be overcome by a more potent direct vergence signal"*.

The Edinger Westphal (EW) nucleus is located close to the oculomotor nucleus, it controls the parasympathetic innervation to the lens of the eye, governing accommodation and pupillary constriction. During near viewing, there is a linear relationship between the firing rate of this nucleus and accommodation<sup>65</sup>. Even under conditions of conflicting accommodation and vergence demands, most of these neurons show the same relationship to accommodation as they do with normal viewing.

The trochlear (4<sup>th</sup>) nucleus contains the motoneurons for the superior oblique muscle. Mays et al<sup>3</sup> have demonstrated that trochlear unit activity in monkeys decreases during convergence, and suggested that the primary reason for this is to assist adduction of the eyes.

## Summary

Although there are still gaps in understanding the neural control of vergence eye movements, it is apparent that the pathway includes the cortex of the brain, the NRTP, the deep cerebellar

nuclei, the SOA and probably the PPRF. The findings that are of particular interest to a study of vergence eye movements are:

- The apparently early coupling of the accommodation and vergence links that are apparent even in the region of the parietal cortex.
- The identification of cells in the interposed nucleus of the cerebellum that are directly related to divergence and relaxation of accommodation
- That an area in the pons controlling the activity of the abducens nerve (equivalent to the supraoculomotor area of the midbrain) has yet to be identified. It is possible that there could be links from the interposed nucleus of the cerebellum to this area (as there are links to the midbrain), but this is yet to be confirmed.

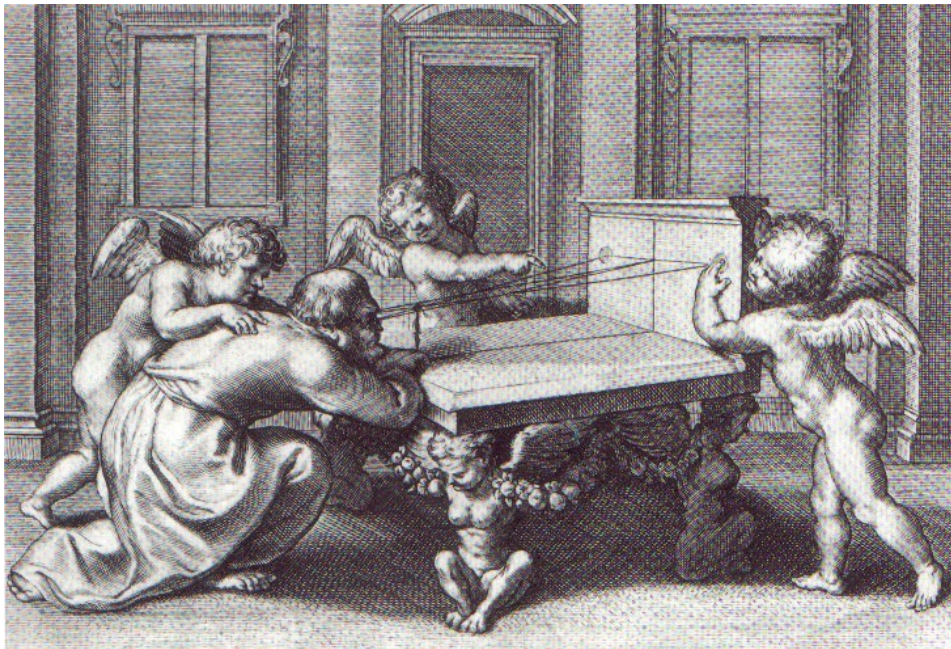
## Chapter 2

### Accuracy of vergence eye movements

#### Binocular Vision

The purpose of vergence eye movements is to maintain the alignment of each eye on objects at different distances from the subject in order that binocular vision can occur.

Classic theories of binocular vision, based on corresponding retinal points and the horopter date back to the early 17<sup>th</sup> Century when Franciscus Aguilonius offered the first explanation of physiological diplopia. He defined the horopter as a vertical plane through the fixation point on which all objects are seen single, whilst all other points appear double. He called this plane of single vision the horopter.



**Figure 2.1 The first horopter experiment.**

Reproduced from Shipley and Rawlins<sup>66</sup>

The horopter is the locus of corresponding retinal points for a certain position of binocular fixation. While it is now known that the horopter changes its size and shape depending on the position of binocular fixation<sup>67</sup>, it is usually described in terms of when an observer is fixing on

a point along the midline and in the horizontal plane. If corresponding retinal points are equidistant from the fovea in each eye, the horopter would form part of a circle, which would pass through the fixation object and the nodal points of each eye. This is called the Vieth Müller Circle.

However, studies using the subjective alignment of two vertical, non fusible rods have shown that the horopter determined in this way (the “Nonius horopter”) is flatter than the Vieth Müller Circle<sup>67</sup>. If this is so, it inevitably implies asymmetry between corresponding retinal points, such that those in the temporal area of one eye are closer to the fovea than the corresponding nasal points in the fellow eye.

Panum showed in 1858 that objects do not have to be located precisely on the horopter to be seen as single, and that similar images situated within a certain range on either side of the horopter may still be seen without diplopia<sup>68</sup>. The area over which this occurs is called Panum’s fusional space, and the relevant retinal regions corresponding to Panum’s fusional space are called Panum’s fusion area, although these two terms are often used interchangeably. Panum’s fusional space is reported to be very small at the point of fixation, representing a visual angle of approximately 6′ (or a radius of 0.026 mm of the corresponding retinal loci) and increases towards the periphery of the binocular visual field<sup>68</sup>. Objects in Panum’s fusional space are normally seen in depth relative to the horopter (stereopsis). It has also been postulated that Panum’s fusional space provides for a steady state to occur without diplopia, enabling the vergence control system to maintain vergence<sup>69 70</sup>.

### Stereopsis

Stereopsis is the subjective appreciation of a change in the position of an object in space relative to the fixation point, that arises from the detection of small retinal disparities. Panum’s area therefore provides the basis for small disparities to occur without diplopia. However, the association between stereoscopic depth perception and Panum’s fusional areas is not as simple as this model implies, as depth can still be perceived in the presence of physiological diplopia (‘qualitative stereopsis’) where images may be accurately located in space even though they may be situated off the horopter and seen as double<sup>71</sup>.

### **Subjective measures of non foveal binocular alignment**

(For summary see Table 2.1)

The presence of Panum’s fusional space at the centre of the horopter, although small, nevertheless gives rise to the possibility of small vergence errors occurring without diplopia. This concept has given rise to a large literature on the phenomenon known as fixation disparity.

### Fixation disparity

The 1967 text by Ogle, Martens and Dyer<sup>71</sup> describes early studies on the apparent misalignment of the visual axes, dating back to an experiment by Hofmann and Bielchowsky in 1900. In that study, haploscopic slides were developed that consisted of identical pages of print with a horizontal line in the centre. On the left slide a short narrow vertical line was drawn in the centre above that line, on the right slide a millimetre scale was placed horizontally below the line.

*“They found that, as the arms of the haploscope were moved to alter the convergence of the eyes ... the position of the indicator mark relative to the scale changed, in spite of the print appearing single. .... As the convergence of the eyes was increased, the indicator mark moved slightly in the direction of a decreased convergence – that is, the images of the print for the two eyes were seen in an uncrossed disparity. They called the discrepancy in convergence a residual disparity.”*

The text also described similar experiments in which targets with both binocular and monocular components were viewed in a haploscope or similar device, and in which the monocular components appeared to be displaced laterally under conditions of fusion demand, that is, the demand for accommodation and convergence were not in harmony and there was a tendency for the visual axes to converge or diverge. They called this phenomenon fixation disparity, *“the phenomenon of the apparent displacement of the unocularly observed details of targets whose other details are fused binocularly”*. Heterophoria is a common condition in which there is a latent deviation of the visual axes, and, as this is a situation where the demand for accommodation and convergence are not in harmony, fixation disparity can be demonstrated. This means that small under or overconvergence of the visual axes is common, particularly for near fixation where most people show a small or moderate exophoria.

Ogle developed this concept as a means of evaluating the association between heterophoria and fixation disparity in the clinical assessment and management of heterophoria and related disorders. He developed the ‘phoropter’, an instrument that has formed the basis of several instruments that have been used clinically to assess fixation disparity. Such instruments provide dissociation of the two eyes, fusible targets, and non-fusible components, one of which is usually a vertical line (for horizontal phoria assessments) and the other a measurement scale. Other versions use two vertical nonius test lines, which are aligned optically or mechanically.

Ogle’s further studies of this phenomenon involved plotting fixation disparity against the effective base in or base out stimulus to vergence. Although the relationship between fixation disparity and induced fusion demand was shown to differ between individuals the most common pattern (at least for an orthophoric subject) is one in which there is a slow increase

in fixation disparity with low fusion demand. However, as the limit of fusional amplitude is approached, the disparity becomes very large, with an abrupt onset of diplopia at the limit of fusional response.

Many phoropter studies have since been carried out<sup>72, 71, 69, 73</sup>, showing fixation disparity of between zero to 30' (although rarely over 20'), depending on factors such as:

- the size, position and spatial frequency of the various stimuli,
- prism adaptation,
- individual differences in the efficiency of binocular vision,
- demands on fusion and
- the presence or absence of foveal or parafoveal cues.

#### Fixation misalignment

“Border enhancement” refers to the visible band that is produced during fixation of a dark/bright border. This band increases with increasing distance from the foveal centre and indicates the retinal location of the border, unaffected by possible changes in visual direction. Remole<sup>74</sup> used this phenomenon to demonstrate larger misalignments than those found in traditional in fixation disparity experiments, and concluded that phoropter experiments do not necessarily indicate the true amount of vergence error. The term ‘fixation misalignment’ was suggested for these errors. If the value of fixation disparity is taken into account in Remole’s study, the mean vergence error can be calculated at around 35', with a maximum value of 56'.

In a subsequent study by Remole<sup>75</sup> similar experiments were performed, but with the simultaneous monitoring of a scleral blood vessel via a video camera. Similar results were obtained. Remole concluded that conventional fixation disparity measurements do not represent the anatomical fixation misalignment that occurs during binocular fusion.

#### Extension of Panum’s Fusional Areas

Several studies have specifically attempted to measure the extent and plasticity of Panum’s fusional areas. Although these studies do not directly provide evidence of vergence errors, the information indicates the ability of the visual cortex to process retinal disparity without suppression or the appreciation of diplopia.

Schor<sup>73</sup> has shown the minimum horizontal limit of fixation disparity to be about 15', this remains unchanged from the fovea to 5° of retinal eccentricity. Therefore, if a central target is used, vergence errors larger than 15' should result in diplopia.

Subsequent studies, particularly those that used stabilised retinal images and/or random dot stereograms, have shown that Panum’s fusional areas may extend far beyond these limits. Research in this area often addresses the issue as to whether this increased tolerance of

disparity is due to 'hysteresis' or 'neural remapping'. In this context 'hysteresis' refers to a type of stretching, or a resiliency, of Panum's areas, that can be demonstrated provided the disparity starts within an accepted range and slowly extends outwards. Once fusion is lost it is only regained at a substantially smaller magnitude than that at which fusion breaks<sup>76</sup>. Presumably, Panum's fusional areas gradually revert to a smaller size and/or a prior system of mapping after fusion is lost<sup>77</sup>.

Neural remapping implies that there is a change in corresponding retinal points, so that there cannot be an unalterable anatomical coupling in the two eyes. This is thought to occur through expansion of, or changes in the position of Panum's areas, or both<sup>78</sup>. Studies that support this concept tend to show similar dimensions of Panum's fusional areas whether they are 'stretched' or whether the disparity is introduced before fusion occurs. However some researchers use different definitions for these terms<sup>79</sup>.

A landmark study was reported by Fender and Julesz in 1967<sup>80</sup>. In this experiment subjects fused binocularly stabilised images of random dot and bar stereograms. To stabilise the images, a motor feedback system was developed that detected eye movements and made compensatory adjustments to the position of the stimulus. Therefore no shift of the retinal image could be compensated by vergence movements, and the range of a single percept could be attributed to the range of Panum's fusional area.

Random dot stereograms were gradually separated in a templewards direction until the stereoscopic image was lost or diplopia was reported. Limits of up to 2° of misalignment were reported, however, once fusion and/or stereopsis were lost, the stereograms needed to be brought to within 6'-10' to become re-fused. Similar experiments using bar stereograms showed toleration of 65' before fusion and stereopsis were lost, with a re-fusion point of 40'. Hyson, Julesz and Fender<sup>81</sup> repeated similar experiments using non stabilised random dot stereograms during divergence (the limits of divergence are easily reached experimentally and provide a natural barrier to corrective vergence movements). Eye movements were also simultaneously recorded to assess any vergence errors (ie, the difference between image separation and eye vergence errors) and similar values were found to those of the 1967 study, that is, an average 'hysteresis' of 2.6° with a maximum value of 4.1°. This larger maximum value was attributed to the use of larger targets.

Erkelens and Collewijn<sup>82</sup> performed similar experiments, however they used a random dot stereogram with only two planes of depth, with the subjects viewing known planes of the image, rather than the spiralling stereoscopic image used by Fender and Julesz. They only analysed results at the break of divergence and found that fused images gradually increased to a value between 1°-2° for the different subjects. However, as long as the angle of

divergence was small, ocular vergence followed accurately the image vergence on the part of the stereogram which was fixated.

Crone and Hardjowijoto<sup>83</sup> used both a single point stimulus and a random dot stereogram to measure fixation disparity, and found maximum values of 5' for the point stimulus and 2° for the random dot stimulus.

Due to experimental problems (mainly the tendency for the eyes to go into 'open loop' convergence when stabilised images stimulated the nasal visual fields) the above studies reported on the extent of Panum's fusional areas in the temple-ward direction only. Piantanida,<sup>68</sup> using a different process for stabilisation of images was able to move the images in both in the nasal and temporal direction. He found similar values to those of Fender and Julesz for the range of Panum's fusional areas when tested from the fusion to break point (to 2°) but found that the re-fusion ranges were larger than those reported by Fender and Julesz. He attributed the difference in results to the additional markings on the random dot stereograms used in the Fender and Julesz experiments, that provided a competing stimulus to fusion and stereopsis once the random dot stereopsis was lost.

Piantanida comments:

*"Teleologically, defining correspondence in terms of retinal areas rather than retinal points is a more reasonable approach to binocular fusion in organisms whose eyes move constantly. Panum's fusional areas may represent one means for compensating the statistical noise of eye movements. However, this description of correspondence implicitly assumes fixed retinotopic image registration; that is, images can be fused if, and only if, they fall within a fixed distance from corresponding retinal landmarks... .. If we were to assume, instead, that the neural mechanism of fusion is capable of redefining which retinal loci correspond, then correspondence need not be defined in terms of fixed clusters of receptors. Within this framework, we could hypothesize that a pair of points that fell on widely disparate non retinotopically corresponding loci on the two retinas might be fused. There are no data that argue against this neural remapping; it just seems superfluous under normal viewing conditions."*

This last sentence implies that binocular fixation functions accurately under normal conditions and that resulting retinal disparities do not occur.

Diner and Fender<sup>76</sup>, using stabilised images and a 3° visual field showed that there is no significant difference between the nasal-ward and the temporal limits of Panum's fusional areas, and that there is no difference whether one stimulus moves across each retina or whether one stimulus is held still on one retina whilst the other is moved across the second retina. Their experimental technique involved the use of stabilised bars (the same as those



used by Fender and Julesz) plus a non stabilised fixation reticule of cross hairs in order to achieve stabilisation. The extent of hysteresis in this study was between 30' to 50', compared with Fender and Julesz who showed a mean of 65' in the temple-ward direction only. The authors comment that this may have been due to normal observer variability and the smaller extent of the visual field, however the fact that the bars in their study stimulated lower retina only, and the presence of the unstabilised fixation reticules, may have both contributed to the difference.

Erkelens<sup>84</sup> repeated the experiments by Fender and Julesz<sup>80</sup>, and Piantanida<sup>68</sup>, using a scleral coil technique. In some situations the disparity was not slowly increased but was immediately presented at a certain value. Although vergence movements were controlled by a stabilising system, the subject was free to make conjugate eye movements, thereby allowing different parts of the stereograms to be fixated. This study found that similar disparities were fused whether or not the targets were presented with gradual or step disparity. Total fusional ranges between 128' and 17' were found in the different subjects, with nasal disparity to 67' and temporal disparity to 112'. Erkelens considered that Fender and Julesz' poorer re-fusion ranges were related to prior stimulation of non fusible disparities of the same type and suggests that this may be related to the recent history of binocular rivalry.

Diner and Fender<sup>79</sup> subsequently carried out similar studies using stabilised bar stereograms, however they also introduced an additional bar as a probe stimulus to test their hypothesis that Panum's fusional areas may shift, rather than be extended, under conditions of vergence demand. Their results from two subjects indicated that although some enlargement of Panum's fusional areas may occur, *"the main component of the modification of the fusional area is a shift across the retina"*. They interpreted this finding as probable remapping, as well as an enlargement of the fusional area. In this study, tolerance to divergent disparities of around 10' and convergent disparities of around 25' were demonstrated.

Wick<sup>77</sup> used entopic foveal 'markers' (after images and Haidingers brushes) to determine retinal correspondence during maximal divergence of unstabilised random dot stereograms. The results in the first experiment that used after images were somewhat equivocal. Only three of the six subjects gave data that indicated a significant change in the alignment of the after images that indicated an altered retinal projection. In one of these subjects a p value of 0.07 was accepted as significant. There was no attempt in this experiment to assess the size of Panum's fusional area.

In a second experiment Haidinger's brushes were used as foveal markers while divergence 'was maintained at its maximum for at least 2 minutes' (there is no detail on how this limit of divergence was determined or whether it changed during the experiment). All six subjects showed two Haidinger's brushes under the experimental condition, and their projection

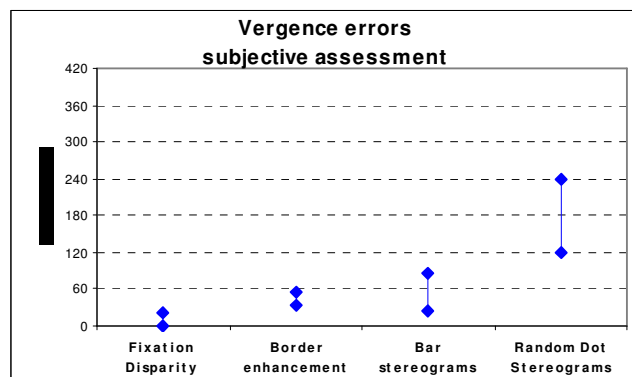
indicated that the retinal correspondence had altered in the appropriate direction. In this experiment there was an attempt to quantify the separation of the Haidinger's brushes in relation to the known angular displacement of one component of the stereogram. If one accepts the assumption that the brushes were perceived in the same plane as the image of the stereogram then the average estimated change in correspondence was  $2.8^\circ$ . This experiment was further developed by having the subjects view the images through convex lenses, thus inducing blur. Under these conditions the separation of the Haidinger's brushes increased to an average of  $5.8^\circ$ . This is an unlikely result as the induced divergence was only around  $3^\circ$ . This inevitably casts doubt on the results determined without blur and the author suggests that *"it is more likely that the locations of the brushes are not actually referred to the plane of the stereoscopic image and the Haidinger's brushes separation is overestimated."*

These values of measured retinal disparity, assessed subjectively in the presence of fusion or stereopsis are summarised in Table 2.1 and Figure 2.2. As Diner and Fender<sup>79</sup> considered that Panum's fusional area may be shifted in the direction of fusion demand, it is probable that one cannot simply add the nasal and temporal ranges to find their overall size. For this reason I have attempted to define in Table 2.1 the nasal and temporal components when both were measured.

**Table 2.1 Tolerance of retinal disparity using subjective methods**

Author	Year	Stimulus	Stimulus size *	Stabilisation	Area of retinal stimulation (Nasal or Temporal)	Demonstrated disparity (min arc)
Ogle		nonius system (fixation disparity)	various	no	Nasal or Temporal	Maximum values rarely exceed 20
Reading	1992	Nonius system (fixation disparity)	central fixation cross 1.72 deg	no	None (resting position at 1 metre)	0.3 - 1.3
Remole	1985, 1986	Border enhancement	Border (fovea)	no	Temporal (mostly)	Mean 35, max 56
Fender & Julesz	1967	Random dot stereograms Bar stereograms "	3.43 deg (1.37 deg) 13x60 min arc	yes yes no	Nasal Nasal	Maximum 120 65 87
Crone & Hardjowijoto	1979	Single dot  RDS	0.3deg  33 deg (?)	no  no	Both  Both	(Mean) 5  Mean 120 (max 'more than 4 deg')
Hyson, Julesz & Fender	1983	RDS	9.8 deg (tip of spiral)	no	Nasal	Average "hysteresis" 156, max 246. Average 'neural
Erkelens & Collewijn	1985	RDS	30 deg (15 deg)	no	Nasal	60-120 (fusion range)
Piantanida	1986	RDS	3 deg (1.5 deg)	yes	Both	68-150 (fusion range), 46-96 (reflexion)
Diner & Fender	1987	Bar stereograms	13x60 min arc with 3 deg restricted visual field	yes	Both	Nasal 14.2 - 26.6 Temporal 14 - 23.6
Diner & Fender	1988	Bar stereograms	13x60 min arc	yes	Both	Nasal 10, temporal 25. Shift of
Erkelens	1988	RDS	30 deg (?)	yes (vergence)	Both	Nasal 49 - 67 Temporal 98 - 112 Total (means) 88 - 156
Wick	1990	RDS	35 deg (12 deg)	no	Nasal	170-330 (?)

\* Figures in parentheses indicates size of stereoscopic image within the random dot stereogram



**Figure 2.2**

Summary of the range of vergence errors without diplopia using various subjective methods of assessment

At first, the large variation between the findings of retinal disparity in these studies is remarkable, they range from 0.3' to 6°<sup>85 83</sup>. However, the wide variation in stimulus and measurement parameters renders these results less surprising.

All of the studies that used random dot stereograms show large tolerance for disparity. The nature of these images (monocular contours are not visible) may prevent normal foveal fusion from acting, and therefore permit much larger disparities to be tolerated. This could especially be evident when stabilisation prevents the edges of the stereoscopically perceived image from being viewed by the foveal region, such as in the original Fender and Julesz experiment<sup>80</sup>. However in that study the central image subtended 1.37°, this is sufficiently small to stimulate the perifoveal region. Erkelens<sup>84</sup> allowed conjugate eye movements to occur while vergence was stabilized and permitted the subjects to fixate on the borders of the stereoscopic image.

Duwaer<sup>86</sup> suggested that the large hysteresis effect found in some of these studies is simply the result of the stereograms eliciting qualitative stereopsis (the stereopsis that can be demonstrated outside Panum's fusional areas in the presence of diplopia), as the nature of the random dot stereogram does not elicit diplopia. This is an interesting comment, however even the limits of qualitative stereopsis are small at the foveal area, (+/- 15 ') <sup>44</sup> and this would not explain the large ranges demonstrated in studies that provided some central component of the stereogram where a spiral image was used, the tip of which was viewed by the fovea<sup>81</sup>.

Whatever is the nature of random dot stereograms that permits large retinal disparities to be fused, there is no doubt that they are, by their very nature, highly artificial.

Studies that used bar stereograms invariably found smaller limits to Panum's fusional areas. Both Fender and Julesz<sup>80</sup> and Diner and Fender<sup>76</sup> used bar stereograms that subtended an area of 13' x 60', sufficiently small to stimulate the foveal region. In these studies a mask was used that allowed a visual field of only 3°, which perhaps accounts for the lower values (maximum 26.6' nasally, 23.6' temporally) than those found by Fender and Julesz (65') who did not use such masking.

Although vergence eye movements were stabilised in these two experiments, the dual nature of disparities presented by stereograms may also have allowed for larger separation of the stereogram to be tolerated. Studies using a non-stereoscopic stimulus all showed much lower values. The findings of Reading<sup>85</sup> (0.3' – 1.3') can probably be explained by the lack of significant fusion demand in this study, and the very small light target (0.3°) provided by Crone and Hardjowijoto<sup>83</sup> gave a minimal stimulus to fusion, resulting in very small values of fixation disparity (mean 5').

The findings by Remole<sup>74, 75</sup> using the border enhancement technique, and confirmed by a simultaneous objective measurement of eye movements, cast doubt on interpretations of fixation disparity as representing the true amount of ocular misalignment. Maximum values of around 56' of 'fixation misalignment' are around ten times larger than the corresponding fixation disparity measurements, and are comparable with the line stereogram results of Fender and Julesz<sup>80</sup>.

However, almost all of the above studies share two features. All use highly controlled artificial stimuli presented in artificial environments. Another feature was the fusion demand that was placed on the subjects, this is common in fixation disparity studies. It is achieved by using subjects with an existing heterophoria, or by presenting situations where the accommodative and fusional demands oppose each other. This feature was not surprising, as the nature of fixation disparity assumes that binocular fixation errors only occur under conditions of fusion demand. Certainly most of the studies showed a clear relationship between fixation misalignments, or tolerance of disparity, and the amount of induced disparity.

### **Objective studies of binocular alignment**

For summary see Table 2.2 (page 34).

#### Objective measurements of fixation disparity

Some of the above studies, such as those using border enhancement<sup>74, 75</sup>, question whether traditional nonius methods fully indicate the true amount of vergence misalignment. The following section reviews studies that have evaluated vergence by using objective methods, (with or without vergence demand) or have combined objective and subjective measures.

Judd, in 1907<sup>87</sup> was probably the first to systematically measure and analyse the motor patterns of vergence eye movements. A small marker ('Chinese white') was placed on the corneas of the subjects' eyes, and the eyes were photographed during movements of convergence and divergence using a 'kinescope' camera. By observing the marker in each frame of the film, and knowing the average exposure time, calculations were made of the position of each eye at the same point in time, and the approximate speed of the eye movements. Average exposure time ranged from 75<sup>σ</sup> to 117<sup>σ</sup> (The sign <sup>σ</sup> was not defined in this article, presumably it referred to frames per second).

Despite this relatively crude method, by modern standards, Judd demonstrated and described the complex patterns of saccades and vergence movements that occur when vergence is induced by fixation to different points in space, and that have been more recently described using modern and more precise measurements of eye movements<sup>88-92</sup>.

*"The evidence has been presented in sufficient fullness to make it clear that there are certain natural individual tendencies of movement in the eyes of different persons, and certain forms of behaviour simpler than convergence or divergence, that tend to creep in during any series of fixations of near and remote objects."* (p411)

The initiation of a vergence movement by an initial saccade was observed:

*"A (fact) which may be noted ...is that in some cases the eyes before they begin the careful adjustment of convergence, execute a lateral movement in which the two eyes sympathize by moving in the same direction rather than in opposite directions as required for convergence and divergence"* (P386)

and the role of ocular dominance in vergence eye movements:

*"At all events, in the case of three subjects, there is a distinct difference in the behaviour of the eyes. In the one case the left eye leads, in another the right, and in the third case there seems to be a balance between the two eyes."* (P381).

However, what is of particular interest for this review is Judd's observation that, as he fused a stereogram through voluntary convergence and divergence, his resulting eye movements were not sufficient to allow bifoveal fixation to occur. From this, he concluded:

*"It would, therefore, seem to be true that in voluntary divergence the optical axes are not brought into a position of direct fixation upon the point, but the eyes are so adjusted that the points to be fused fall approximately at the centres of vision, though in reality somewhat at the side. This confirms the general results reported throughout the earlier investigations of eye movements both in the Yale Studies and in the paper by Dr Dearborne, where it is shown that there is no definite centre of fixation, but a somewhat extended area which is entirely satisfactory to the subject."* (P409)

Hebbard<sup>93</sup> in 1962, was the first to publish results comparing subjective and objective measurements of fixation disparity. He noted that subjective measures of fixation disparity only presume that the monocular visual direction is projected in the same way under both monocular and binocular conditions, whereas objective methods measure the actual deviation from precise alignment.

Hebbard used a haploscopic device to measure subjective fixation disparity when vergence was stimulated by prisms. Objective measurements were made separately using an "optical lever method" in which a split beam was reflected by mirrors onto small flat mirrors, attached by a short stalk to contact lenses on each eye, and recorded by a camera. This method was claimed to detect changes in eye position of a few seconds of arc. Using these techniques the position of the eyes of one subject were compared under monocular and binocular conditions

during fixation disparity experiments, using the assumption that that any difference between the monocular and binocular positions of the eye could be regarded as the objective measurement of fixation disparity. Subjective and objective measurements were made separately, *“under conditions which were as similar as possible”*.

Differences were found between these two methods, in all cases the objective measure was greater than the subjective measure, the largest difference being 7'. Nevertheless Hebbard considered that his results did not support the concept that discrepancies in convergence as large as several degrees do not lead to diplopia, but that suppression of one image probably prevented diplopia. In concluding that there was good agreement between the subjective and objective measurements and that any apparent differences were within experimental error, he commented that, *“from an experimental point of view this is fortunate, since the subjective method is much more simple than the objective one”*. In this experiment only one subject was studied, and that the subjective and objective measurements were made in different experiments.

Kertesz and Lee<sup>94, 95</sup> noted these problems in Hebbard's experiment, and reported their own experiments where subjective and objective components of fixation disparity were measured simultaneously using Purkinje Image Eyetrackers and oscilloscope generated dichoptic stimuli. The conceptual model they followed was the same as that of Hebbard:

- that the position of the eye during monocular fixation (when the other eye is occluded) represents the position of zero fixation disparity,
- that the change in the position of this eye during binocular fixation is a measure of the unocular component of (objective) fixation disparity in that eye,
- that the total fixation disparity is the sum of the unocular measures of objective fixation disparity, and
- that the difference between the monocular and binocular alignment of the nonius lines represents the subjective measure of fixation disparity.

The unocular components of fixation disparity were different for each eye in all twelve cases, seven reaching statistical significance. In some cases the direction of disparity was different in each eye. For these reasons, the authors concluded that monocular measurements cannot be extrapolated to estimate the total value of fixation disparity.

Robertson and Schor (1986) found that for vergence angles greater than about 1°-2°, the difference between the objective and subjective fixation disparities increased in a relatively linear fashion. Over this range the objective fixation disparity was consistently greater than the subjective fixation disparity. This was interpreted as a change in retinal correspondence.

Simonsz and Bour<sup>96</sup> also questioned whether the foveolae are really 'pointed' at the nonius lines or not. They used a traditional nonius line technique to measure subjective fixation disparity during fusion of base out prisms from 0-5 $\Delta$ , the movement of one eye on covering the other was measured using a double magnetic induction method. As with the experiments carried out by Kertesz and Lee<sup>94</sup> the difference between the positions of the eyes with and without 'fusion lock' (a binocular paramacular stimulus) was considered to be the measure of objective fixation disparity.

The results showed slight changes in eye position when the fellow eye was covered (12' in one situation, but only to 6' in the remaining 20 situations). The total objective measure was from 2' to 10' – in some cases it was divergent for one eye and convergent for the other. One particularly interesting finding of this study was that the amount of unocular fixation disparity seemed to be related to ocular dominance, with the dominant eye showing smaller values. This is an understandable finding, as the asymmetrical distribution of the disparity would allow for better acuity in the dominant eye.

Fogt and Jones<sup>97</sup> also studied the subjective and objective responses to forced vergence in five subjects, however direct binocular recording of vergence eye movements were made using binocular scleral search coils (rather than with the monocular occlusion method used by Simonsz and Bour<sup>96</sup>). Subjects were immobilised by a head rest and a bite bar whilst targets were presented on a computer monitor in a darkened room. Monocular viewing was achieved via an anaglyphic presentation while fusible targets were presented about the mid saggital plane, first at 4' of relative convergence and then at divergence angles from approximately 1 $^{\circ}$  to 8 $^{\circ}$ .

At each position nonius lines were aligned, and ten consecutive digitized signals from each eye were recorded. By subtracting the vergence angle of the eyes from the angular separation of the fusion targets the objective fixation disparity could be determined, and the difference between the angular separation of the nonius lines and the angular separation of the targets yielded the subjective fixation disparity. The authors concluded that in three of the five subjects *"an additional process (is involved) that supplements the normal fusion process first elucidated by Panum. This process is a small alteration in retinal correspondence which facilitates sensory fusion by shifting Panum's area toward the fusion target."* They also suggested that the vergence errors found objectively represented steady state errors used by the fusional vergence control system to maintain vergence.

#### Vergence accuracy under normal conditions

Most of the above studies were primarily designed to elucidate differences between objective and subjective measures of fixation disparity, rather than to evaluate total vergence errors. Nevertheless they demonstrate that errors of over 1 $^{\circ}$  can occur in the absence of diplopia. These errors usually only become significant with the larger angles of vergence demand.

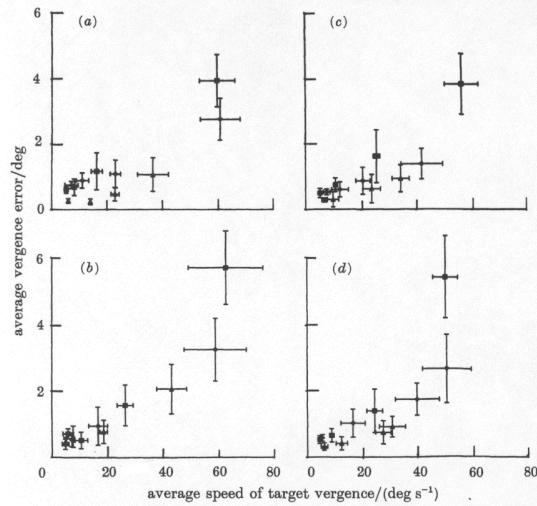


However, these studies were, by their very nature, carefully controlled. The vergence stimuli were limited, two dimensional, and were usually presented on a screen or in a haploscopic device. The subjects were given time to make careful observations and adjust nonius lines. They provide information on fixation disparity curves, and further our understanding of retinal correspondence, but they do not represent conditions of normal viewing where there may be rapid changes of fixation, combined version and vergence demands, head movements and complex visual input.

Studies on direct evaluation of the accuracy of vergence eye movements under normal viewing conditions are rare, and are often secondary to the primary purpose of the study. Erkelens, Steinman and Collewijn<sup>91, 92</sup> recorded horizontal binocular eye movements while the subjects fixated a natural target under normal room illumination. The main purpose of their studies was to assess the pattern of eye movements, especially when there was a combined demand for vergence and version movements. However, they also reported on the accuracy of the measurements where this was observed.

In the first study<sup>91</sup> a scleral coil was used to measure vergence in three conditions: when the target was moved manually by examiner, by the subject, or when the subject moved upper torso towards the target. Target speeds were classified as 'slow' medium (20-30<sup>0</sup>/sec), fast (40-60<sup>0</sup>/sec) or very fast (70-110<sup>0</sup>/sec).

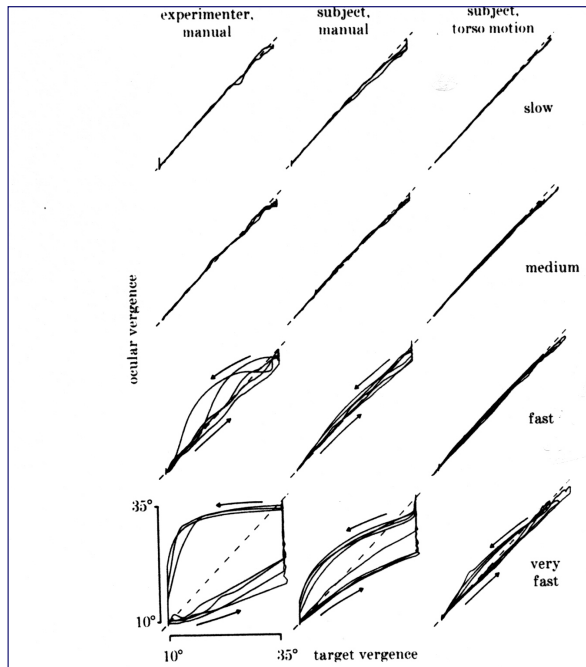
Figure 2.3 illustrates vergence errors at different speeds of the target, under different experimental conditions. Errors of around 1<sup>0</sup> are common for target speeds of up to 20<sup>0</sup>s<sup>-1</sup>, but they rise sharply, to 4<sup>0</sup> - 6<sup>0</sup> for faster speeds (up to 60<sup>0</sup>s<sup>-1</sup>). Figure 2.3 shows the difference between ocular and target vergence in one subject, where inaccuracies are particularly evident with fast speeds and when the target was moved manually by the experimenter. It is intriguing that the most accurate vergence occurred when the distance between the eyes and the target was changed via movements of the observer's upper torso. Perhaps the predictability of the target's position in space was better in this situation than when either the experimenter or the subject moved it manually. Errors tended to be greatest when the experimenter moved the target, implying that predictability of target position was important in determining vergence accuracy.



Mean vergence errors of each of the four subjects ( $\pm 1$  s.d.) as a function of the average speed of target vergence ( $\pm 1$  s.d.) in each of the four speed ranges used. (a) H.C.; (b) J.S.; (c) R.D.; (d) A.M. Squares: target moved by the experimenter; diamonds: target moved by the subject; triangles: changes in target distance induced by movements of the subject's upper torso.

**Figure 2.3 Mean vergence errors from four subjects as a function of the average speed of target vergence (vergence/(deg s<sup>-1</sup>)).** From Erlelens et al<sup>92</sup>

The Y axis shows vergence errors (error/deg), the Z axis represents average speed of target vergence. The largest errors occur for the fastest movements of the target (up to 60°s<sup>-1</sup>).



**Figure 2.4 Ocular vergence as a function of target vergence.** From Erlelens et al<sup>92</sup>

The difference between ocular and target vergence in one subject, where inaccuracies are particularly evident with fast speeds and when the target was moved manually by the experimenter.

Vergence errors of up to  $25^\circ$  in the most demanding conditions did not give rise to diplopia, possibly because of the short period of time that they were present (less than 300 ms). The authors comment:

*“Such transient large disparities of an attended, moving object may occur so commonly in ordinary behaviour that subjects do not notice or remember diplopia, unless they are specifically alerted to the condition.”*

In a follow up study using stimuli requiring both symmetrical and asymmetrical vergence at different distances in real space, Erkelens et al<sup>92</sup> stated that *“ocular vergence was invariably too small: it left a residual fixation disparity.... which increased in absolute size as a function of target vergence”*. Although the authors tend to dismiss this residual error as being only a small proportion of required vergence (between 2% and 6%), these errors nevertheless measured (approximately) between  $0.5^\circ$  -  $1^\circ$  for symmetrical vergence to a target 14 cms from the eyes and  $1^\circ$  -  $2.25^\circ$  for vergence to a target 10 cms from the eyes. Findings for asymmetrical vergence were similar.

#### The influence of head movements

Most of the above experiments were carried out with the head stabilized by bite boards or head/chin rests. This was necessary in order to precisely quantify the required and actual eye movements. However, such conditions usually do not involve the input of the vestibular system to the motor and perceptual aspects of these movements.

Steinman and Collewijn<sup>98</sup> studied stability of the retinal image during active head rotation, using the supposition that if the eyes made perfect compensation in this condition, then a stable retinal image would result. However they found that, even though the two eyes often responded differently, (giving unwanted vergence of approximately  $1^\circ$ ), the image still remained single and stable. One implication of these findings was the possibility that *“vestibular signals are monitored by the visual system and used to compensate for retinal image motion that accompanies bodily movement (however) ..... we may simply find that vision under the conditions of retinal image motion .... is actually much less keen than our phenomenological observations suggest.”*

Steinman, Levison, Collewijn and van der Steen<sup>99</sup> showed that although contrast sensitivity was reduced for high spatial frequencies during active head rotation, it was increased for spatial frequencies under 6 cycles per degree. Stereopsis remained remarkably resilient under these conditions. All three subjects in the experiment claimed that it was easier to fuse the stereogram while they were moving their head. In another experiment, where random dot stereograms were introduced during rapid head movements, all subjects found it impossible to break fusion, but easy to reestablish it, when they were moving their heads, although significant changes of vergence (up to  $2.5^\circ$ ) were occurring. These findings supported the

earlier hypothesis that vestibular signals are monitored by the visual system and are used to compensate for retinal image motion. Vestibular signals may also have contributed to stable binocular vision in the presence of vergence errors.

Epelboim et al<sup>100</sup> used magnetic coils to record eye and head movements as unrestrained subjects either tapped predetermined sequences of coloured LEDs located in front of them, or only looked at them without doing anything else. There was some expectation that adding arm movements to the looking task could alter the eye movements and possibly improve performance.

Although this study was designed to evaluate different eye movement characteristics in sequential looking and tapping tasks, the authors also reported on significant cyclopean (lateral) gaze errors that occurred, particularly during the search episodes. Mean gaze errors of 1.2° to 2.7° were found during the 'sequence episodes', with the errors for 'looking only' being smaller than those for tapping. The errors during search episodes were larger, between 2.7 to 5.4 deg, these episodes also contained fewer corrective saccades.

Although this report analysed only the lateral gaze errors, visualisation of this, and similar experiments are available from the Internet (<http://brissweb.umd.edu/>). Observation of the vergence occurring during the tasks indicate that considerable inaccuracies are occurring, with under convergence occurring much more frequently than overconvergence. In some instances there is gross under convergence, yet the tapping task appears to be carried out quite successfully.

In a subsequent publication, from the same laboratory, Malinov<sup>101</sup> used a similar test design. The four subjects were reported to 'under-converge' by between 32%-37% for the 'look' task and by between 22% to 41% on the 'tap' task. Calculations from the data presented in Table 1 of this publication (based on a pupillary distance of 62mm) suggest that these errors measured approximately 1.4° – 3°. No subjects reported diplopia.

A summary of the above studies is presented in Table 2.2

**Table 2.2**  
Tolerance of retinal disparity using objective methods

Author	Year	Conditions	Head Restrained?	Fusion demand?	Maximum demonstrated disparity (min arc)
Judd	1907	Stereogram (free space)	No	Yes	Not known
Hebbard	1962	Fixation disparity experiment. Eyes measured separately	Yes	Yes	12 (approx)
Remole et al	1985, 1986	Fixation disparity experiment using 'Border enhancement'	Yes	Yes	36
Kertesz & Lee	1987	Fixation disparity experiments. Eyes measured separately	Yes	Yes	18
Simonsz & Bour	1991	Fixation disparity experiments, Eyes measured separately	Yes	Yes	10
Fogt & Jones	1998	Fixation disparity experiments. Binocular recordings	Yes	Yes	90
Erkelens et al	1989a	Free space. Target moved forwards or backwards, or subject moved torso	Yes	No	360 (25deg briefly)
Erkelens et al	1989b	Symmetrical and asymmetrical vergence in free space	Yes	No	135
Steinman & Collwijn	1980	Active head rotation	No	No	60 (approx)
Steinman et al	1985	RDS introduced during active head rotation	No	No	150
Epelboim et al	1998	Looking and tapping targets	No	No	Not quantified but over 180
Malinov	2000	Looking and tapping targets	No	No	180

### Discussion

This review of the literature on fixation disparity and vergence errors has documented misalignments of the visual axes of between 1' and 25° without diplopia that occur in subjects with normal binocular vision. The variation is to be expected, given the very different nature of many of the experimental situations. However, despite the vast literature on fixation disparity, with many different stimulus conditions, subjective misalignments were almost always under 1°. Even when border enhancement was used to demonstrate that 'fixation misalignments' were larger than those using conventional fixation disparity techniques, the misalignments were still smaller than 1°.

The experiments that were carried out in a more normal environment reveal higher levels of vergence errors, Erkelens et al<sup>92</sup> demonstrated vergence errors of up to 6°, with the highest errors occurring when there was the fastest change in target vergence and when the subject did not control the speed of this change. When subjects changed fixation between targets in real space with the head controlled errors of up to 2.5° were found.

Steinman and Collewijn<sup>98</sup> and Steinman et al<sup>99</sup> showed that significant vergence errors of up to 25° could be tolerated during active head rotations, and suggested that the input of the vestibular system in these situations may assist in the sensory compensation of the retinal disparity.

What is of particular interest in these 'free space' studies is that none deliberately induced vergence demand, the various stimuli to vergence were normally acting in harmony (apart from the situations where a subject was presbyopic). Yet these studies were the ones in which significantly large vergence errors were reported.

### **Summary**

Binocular alignment outside the traditional limits of Panum's Fusion Area can occur without diplopia in subjects with normal binocular vision. These 'errors' of vergence are more likely to occur in natural conditions, suggesting that a full visual field with varying stimuli and multiple disparities, combined version and vergence movements and different head positions may contribute to the absence of diplopia. The following experiments were designed to evaluate the contribution of some of these factors to the accuracy of binocular alignment.

## Chapter 3

### The influence of angle size and rate of change on horizontal vergence eye movements

(This chapter is modified from the following publication: Cornell, E.D., H.G. MacDougall, J. Predebon, and I.S. Curthoys, *Errors of binocular fixation are common in normal subjects during natural conditions*. Optometry & Vision Science, 2003. 80(11): p. 764-71.)

#### Introduction

The analysis in Chapter 2 has identified that ocular vergence in subjects with normal binocular vision and ocular muscle balance does not always result in bifoveal vision, and that errors of up to 6° without diplopia can occur. This was more likely to occur when the experiments were carried out in a natural environment and used objective methods to assess ocular alignment.

However, many of these studies had only a relatively small number of subjects, who were likely to be experienced in eye movement research and were possibly aware of the expected outcomes. Most used scleral search coils to measure the eye movements<sup>91, 92, 70, 101, 96, 98</sup>, however these measurements can be affected by slippage of the coils<sup>102</sup> and other factors that may affect the kinematics of eye movements<sup>103</sup> possibly resulting in artifactual measurements of eye position and resulting apparent vergence errors.

The purpose of this study was to investigate, under conditions as natural as possible, in a group of normal young adults who were naive to eye movement research:

- the accuracy of vergence eye movements for both near and far fixations
- the effect of the size of vergence change, and the rate of change, on any vergence errors using a precise video image processing method of measuring binocular eye positions.

#### Methods

##### **Subjects**

Twenty nine subjects aged between 18 and 27 years were studied following informed consent. All had 20/20 vision in each eye (either uncorrected, or corrected with contact lenses) and were within 2<sup>Δ</sup> of orthophoria for far fixation, and were within 8<sup>Δ</sup> of exophoria to 4<sup>Δ</sup> of esophoria for near fixation as measured by the alternate prism cover test. All had stereopsis of at least 60" on the Wirt stereopsis test, full ocular rotations and a convergence near point of 8 cms or better.

## Procedures

The video eye movement system (VidEyeO) used an IBM compatible PC (Intel P3 CPU at 600 MHz, 128 Mb Ram) that incorporated two analog monochrome video acquisition cards (National Instruments PCI NI-IMAQ 1408) that were hardware synchronized using the RTSI (real time systems integration) bus.

The video headset consisted of an adjustable headband that held an alloy frame on which two monochrome infrared sensitive CCTV video surveillance cameras (480 H-Lines SONY HAD CCD & SONY Chipset) were mounted. Two half silvered "hot mirrors" (WBHM/Glass/1 Side CT from OCLI Santa Rosa, California USA) reflected the infra-red image of the eye to the cameras which were placed off to each side in order to afford the subject an unobstructed view of the fully lit laboratory. Each eye was illuminated, from above and from below, by two InfraRed LED emitters that were invisible to the subject, whilst infra red pass filters (Infra-Red PASS: ~ 730 nanometres wavelength Film 0.1 mm flexible) on the camera lenses prevented ambient light from affecting the image of the eye. Synchronized video images of both eyes were analyzed using in house software written for the project. This software was written in a development environment ("LabView") and used a library of image analysis functions ("Vision"), both from National Instruments (Austin, TX, USA).

The video images of each eye were adjusted to give maximum contrast that clearly identified each pupil. Horizontal and vertical eye positions to a resolution of  $0.1^\circ$  could then be calculated by tracking the centre of mass of the largest black object (the pupil) in each binary (thresholded) video image and converting its position into gaze angles using geometric transformations and calibration procedures that we have previously published.<sup>104, 105</sup> The sampling rate was 17 Hz, which although relatively low, permitted a highly accurate binocular measurement of the eye position during the fixation period following the vergence movement. The dynamic properties of the eye movements, which showed evidence of combined saccades, vergence and at times, corrective movements, were not analyzed in this study, since the aim was to measure the accuracy of eye position during the fixations. During recording sessions the video images tracked by the system could be viewed by the examiner, and recordings were deleted if other ocular landmarks (such as the eyelids) interfered with the pupil measurement. Vergence was calculated as the difference between the gaze angles for the two eyes.

As the position of the eye was determined by the centre of mass of the pupil there was a possibility that this could be affected by idiosyncratic or asymmetrical changes in pupil size. Yang et al<sup>106</sup> 2002 have demonstrated that the pupil centre shifts approximately 0.133 mm temporally between mesopic and photopic conditions. During development of the VidEyeO system this possibility was tested on four subjects using frequency analysis to separate the effect of pupil dilation from other sources of variability. The results showed an absence of any



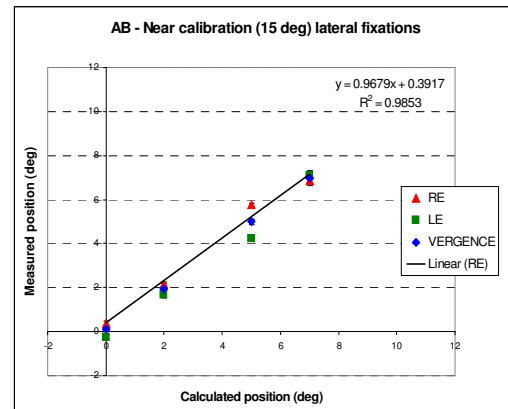
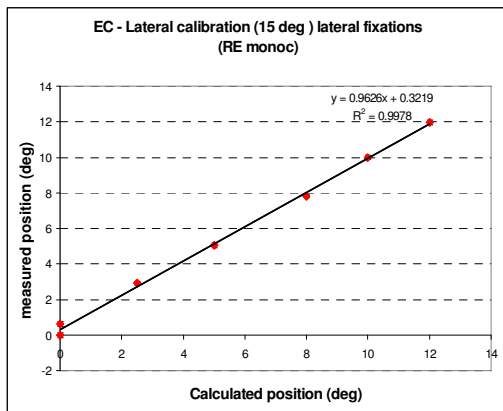
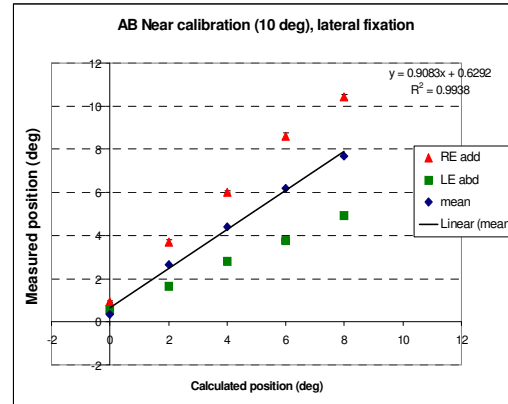
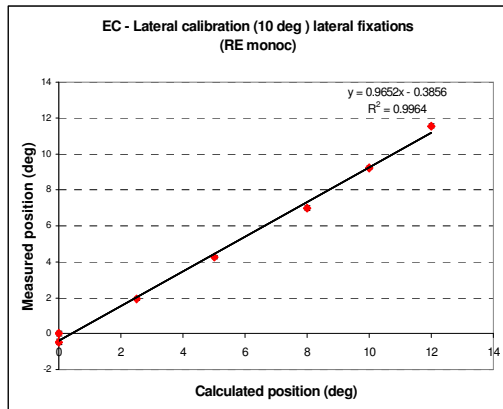
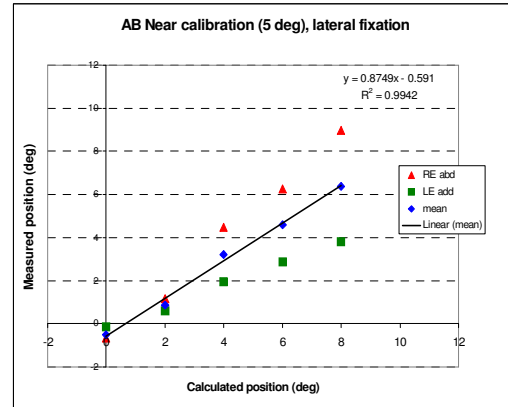
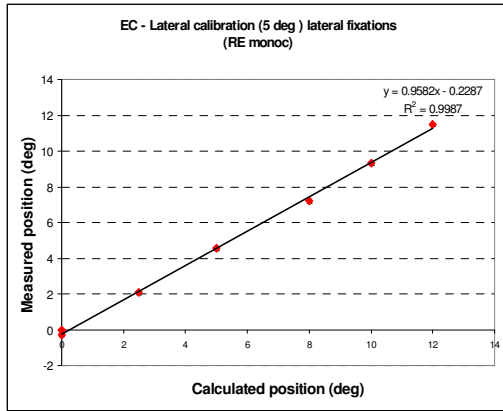
systematic interaction between pupil dilation induced by sinusoidal modulation of ambient lighting and horizontal and vertical position measurements. For this study, recordings from each subject were also individually analyzed to determine whether there was any apparent effect of change in pupil size on the measured horizontal position of the eye (see Results).

### **Calibration**

In order to determine errors of binocular fixation, the assumption was made that careful monocular fixations on detailed targets at both far and near represented foveal fixation, and that any variation from these positions under conditions of binocular vision represented a vergence error. This assumption is similar to that made by of Simonsz and Bour and others in studies of foveal alignment during fixation disparity<sup>93-96</sup>. Calibration was therefore carried out monocularly with each eye before each recording. The geometric transformations that formed part of the software gave highly linear and stable two point calibrations that were confirmed in a preliminary study. The subject fixated carefully with one eye on the far target for five seconds and the resulting recording was then observed by the experimenter and was accepted only if it demonstrated steady fixation, without any blinks. Fixations that showed any blinks or small saccadic movements could be deleted and the process repeated. The mean value for this fixation was then automatically computed. The process was repeated for the near target, and the entire sequence was repeated for the other eye.

In order to overcome any artifacts that may be caused by possible asymmetric pupillary constriction associated with vergence during the test, calibration was carried out on the near and far targets rather than on laterally displaced targets. Any small lateral differences between the movement of each eye that may have occurred if the near target was not precisely on the midline would not have affected the overall measure of vergence as this was calculated as the sum of the right and left eye positions.

Figure 3.1 shows test calibrations. In the left column, monocular lateral calibrations were made from the far straight ahead fixation point to images 5°, 10°, and 15° to the right, then monocular measurements were made targets located 0°, 2.5°, 5°, 8°, 10° and 12° to the side of the central fixation point. It can be seen that linearity of calibration is maintained for each angle from 0° to 12° of lateral fixation. In the right column, monocular lateral calibrations were made from the far straight ahead fixation point to near images on the midline that required 5°, 10°, 15° of convergence, then monocular measurements were made to lateral located targets located 2°, 4°, 6° and 8°, to the side of the central fixation point. The figures show that while the combined right eye and left eye positions are consistent with the calibrated angles, monocular positions differ in a consistent manner. This is almost certainly due to near targets not being situated precisely on the midline, thus requiring slightly different lateral shifts for each eye. This result indicates that this method of calibration provides accurate measurements for vergence, but it cannot be used to assess the lateral position of fixation. For this reason only vergence angles were considered in this study.



**Figure 3.1 Test calibrations**

Test calibrations. The Y axis represents the measured angle, the X axis the calibrated angle. In the left column, monocular lateral calibrations were made from the far straight ahead fixation point to images 5°, 10°, and 15° to the right, then monocular measurements were made targets located 0°, 2.5°, 5°, 8°, 10° and 12° to the side of the central fixation point. In the right column, monocular lateral calibrations were made from the far straight ahead fixation point to near images on the midline that required 5°, 10°, 15° of convergence, then monocular measurements were made to lateral located targets located 2°, 4°, 6° and 8°, to the side of the central fixation point. Red data point represent right eye fixations, green data points represent left eye fixations, blue data points represent binocular fixations.

## Experimental protocol

Initially two experiments were carried out to evaluate any effect of the distance of the far target, that is, whether the need to fully relax convergence on a far distance target would have any effect on the resulting binocular fixation. In the first experiment the far target was a chimney approximately 200 metres away, seen through a window. The near targets were set at 71cms, 34.4cms, and 23.5 cms requiring  $5^\circ$ ,  $10^\circ$  and  $15^\circ$  of vergence change. For the second experiment the far target was set at 2 metres from the subject. The proximal targets were set at 52.5 cms, 30 cms, and 21 cms, requiring  $5^\circ$ ,  $10^\circ$  and  $15^\circ$  vergence change ( $6.8^\circ$ ,  $11.8^\circ$  and  $16.8^\circ$  of absolute convergence on the near target). A pupillary distance of 62mm was assumed to define these positions. As errors were calculated from these calibrated distances, normal variations in pupillary distance would have simply meant that the baseline position was slightly smaller or larger than  $5^\circ$ ,  $10^\circ$  or  $15^\circ$ , but this would have a negligible effect on the measurement of any error.

Results were only analysed from subjects whose recordings were acceptable under all conditions, that is, they were not affected by the lids or eyelashes, or apparent movement of the head.

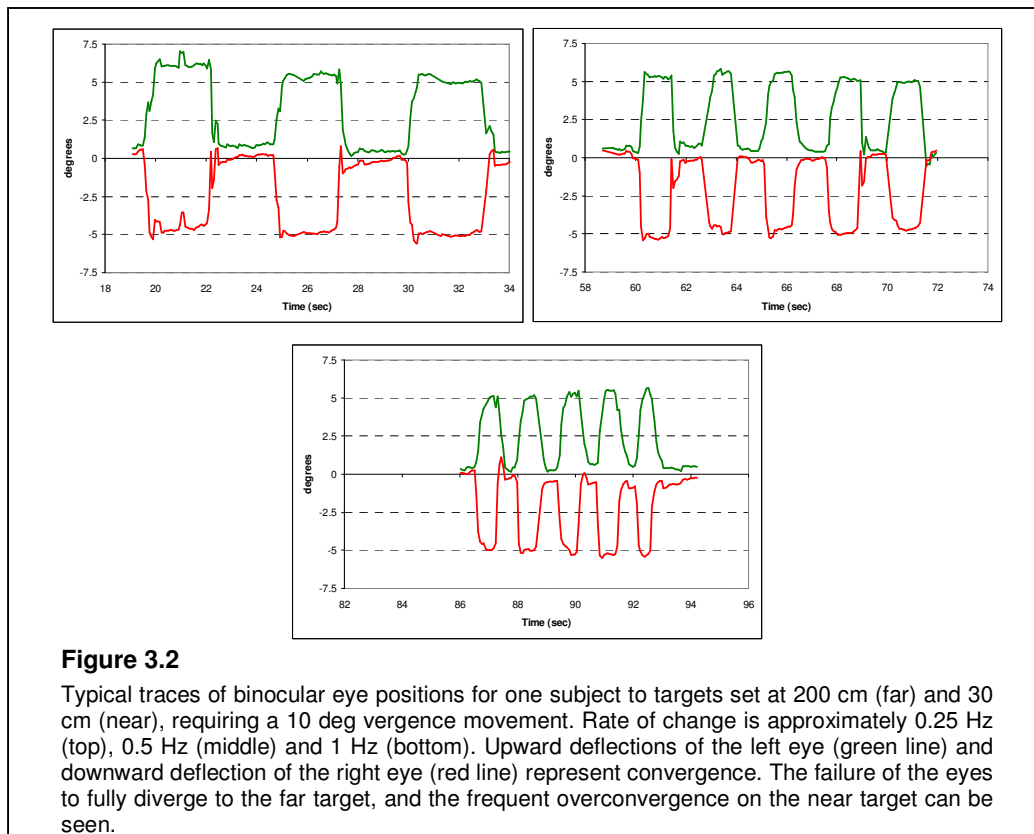
In both experiments, viewing conditions were kept as normal as possible, however it is acknowledged that the experimental situation that involved a head mounted recording device, eye movements initiated by instruction, and the use of a bite bar did not provide a completely natural situation. In this study the near target was a black and white image of a star ( $13 \text{ mm}^2$ ) with a central cross ( $5 \text{ mm}^2$ ) that could be moved up or down a fine rod to be at eye level. For the first experiment, a distant roofline was viewed through a window (90 cms x 240 cms) and the far target, the chimney, seen approximately through the middle of the window, was clearly visible against the sky. For the second experiment, the far target was a star similar to the near targets ( $50 \text{ mm}^2$ , central cross  $15 \text{ mm}^2$ ). The chair height and headrest were set so that the targets were along the subject's midline at eye level, thus requiring horizontal eye movements only. There was no attempt to control any of the varied peripheral visual stimuli in the laboratory, however a bite bar was used to ensure that the distance of the fixation targets from the eyes did not vary during the experiment.

For each subject, three data sets were obtained, each represented a specific size of vergence change ( $5^\circ$ ,  $10^\circ$  and  $15^\circ$ ), during which the rate of change was varied. For each rate of change, three or four changes of fixation on each of the near and far targets were recorded. These fixations were generally very similar within each condition and the standard deviation was usually less than  $10'$ . The order of both angle of change and rate of change was randomised between subjects.

Initially a metronome was used to direct the subject when to change fixation. However, this produced anticipatory eye movements and confusion when the subject got out of step with the metronome beat. Better results were achieved if the experimenter, observing the subject's

eyes on the video monitor, gave verbal instructions by counting aloud at a rate of approximately 0.25 Hz for each fixation during the 'slow' changes (2 seconds for each fixation at far and near) 0.5 Hz for the 'medium' changes (1 second for each fixation at far and near) and 1Hz for the 'fast' changes (0.5 seconds for each fixation at far and near). This observation and control by the examiner allowed for corrections and repeated movements if necessary. All measurements used in this report used this verbal signalling method. Subjects were asked to report diplopia if this occurred.

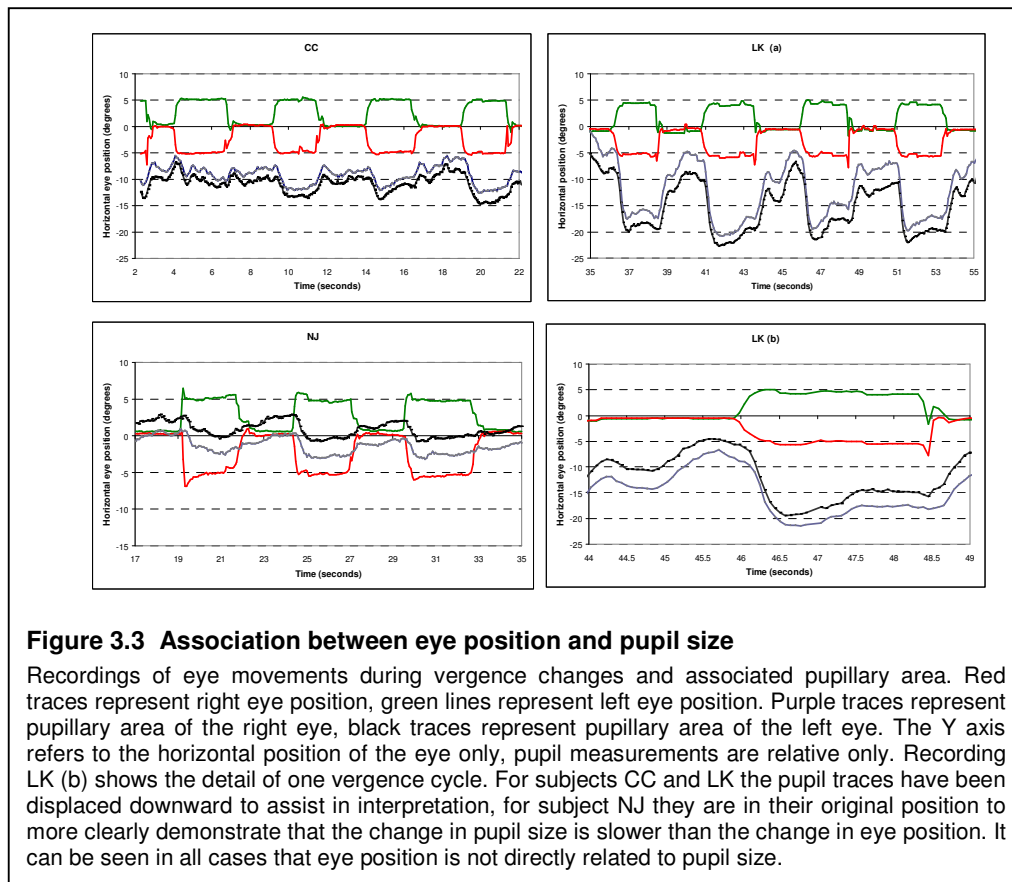
The resulting recordings were examined. Although there was a relatively slow sampling rate, each vergence movement could be recognized by a fast vergence movement that often included a small conjugate corrective movement, followed by a relatively stable phase during fixation (Figure 3.2). The position of each eye during the fixation period was determined subjectively. Although the period of the initial glissade or compensatory saccade was excluded from the measurement, small square wave jerks during the fixation period were included, as these conjugate movements did not affect the measure of vergence. However, movements that were affected by blinks or were clearly abnormal were excluded. In most cases three or four fixations were suitable for analysis for each rate of change. The software used in the analysis gave the mean horizontal position for each eye, the standard deviation and the number of data points for each fixation. The measured value of the position of each eye was subtracted from the calibrated value and the resulting vergence errors were expressed in minutes of arc. As there were very small standard deviations (usually less than 10') the pooled mean measures of vergence for each condition, and for each subject were used for further analysis. The significance level was set at 0.05.



## Results

There were no statistically significant differences between any of the nine conditions (three changes of angle x 3 rates of change) in each of the two experiments, so the data from the two experiments were pooled. Raw data is presented in Appendix 3A

Inspection of the recordings indicated that there was, as expected, a moderate relationship between pupil size and fixation distance. However, the onset of the vergence movement usually did not coincide with the onset of pupillary constriction or dilation, and there were many fluctuations of pupil size that were not associated with change in the measured position of the eye. (Figure 3.3). These observations indicate that the measurement of horizontal eye position using our system were not directly affected by changes in pupil size. A further testing of this assumption involved calculating correlation coefficients of pupil size with eye position on each eye of all subjects Twenty five subjects (86%) had  $r$  values less than 0.3 in one or both eyes, of these, 16 (64%) subjects had  $r$  values that were less than 0.1 in each eye. Figure 3.3 shows a sample recording of the subject (LK) showing the highest correlations ( $r=0.42$  in both eyes). Comparison of the change in the horizontal eye position and pupil area in this subject over 20 seconds, and the detail of one cycle of far and near fixation, demonstrates that fluctuations in pupil size did not influence the measurement of eye position.

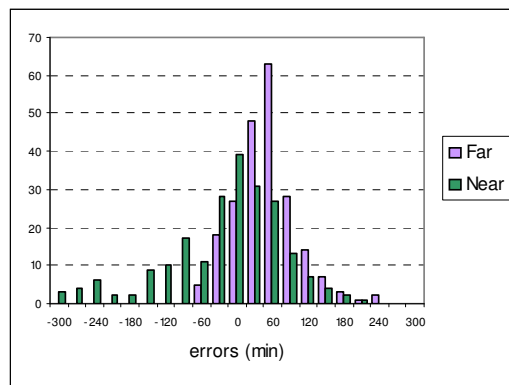


**Figure 3.3 Association between eye position and pupil size**

Recordings of eye movements during vergence changes and associated pupillary area. Red traces represent right eye position, green lines represent left eye position. Purple traces represent pupillary area of the right eye, black traces represent pupillary area of the left eye. The Y axis refers to the horizontal position of the eye only, pupil measurements are relative only. Recording LK (b) shows the detail of one vergence cycle. For subjects CC and LK the pupil traces have been displaced downward to assist in interpretation, for subject NJ they are in their original position to more clearly demonstrate that the change in pupil size is slower than the change in eye position. It can be seen in all cases that eye position is not directly related to pupil size.

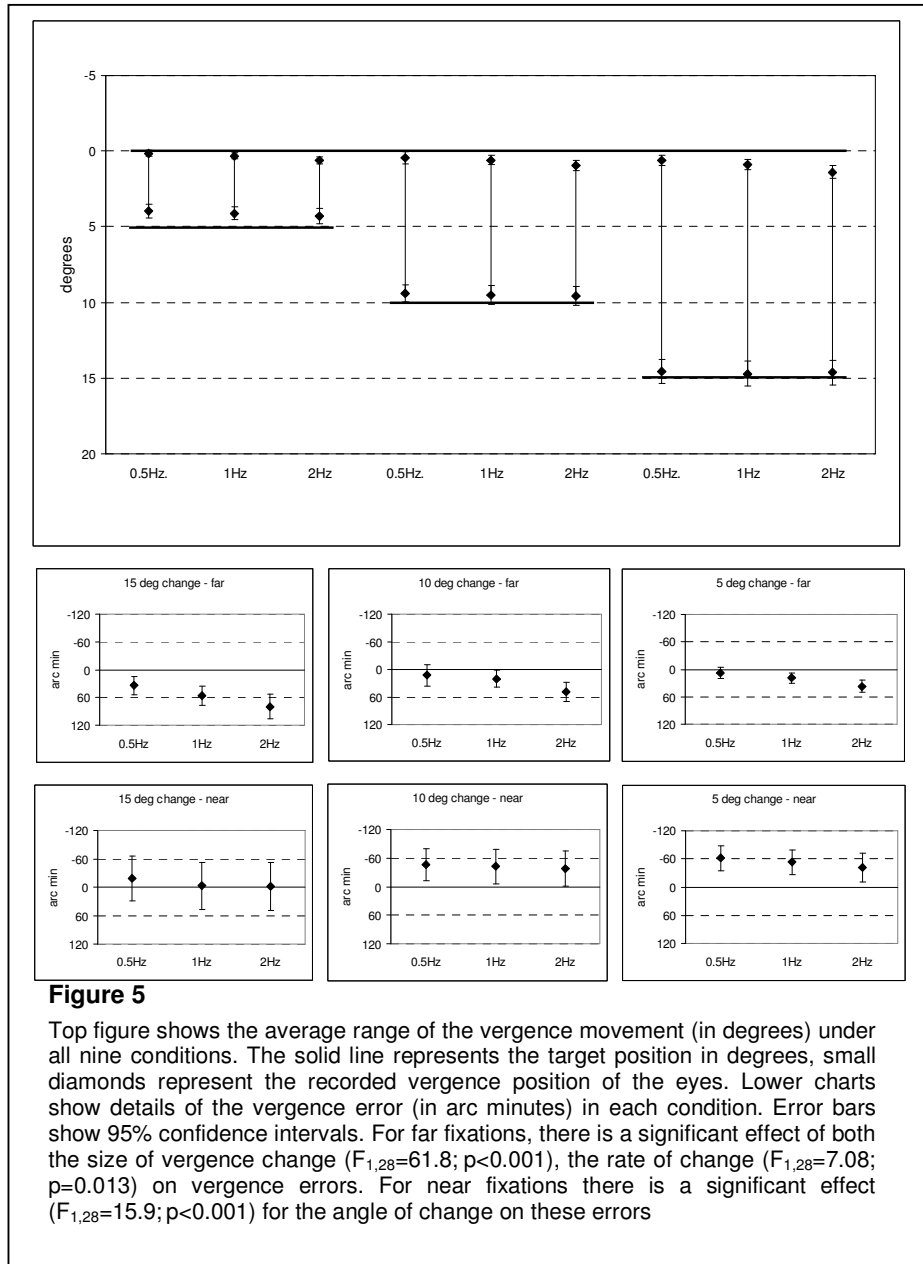
The distribution of all vergence errors is shown in Figure 3.4, descriptive data is shown in Table 3.1. For far fixation, vergence errors were between -323' to +180'. The mean value was -29.7', with standard deviation of 94' and a median value of -9.6'. For near fixation, vergence errors were between -70' to +232'. The mean value was +38', with standard deviation of 50.5' and a median value of 34'. Whilst these data demonstrate considerable variation in the results between subjects, especially for near fixation, the recordings for individual subjects showed little variation.

The overall amplitude of the vergence movements tended to be hypometric, resulting in underconvergence on the near target and overconvergence (or underdivergence) on the far target (Figure 3.5). This effect was greatest for the large and fast movements. ANOVA testing (planned orthogonal contrasts) using the vergence error data confirmed a significant effect for far fixations of both the size of vergence change ( $F_{1,28}=61.8$ ;  $p<0.001$ ), the rate of change ( $F_{1,28}=7.08$ ;  $p=0.013$ ), and the interaction between these two factors ( $F_{1,28}=7.17$ ;  $p=0.012$ ) on resulting errors, with the eyes showing greater overconvergence on the target for the larger and faster fixation changes. For near fixations, there was a significant effect ( $F_{1,28}=15.9$ ;  $p<0.001$ ) for the angle of change with the larger vergence changes producing relatively more convergence, thus reducing the mean vergence error. There was no significant effect for the rate of change on errors for near fixation. Although the mean values suggest similar effects as those found for far, the larger variability in the near errors may have affected this conclusion.



**Figure 3.4 Distribution of mean vergence errors**

Distribution of mean vergence errors for each vergence change condition for all subjects at both far (green bars) and near (mauve bars). Most errors are between 120' to +120' for far fixations, and between -30' to +120' for near fixations.



## Discussion

Errors of between  $-323'$  and  $+232'$  were found, but most were within  $120'$ . These limits are similar to those found in similar free space experiments by Erkelens et al<sup>91, 92</sup>, Collewijn et al<sup>88</sup> and Malinov et al<sup>101</sup> when subjects made voluntary shifts between stationary targets. It is of interest that these values are similar to the  $3^\circ$  limits of 'dimpling' of the horopter under forced vergence as reported by Fogt and Jones<sup>97</sup>, although that study only demonstrated dimpling of the horopter in relation to stimulation of a small, central target.

The highest average errors occurred for the large and fast fixation changes to a far target, that is, after a divergence movement. Whilst the sampling rate for this study was not sufficient to provide reliable data on the dynamics of the eye movements, our findings are qualitatively consistent with the reported slower velocities and longer latencies for divergence that have been reported by Hung et al<sup>107</sup>. Studies of the neural pathways for vergence eye movements in experimental animals have identified cells that fire in response to both convergence and divergence movements<sup>52, 49, 50, 108, 58</sup>, however the identification of cells in the posterior interposed nucleus of the cerebellum that respond only to divergence and/or relaxation of accommodation<sup>59</sup> indicates that the pathways for convergence and divergence are at least partly independent. Our findings suggest that there are different effects of convergence and divergence on the type and extent of vergence errors during binocular fixation that could be attributed to these neurological factors or possibly to an overall insufficiency of the vergence system. However, they could also be attributed to anatomical factors such as the visco-elastic properties of the medial and lateral rectus muscles and their associated fascia.

This study has also demonstrated that these misalignments can be affected by the amplitude of vergence change for both distances on binocular fixation errors, with larger changes producing relatively more convergence. The resulting decrease in error size for near fixation with the large and rapid fixation changes may be related to the reduced need for convergence when the eyes are already partly overconverged on the far target. However, this should also result in a change in vergence size with each fixation, an effect that was not evident in this study. The small number of fixations (3-4), although very similar in size within each condition, may have masked this effect.

The absence of diplopia in the presence of significant errors of binocular alignment was a particular finding of this study. However, diplopia in itself is a rare symptom in subjects with normal binocular vision, indicating either that eye movements are always precise, or that under certain conditions, significant disparity can be tolerated.

Although the head was stabilized for this experiment, others<sup>101, 98, 99, 59</sup> have demonstrated that images can remain subjectively stable despite significant retinal image disparity induced by head movements. Duwaer<sup>86</sup> using an afterimage technique demonstrated much smaller disparities, however this is consistent with the differences found between studies using objective and subjective methods. Under natural viewing conditions there is a full visual field with multiple retinal disparities, a person is constantly changing fixation, the person, or the person's head may be moving, or other objects in the visual field may be moving. Fixations may be brief and of little importance to the person, so it is unlikely that the alignment of the eyes is always precise. Physiological diplopia in everyday situations is rarely noticed, clinicians are aware that it is often very difficult to demonstrate this phenomenon to someone who was not previously aware of it. The results of this study suggest that it is tolerance of



disparity, perhaps associated with frequent eye movements, rather than precision of eye movements that makes diplopia an unusual symptom for most people. As was discussed in the Chapter 2, studies that imply that precise alignment of the eyes is necessary for single vision are normally carried out under experimental conditions or use subjective methods<sup>86, 71, 69, 109-111</sup>, whilst those that have demonstrated tolerance of disparity similar to those of this study are usually carried out under 'free space' conditions that included many of the conditions listed above<sup>88, 112, 91, 101</sup>. As Erkelens, Steinman and Collewijn commented from their experiments on ocular vergence under natural conditions "*Such transient large disparities of an attended, moving object may occur so commonly in ordinary behaviour that subjects do not notice or remember diplopia, unless they are specifically alerted to the condition*"<sup>91</sup>.

It was evident in many subjects that the large and fast changes of fixation did not allow sufficient time for a stable period of fixation. However, such eye movements do exist in natural conditions, such as many sporting activities, and should be considered part of normal viewing. The characteristics of these movements are similar to those reported by Erkelens et al<sup>92</sup> where errors of up to 6° were reported. Other studies<sup>113-116</sup> have shown that suppression of vision can occur during a vergence movement. Although the reported time course of this visual suppression is very short, it may have been influential during the large and fast movements induced in this study. This visual suppression associated with eye movements is a binocular phenomenon, not the uniocular form of suppression that may be expected to accompany a vergence error during fixation. It is possible that any saccadic movements during both the vergence movement and the fixation period could also have contributed to visual suppression, however the recording system used in this study did not permit a detailed analysis of this possibility.

### **Conclusions**

Objectively measured errors of symmetrical vergence eye movements of up to 2°, without diplopia, are common in subjects with normal binocular vision. Occasional errors of up to 5° occur. However even with such large errors diplopia is not experienced. Vergence errors tend to be those of underconvergence on a near target and overconvergence (or underdivergence) on a far target. These errors are also influenced by rapid, large vergence change, which result in more convergence, thus increasing errors for far fixations, and decreasing errors for near fixations. The lack of diplopia, despite relatively large disparities, could be attributed to an extended form of vergence related suppression, however, it also brings into question the usefulness of Panum's fusional space as an explanatory concept for natural viewing conditions.

## Chapter 4

# The accuracy of binocular alignment following combined vergence and saccadic eye movements

### Introduction

Eye movements in response to targets along the mid sagittal plane are rare outside experimental situations, as changes of fixation usually redirect the eyes both in distance and direction, requiring an eye movement with properties of both vergence and saccade. Such asymmetrical eye movements are also required for 'conjugate' movements in people with anisometropia corrected by spectacles<sup>88</sup>, as the optics of the correcting lenses result in different sized images to each eye. This dichotomy was recognised theoretically by Hering in 1868 and has stimulated much research on the nature of combined vergence and version eye movements.

Yarbus, in 1967<sup>117</sup> constructed a model based upon a simple addition of these two systems stating that:

*“Any change of stationary points of fixation in space (unless these points are situated along the same axis of the cyclopean eye) consists of the sum of two independent eye movements - convergence or divergence, and saccade.”*

To illustrate this Yarbus described the eye movement recorded from a 'photokymograph' while the subject looked from a near object to one further away but to the right. He stated that there was an initial small, symmetrical divergence eye movement, then a saccade to the right until the disparity was equal in each eye, then a symmetrical divergence to achieve binocular fixation. This process was reversed for refixation on the near target.

Yarbus does acknowledge, however, that asymmetrical eye movements do occur and that *“the process of vergence is continuous, regardless of whether it is accompanied by saccades ... or not.”* He also recognised that the dynamics of convergence and divergence may be different and that the addition of the saccade significantly increased the velocity of the vergence movement.

*“Frequently the maximal angular velocity of the eye movement during convergence and divergence may attain several tens of degrees per second. Naturally, with these speeds, normal perception is no longer possible.”*

Studies of the dynamics of these combined shifts have been evaluated in real space<sup>88, 118, 119</sup>, with dichoptically presented targets<sup>120</sup>, or in combined conditions<sup>121</sup>, in both the light and the dark<sup>122</sup>, in subjects with aniseikonia, either spectacle induced<sup>112, 123</sup> or artificially induced<sup>124 125</sup><sup>126</sup>, or under other experimental conditions that necessitate an asymmetrical response<sup>126</sup>. Oohira<sup>123</sup> and Averbuch-Heller et al<sup>126</sup> have also shown that the motor programming for a change in these combined movements can occur rapidly.

A major study by Collewijn et al<sup>88</sup> documented the dynamics of voluntary gaze shifts to real, three dimensional targets that ranged in vergence changes of 0° to 25° and version changes of 0° to 65° and intermediate positions of a combination of these, and concluded that: *“within manual working space, binocular gaze-shifts are effected by the highly integrated action of conjugate and disjugate mechanisms, both of which are expressed preferentially in fast, saccadic movements.*

The findings from this study, and others, confirm that ‘pure’ vergence and versions rarely occur, even in experimental situations where the stimulus would seem to need only one type of movement<sup>88, 127, 112, 120, 128, 129, 122, 117, 119</sup>. A fixation change along the horizontal midline, that should only require a vergence movement, almost always has some component of a saccade (although Collewijn et al<sup>88</sup> could demonstrate a ‘vergence only’ movement when the differences in target vergence were small), and horizontal saccadic movements frequently have an initial small divergence movement of one eye, with a subsequent faster velocity of that eye during the subsequent saccade<sup>88, 117, 119</sup>. Maxwell<sup>129</sup> found the same patterns in monkeys, although the study only reported on vergence movements to targets on the midline.

The dynamic pattern of these combined movements is typically one where there is an initial small vergence movement (usually divergence) followed by a disjunctive saccade (an *‘intrasaccadic pulse of vergence change’*<sup>130</sup>), then a small corrective vergence movement. This intrasaccadic component of vergence increases with increasing version demand. For divergence, it accounts for 50%-100% of the vergence change, and from 40% to 70% for convergence<sup>88</sup>. Other factors that influence saccadic input include the conditions under which the interaction is studied (the movement is faster under natural conditions<sup>91</sup>) the distance of the target (rapid adaptation of the process is more likely to occur for distance fixation)<sup>125</sup>, whether the movement is one of convergence or divergence (the peak divergence speed is usually higher for divergence although in some case this is idiosyncratic<sup>126, 88, 91, 129, 122, 125, 117</sup>) and whether the stimulus is one that requires a voluntary change in fixation, rather than a slow change in disparity of the targets<sup>131</sup>. Schor<sup>132</sup> has also shown that saccades reduce the latency and increase the velocity of accommodation.

While this saccadic input speeds up vergence, the small divergence movement that usually precedes a saccade slows the velocity of the saccade. Thus while version accelerates vergence, vergence slows down version<sup>88</sup>.

Collewijn et al<sup>89</sup> found the corrective post saccadic vergence to be symmetrical, consisting mainly of convergence along the 'iso directional line'. Enright, however<sup>133</sup> concluded that these post saccadic movements were usually asymmetrical. The better aligned eye was typically as well aligned on the target as it would be after pure conjugate saccades, but the other eye deviated much more, requiring an asymmetrical post-saccadic vergence movement. Enright considered that the better monocular foveation of one eye would provide immediate good resolution of the target and would permit a more rapid and efficient shift of gaze than that achieved by slow symmetrical vergence.

There was no consistent evidence in Enright's study (using three subjects) that this post saccadic asymmetry was related to eye dominance, as assessed by a simple pointing test, although for one subject there was a strong correlation ( $p=0.001$ ) between the eye that was dominant and the one that was better aligned with the target.

In experimental situations where the near target is aligned along the visual axis of one eye, there is usually a small, initial abducting movement of this eye before the vergence movement occurs<sup>134-136</sup>, thus initiating a larger intersaccadic movement than would be predicted by the target position. Pickwell<sup>136</sup> and Enright<sup>130</sup> found that this is partly influenced by ocular dominance, with four of seven subjects making a consistently smaller movement with the dominant eye.

All of these studies indicate that the eye movement to a target that requires both a shift in direction and distance is pre-programmed and faster than a simple vergence movement, and some also suggest that the dynamics of the eye movements are influenced by ocular dominance and/or the better aligned eye. If there are vergence errors following the change in fixation then these errors may also be influenced by either ocular dominance or the lateral position of the near target.

Although ocular dominance is often assessed by a sighting test (near and far targets are aligned with the 'dominant' eye) Coren and Kaplin have shown that eye dominance is not a simple phenomenon, but is task dependant<sup>137</sup>. As the eyes converge to a target brought in towards the nose, at a point approximately 6 cm from the bridge of the nose, one eye tends to lose fixation and diverge, with resulting diplopia and blurred vision. The eye that 'fails' is usually consistent for a particular subject. This behaviour was one of the markers for dominance in Coren and Kaplin's study.

In an asymmetrical situation, where one eye needs to converge more than the other, the accuracy of the movement may be affected if the eye that normally fails on convergence is the one that needs to make the larger movement.

The above studies on asymmetrical vergence have evaluated the dynamic components of the movement, not the resulting accuracy of the alignment. Some of the studies discussed in Chapter 2, especially those with the head unrestrained<sup>138, 91, 92, 101, 98</sup> also stimulate asymmetrical vergence, but none specifically evaluated the effect of laterality or ocular dominance on resulting errors.

The first experiment (Chapter 3) revealed that errors of vergence are influenced by the size and the rate of change of the eye movement. The following experiment was designed to examine the influence of asymmetrical horizontal vergence movements on vergence errors. The 10°, 0.5Hz paradigm from the first experiment was used in this experiment as it represented the middle range of vergence errors that were documented in that study. The aim of this experiment to determine:

1. Whether there are any differences in the accuracy of binocular fixation following vergence movements from a far target (200cm) to a near target situated:

- along the mid sagittal plane, requiring symmetrical 5° vergence for each eye,
- 5° laterally to the right requiring 2.5° convergence for the right eye, and 7.5° convergence for the left eye,
- along the visual axis of the right eye, requiring 10° convergence for the left eye only,
- 5° laterally to the left requiring 2.5° convergence for the left eye, and 7.5° convergence for the right eye,
- along the visual axis of the left eye, requiring 10° convergence for the right eye only.

2. Whether any patterns in errors are related to ocular dominance, either defined by a sighting test or as the eye that fails at the convergence near point.

## **Method**

### **Subjects**

All subjects were young university students between 18 and 30 years of age with ocular motility and visual standards the same as for experiment 1. Twenty two subjects fitted the criteria for the experiment and gave suitable recordings in each condition.

The recording system (VidEyO) is outlined in Chapter 3.

For the same reasons as outlined in that experiment, assessment was made of the accuracy of the final binocular fixation, the dynamics of the eye movements were not studied.

### **Calibration**

The findings from Chapter 3 confirmed that changes in the size of the pupil did not influence horizontal eye movement position. For this reason calibration to 10° laterally displaced targets was used in this experiment, as this gave more precise measurements of the lateral position of each eye, a feature that was relevant for the study.

### **Experimental protocol**

The dominant sighting eye was assessed by asking the subject to hold both arms outstretched in front of the face, with the palms facing away from the subject, and forming a small diamond between the thumb and index finger. The subject was asked to look at the experimenter through this hole. This was repeated three times, although in every case the same eye was used to sight. A fixation target was moved towards the subject's nose with the instruction to continue looking at it. The eye that maintained fixation when convergence eventually failed was also recorded.

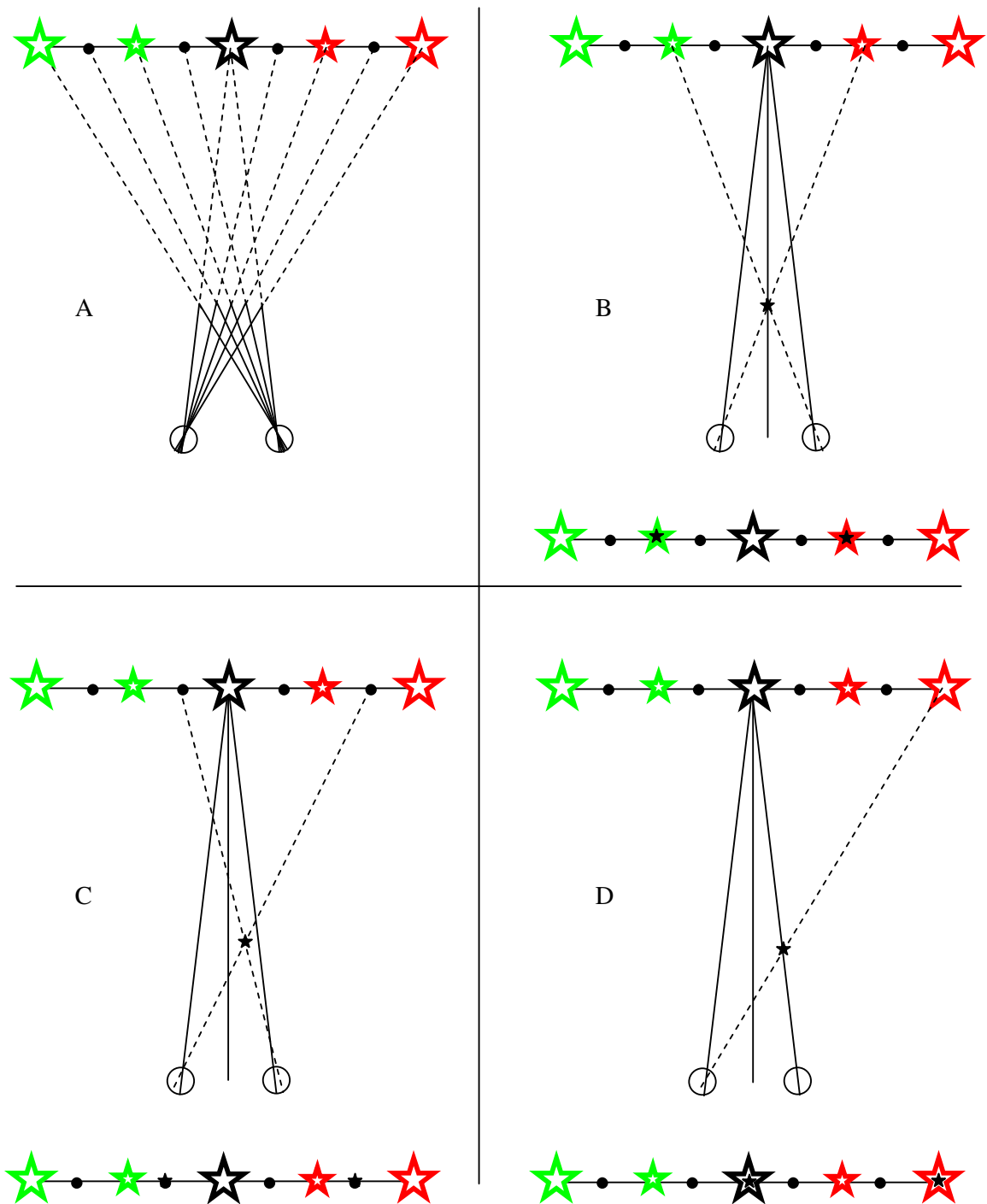
The targets for far and near fixation were the same as those used described in Chapter 3. As the position of the near target for each of the five positions would differ for subjects depending on their inter pupillary distance, the desired position was achieved by allowing the subject to align the target using physiological diplopia. In addition to the central star that was set at 200 cm along the naso- occipital axis, two additional stars were placed 26.3 cm and 35.3 cm on either side of the central star, to subtend angles of 5° and 10° at the nodal point of each eye (Figure 4.1(A)). To enable the subject to readily distinguish the different stars during the experiment, different colours and sizes were used. Small black marks were placed midway between the stars to identify the correct position for the 7.5° / 2.5° lateral shifts.

For the straight ahead position, the subject was asked to fix on the far target and move the near target until its two images were superimposed on the two lateral inner stars. This required 5° of vergence of each eye when the near target was fixed (Figure 4.1B). For the intermediate shift to the right, the subject again fixed on the far target and moved the near

target to the right until the right image was positioned exactly between the two left stars and the left image was between the central star and the small green star (Figure 4.1C). For the full shift to the right, the near target was moved further to the right until the left image was superimposed on the central star and the right image was superimposed on the large red star (Figure 4.1D).

During each recording session four fixations were recorded for far and near fixations in each of the five positions at a rate of approximately 0.5 Hz, using the verbal counting method described in Chapter 3. The order of the positions was randomised between subjects. The measured value of vergence at each fixation was subtracted from the stimulating value and the resulting errors were expressed in minutes of arc. A single mean value was used for further analysis.

The significance level was set at  $p < 0.05$



**Figure 4.1 Positioning of the near target using physiological diplopia.**

A..Far screen. The small stars are  $5^\circ$  from the central star, and the large stars are  $10^\circ$  from the central star when the subject is seated 200 cm away. The small black dots are  $2.5^\circ$  from the adjacent stars.

B,C,D: Upper picture: The near target is positioned by the subject until the diplopic images are superimposed on relevant markers on the far screen (see text).

Lower picture: Perception of the diplopic images by the subject.



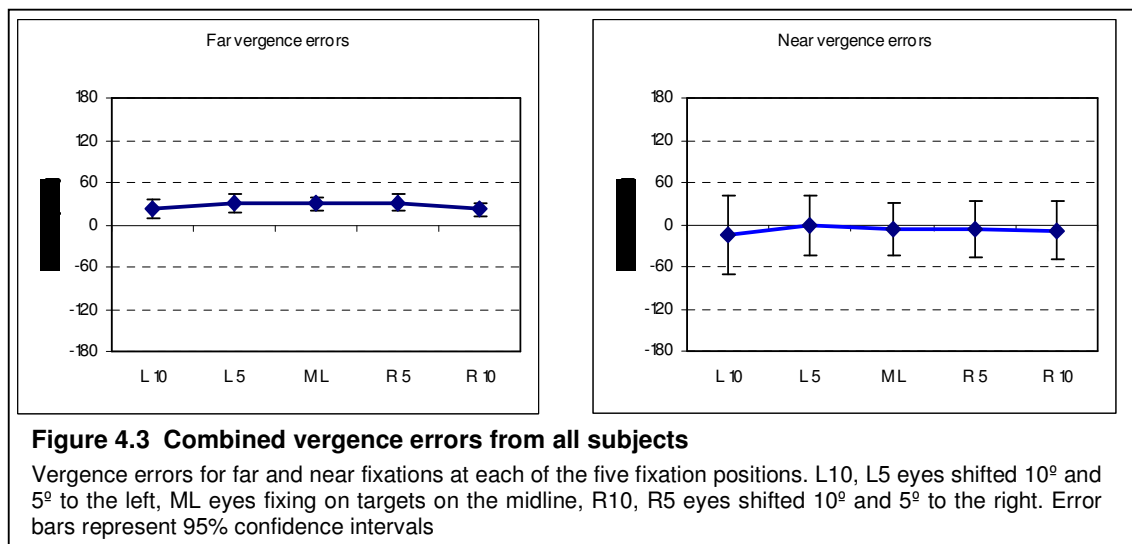
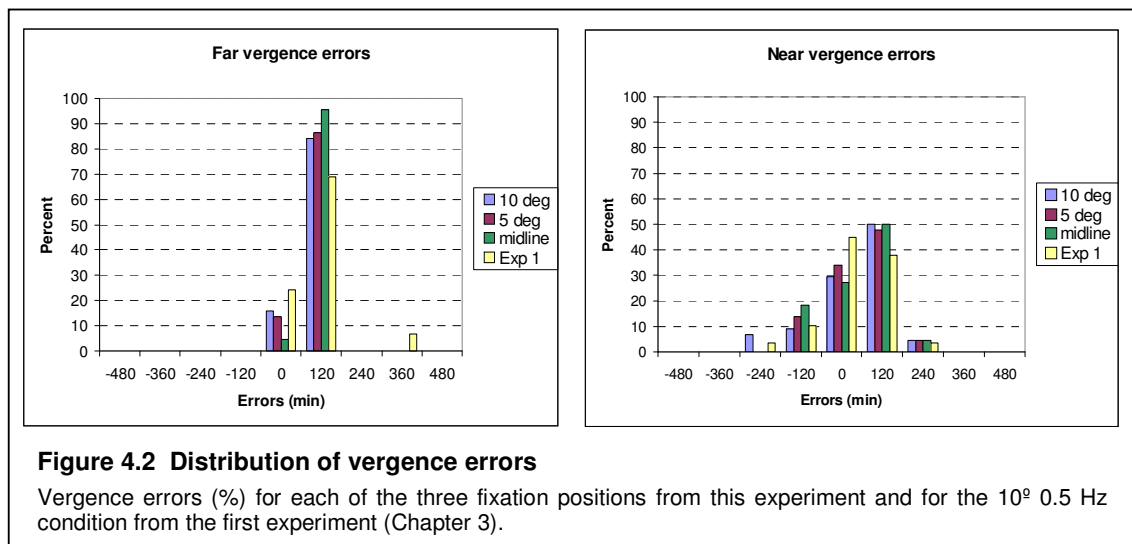
## Results

All subjects, except one, maintained fixation with the right eye at the convergence near point, that is, the left eye 'failed' in almost every case. Eighteen subjects had right eye dominance and four were left eye dominant as assessed by the sighting test.

### Vergence errors

For near fixations vergence errors ranged from  $-325'$  to  $211'$ , and for far fixations from  $-39'$  to  $114'$ . This range is similar to the distribution of errors that were found for the  $10^\circ$  0.5 Hz condition in the previous experiment (near  $-250'$  to  $232'$ , far  $-63$  to  $249'$ ) (Figure 4.2) Raw data is presented in Appendix 4A

Mean values for each of the fixation conditions is shown in Figure 4.3. There are no significant differences between each of the fixation conditions.



Although there were no significant differences between the mean values that were related to the position of fixation, observation of individual results suggested that there may be some effect of lateral position for some subjects.

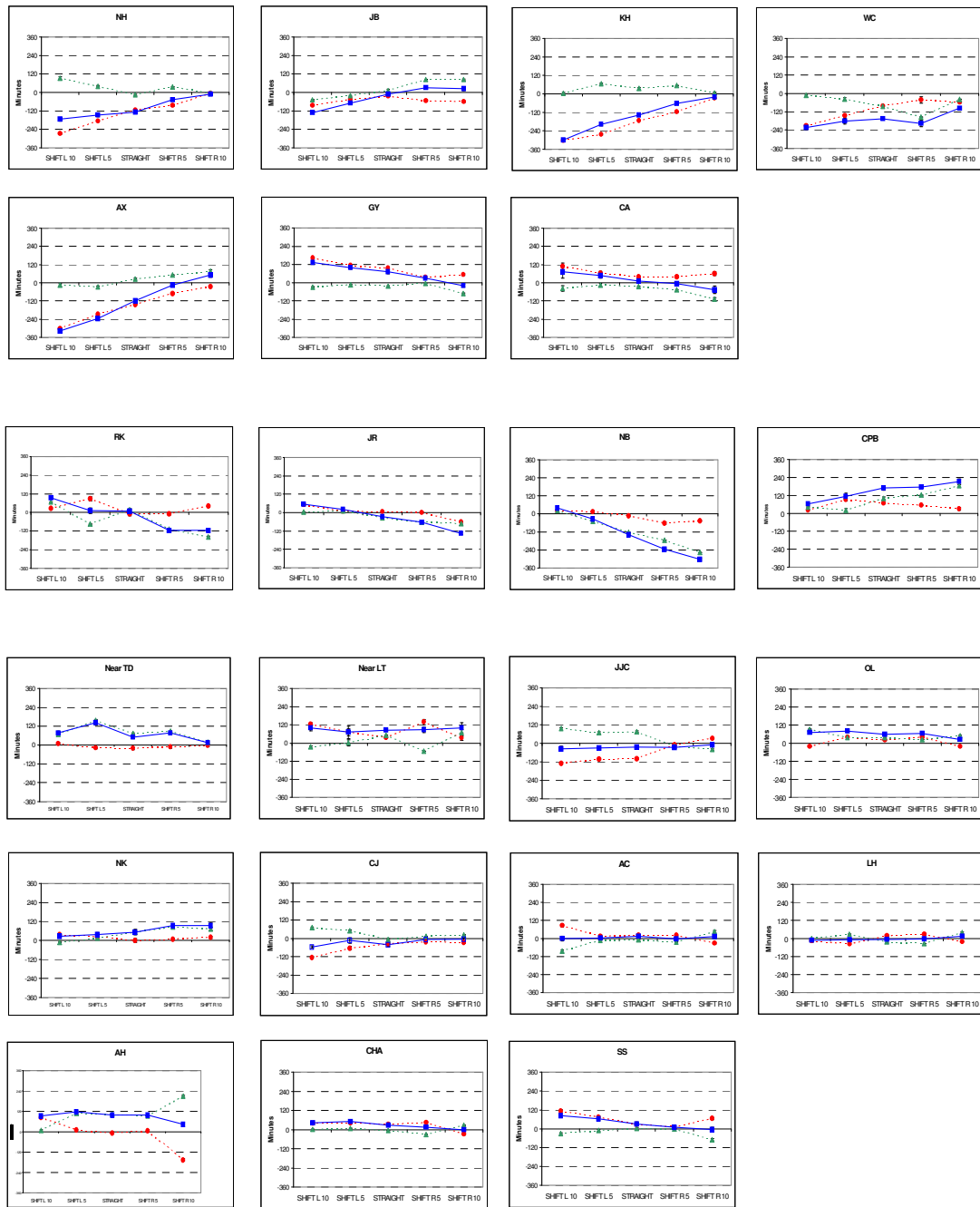
Variation in vergence errors

For the purpose of analysis the results from all subjects were classified as to whether or not there was a change of 2° or more from 10° right to 10° left gaze. Using this criterion, there was no effect of gaze angle on vergence errors for far fixation, the largest difference was a only 41'. However, for near fixations eleven subjects (50%) showed a consistent change that depended on gaze angle, in seven, the errors increased as the eyes moved to the left. In these eleven subjects the adducting eye (ie, the non aligned eye) contributed to most to the vergence error, while the aligned eye was relatively accurate. While this might be expected, it is clear that the errors are not directly related to ocular dominance (as assessed by a sighting test) or the eye that fails at the convergence near point. Seven of the eleven subjects showed increased errors when the eyes shifted to the left yet all of these subjects showed right eye dominance on the sighting test and at the convergence near point. Charts for all subjects are shown in Figure 4.4, error data for all subjects are presented in Table 4.1.

**Table 4.1**

Vergence errors for near and far fixations at each position. The difference between the two 10 lateral positions is shown in red. Differences larger than 2° are shown in red.

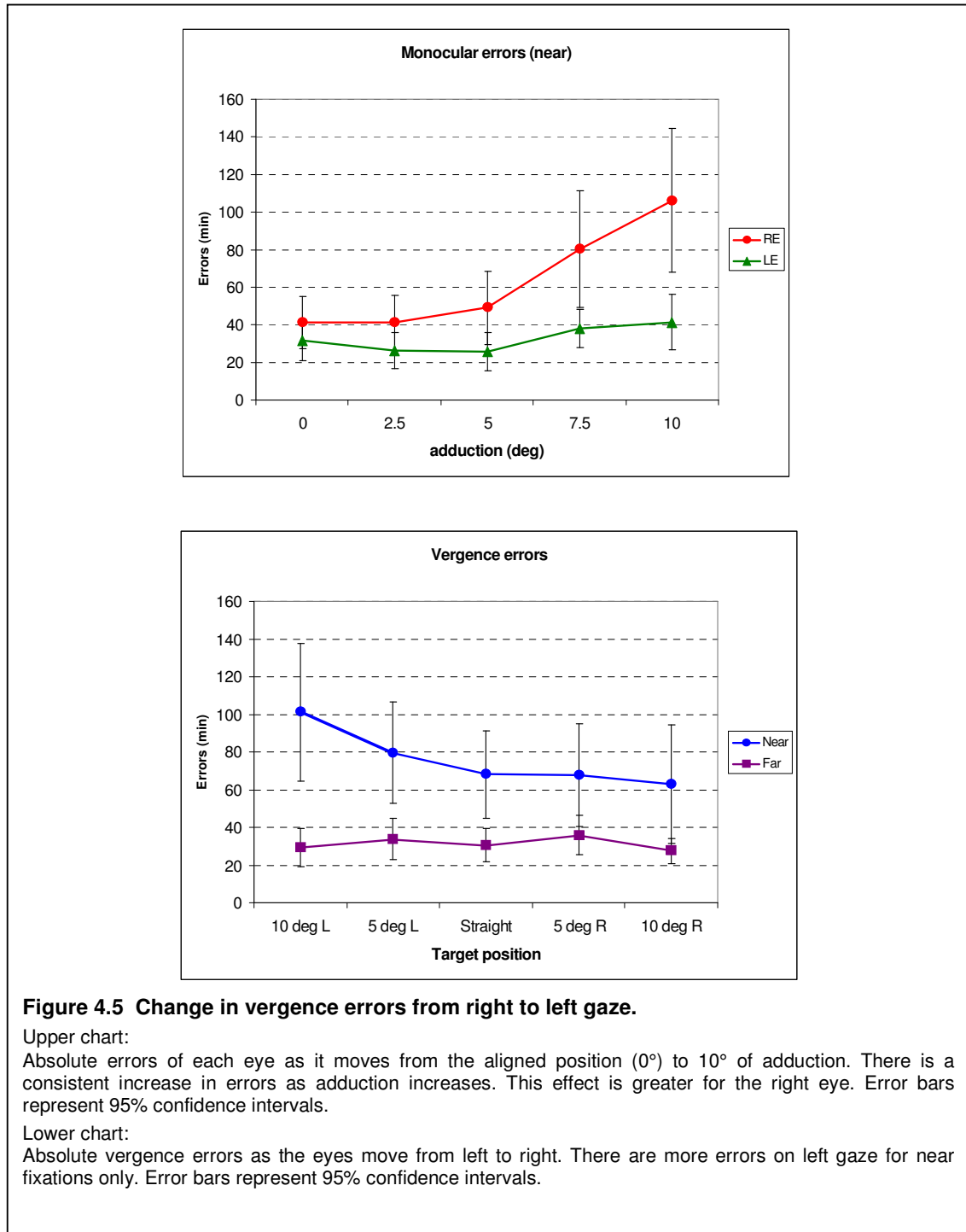
NEAR		L 10	L 5	ML	R 5	R 10	Change
AC		1.4	3.4	14.3	-3.7	12.9	11.5
AH		93.6	118.1	97.1	97.7	43.1	-50.5
AX		-315.9	-236.3	-117.5	-16.7	51.0	<b>366.9</b>
CA		73.7	50.0	12.9	-5.8	-46.5	<b>-120.3</b>
CHA		41.9	50.0	27.5	15.5	-1.1	-43.0
CJ		-54.6	-13.6	-41.1	-8.6	-4.9	49.6
CPB		62.3	111.8	167.4	174.2	211.7	<b>149.3</b>
GY		133.6	98.0	72.3	29.6	-18.6	<b>-152.2</b>
JB		-130.9	-67.8	-12.7	29.4	22.8	<b>153.7</b>
JJC		-35.0	-30.4	-24.3	-26.7	-7.8	27.2
JR		54.4	21.6	-25.8	-63.5	-134.8	<b>-189.2</b>
KH		-325.3	-173.4	-163.0	-87.5	-46.1	<b>279.2</b>
LH		-13.7	-10.3	-4.6	-3.9	16.2	29.9
LT		99.2	71.8	85.7	86.0	99.5	0.3
NB		40.9	-34.3	-137.8	-235.3	-301.7	<b>-342.6</b>
NH		-174.0	-148.0	-128.5	-49.4	-12.2	<b>161.9</b>
NK		27.5	38.9	53.6	93.5	94.0	66.5
OL		72.0	78.6	58.1	64.7	26.0	-46.0
RK		94.3	12.7	8.4	-116.6	-116.8	<b>-211.2</b>
SS		83.8	63.6	29.8	9.4	-5.4	-89.2
TD		75.6	140.9	50.8	76.1	14.3	-61.3
WC		-223.1	-180.6	-165.9	-196.5	-97.3	<b>125.8</b>
FAR		L 10	L 5	ML	R 5	R 10	Change
AC		36.3	47.0	33.9	31.2	22.5	-13.8
AH		28.2	37.7	17.9	33.9	47.1	18.9
AX		11.7	33.2	44.6	20.1	29.3	17.6
CA		26.4	43.0	21.2	70.0	22.1	-4.4
CHA		23.2	27.5	28.7	25.7	28.5	5.3
CJ		8.9	29.9	11.6	32.6	30.0	21.1
CPB		12.6	25.8	43.0	1.1	4.2	-8.4
GY		37.7	42.2	44.8	51.0	24.9	-12.8
JB		-9.7	8.0	24.6	16.0	5.7	15.4
JJC		112.2	114.8	97.2	78.4	71.9	-40.4
JR		37.9	23.3	31.6	75.6	28.5	-9.4
KH		-28.9	-4.5	29.9	18.7	8.7	37.6
LH		8.6	3.0	13.7	13.5	12.1	3.5
LT		-0.5	-0.7	15.5	12.0	35.1	35.6
NB		30.7	44.0	28.4	23.6	23.1	-7.6
NH		62.9	66.3	38.2	72.0	44.7	-18.2
NK		10.7	16.7	29.9	21.3	-1.3	-12.0
OL		25.8	67.3	61.3	62.7	22.3	-3.5
RK		6.3	-23.4	3.9	-24.7	-35.4	-41.6
SS		49.6	21.1	40.7	13.7	48.8	-0.9
TD		36.3	51.5	5.0	71.2	31.7	-4.6
WC		-39.3	-12.4	-8.6	-22.5	-27.0	12.3



**Figure 4.4 Individual charts for each subject.**

Red dotted lines represent the right eye, green dotted lines represent the left eye, blue lines represent vergence. For seven subjects (top) there was a change of 2 deg or more with the largest errors looking 10° to the left. For four subjects (middle) this change occurred when looking 10° to the right. For the lower eleven subjects there is no consistent change.

If the matter of over or under convergence is ignored, and the errors of all subjects are converted to absolute (positive) values, the difference between the aligned position and the 10° adducted position was significant for each eye (right eye,  $F_{1,21}=9.34$ ;  $p=0.006$ , left eye  $F_{1,21}=1.54$ ;  $p=0.034$ ). This is shown in Figure 4.5 (top). As these errors were greater for the right (adducted) eye, there was also an effect of binocular vergence errors increasing to the left. This binocular effect was only significant between the left aligned position and the straight ahead position ( $F_{1,21}=4.6$ ;  $p=0.038$ ) and left aligned position and the 5° shift to the left ( $F_{1,21}=4.9$ ;  $p=0.04$ ). (See Figure 4.5, bottom)



## **Discussion**

This study has confirmed the tendency for over-convergence for far fixations and under-convergence for near fixations that was reported in Chapter 3. However, the results also suggest that asymmetrical vergence is more likely to result in more absolute vergence errors for near fixations than symmetrical vergence.

These errors are more likely due to be the result of inaccuracies in the eye that is making the larger adducting movement, and, in this study this effect was more likely to occur for the right eye. Eleven subjects showed errors that increased by more than 2° when looking to the left, and another four (JJC, OL, CHA, SS, see lower charts of Figure 4.4) showed a smaller but consistent increase to the left. This was surprising, as the right eye was the dominant eye in 18 of the 22 subjects, and it was the eye that maintained fixation when convergence failed in almost all subjects. It is difficult to explain this effect as a consequence of ocular dominance, it may have been random chance or it may be due to more generalised aspects of right/left laterality of the body or egocenter. The design of this study did not permit further analysis of this possibility

The more precise position of the aligned eye is consistent with the findings of Enright<sup>135</sup>, in that, if the fixation target is better aligned with the fovea following the intrasaccadic component of asymmetrical vergence, then this eye may be more likely to make an accurate vergence movement. It is also consistent with the findings of Collewijn et al<sup>89</sup>, who showed that if the final vergence movement is symmetric, then any resulting error of fixation would be greater in the non aligned eye, as was the finding in this study.

However, the errors may not be directly related to the eye being aligned, but instead be simply related to the different excursions required of each eye, with the larger excursion being less precise. This is supported from the data from the right eye, the increase in errors as the eye moves towards the left does not become significant until the eye is adducted 7.5° to the left ( $F_{1,21}=4.2p=0.05$ ), for the left eye the only significant difference in errors occurred between the aligned position and the 10° adducted position.

## **Conclusions**

Binocular fixations for near are more likely to be imprecise following asymmetrical vergence than those following symmetrical vergence. These vergence errors are likely result from the eye that makes the larger adducting movement. The findings from this study suggest that it is the adducting right eye that tends to be less precise, resulting in more errors on left gaze. Although there was a strong association between the right eye as the dominant eye and the eye that was less precise, it is not readily apparent how this would form a causal relationship. These findings are therefore not directly related to ocular dominance.

## Chapter 5

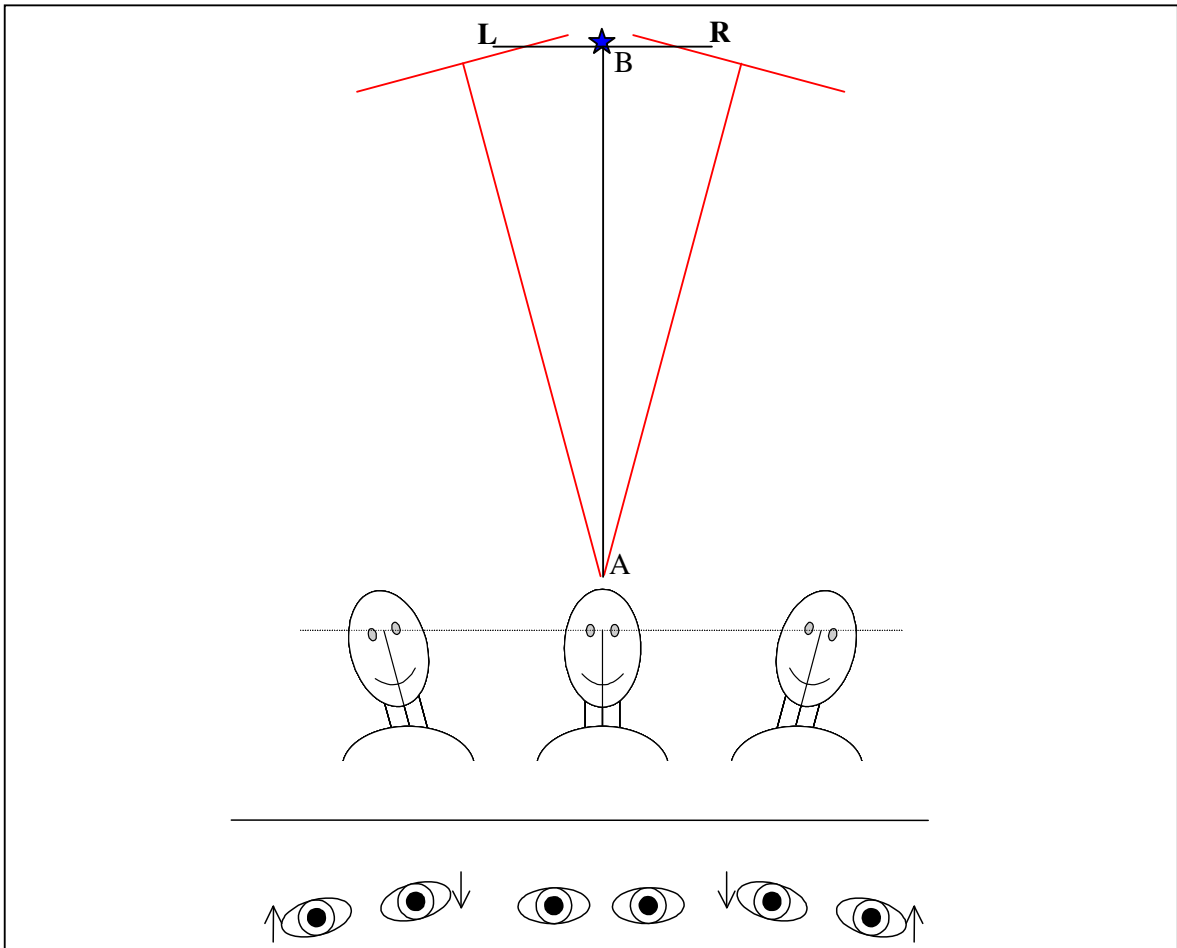
### **The influence of vertical disparity associated with roll head tilt on horizontal vergence eye movements.**

#### **Introduction**

During everyday viewing, a person occasionally tilts the head to one side. There is no single axis of rotation for this action, with all cervical vertebrae being involved<sup>139</sup>. This tilt induces ocular counter-roll, an otolith induced conjugate torsional movement of the eyes, with the 12 o'clock meridian rotating in the opposite direction to the tilt. (See Chapter 1). The static component of this counter-roll compensates for about 10% of head roll for positions up to 20° from the upright position<sup>22</sup>. This tilt is therefore too small to fully compensate for the head rotation, but it may be a phylogenetically vestigial response in humans, as it is much stronger in animals with laterally placed eyes<sup>140</sup>. Tilting the head to an earth fixed target on the midline also requires vertical divergence as the contralateral orbit is moved below the midline and the ipsilateral orbit is moved upwards (for moderate degrees of tilt). (Figure 5.1)

If the person is fixing a far target, counter-rolling about naso-occipital axis results in images of objects closer than from the fixation point falling above the horizontal meridian of one eye, and below the horizontal meridian of the other eye, this increases with convergence. (Figure 5.2). Misslisch, Tweed and Hess consider that this vertical disparity conflicts with stereopsis, as *“the stereoptic system, when it looks for corresponding images in the two eyes, must search not just horizontally but also vertically, a two dimensional task that increases the computational work”*<sup>140</sup>. They showed that in monkeys, OCR is reduced for near viewing, and concluded that vergence (and thus stereopsis) dominate when there is a conflict between the old gravity driven reflexes and the newer vergence/stereopsis system.

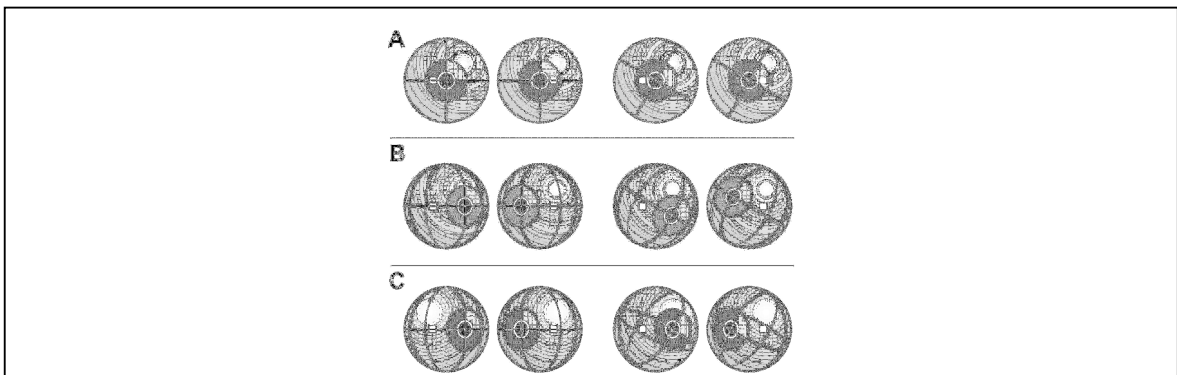
In the above experiment, head fixed targets were used, so the images of the near targets were always equally displaced laterally, and any vertical disparity was also symmetrical. However, a head tilt to an earth fixed target in natural conditions also involves lateral translation of the head with a corresponding lateral shift of the eyes. This results in asymmetrical displacement of the near target on each retina and means that the image of the near target is placed close to the fovea of the contralateral eye, and well into temporal retina of the ipsilateral eye. Although the tilt would induce a small amount of vertical disparity (Figure 5.1) the effect of OCR, in rotating the retina, exaggerates this vertical disparity (Figure 5.3). This 'incorrect' information as to the position of the near target may not only affect stereopsis, but it may also influence any pre-motor programming for convergence to the near target, resulting in decreased accuracy of the final alignment of the eyes.



**Figure 5.1 Head rotations in relation to an earth fixed target**

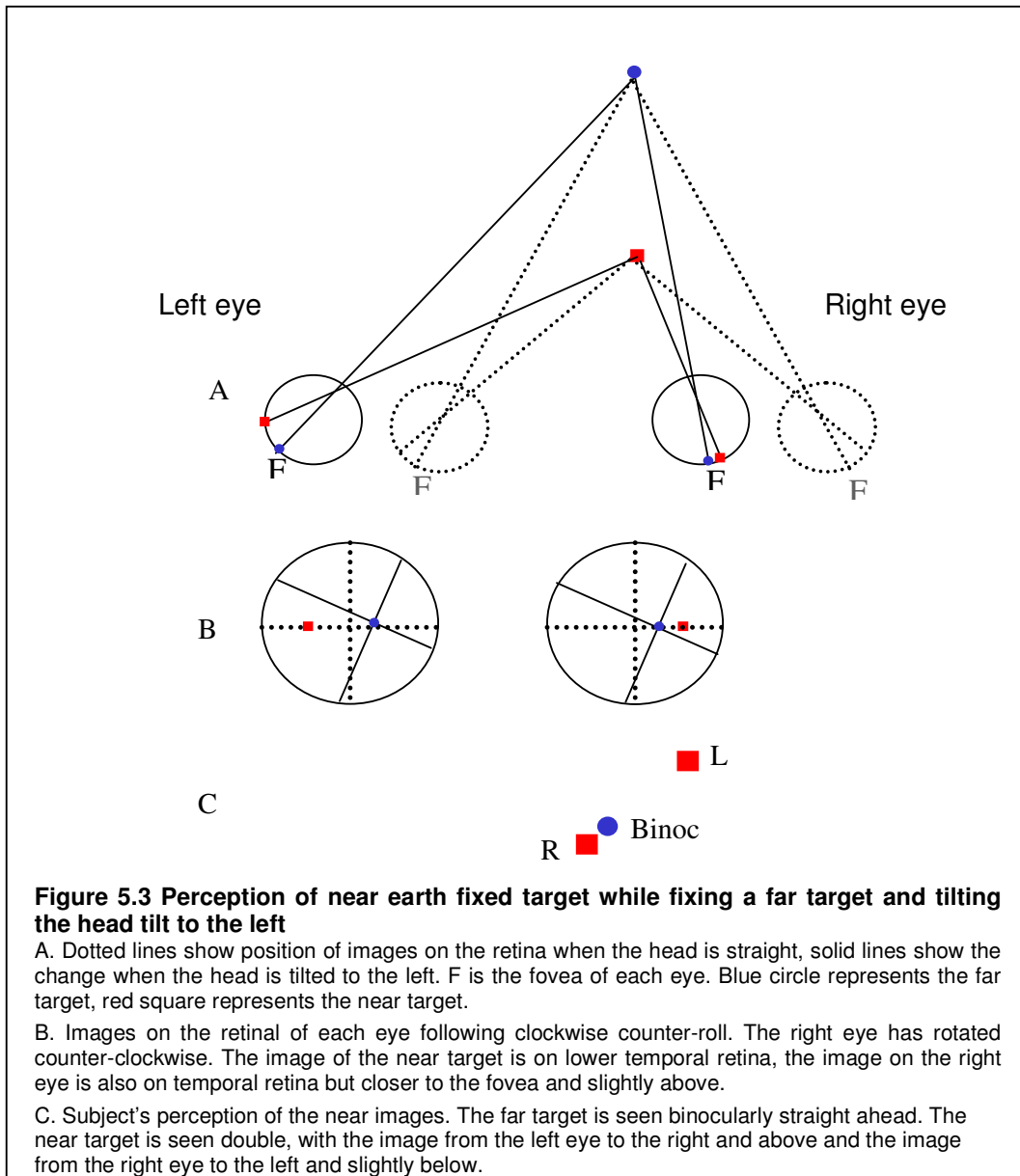
The top figure is drawn to scale for a subject with a 62 mm interpupillary distance and simplified rotation around the long axis that occurs from the base of the neck, 14.5 cm below the eyes (average data from this experiment). Fixation is on a target straight ahead on the midline. Black lines represent the situation when the head is straight, red lines represent the situation when the head is tilted 15°. When the head is tilted LED the left eye moves further to the left and below the target, the right eye moves slightly to the left of the midline and above the target.

Bottom figures show the position of the head and eyes in relation to a fixed horizon. The eye ipsilateral to the head tilt needs to move up to fixate, the eye contralateral to the tilt needs to move down.



**Figure 5.2 (From Misslisch Tweed and Hess, 2001).<sup>140</sup>**

(A) Position of the eyes as seen from the front fixing on a far target with the head straight (left) and with the head tilted right ear down and the counter-rolled to the subject's left(right). The small white square represents an image of a near object on the retina that falls above the horizontal meridian of one eye, and below the horizontal meridian of the other eye. Assuming that OCR occurs around the naso-occipital axis and not an axis orthogonal to the straight ahead direction (B), the vertical separation of objects that are closer than the near target increases with convergence.



Tilting the head therefore brings added complexities to vergence eye movements, especially to earth fixed targets. However, while many of the studies to date (on the relationship between combined vergence and torsion) are concerned with how convergence affects torsion<sup>1, 29, 36, 2-8</sup>, the question of whether vestibular induced eye movements influence the accuracy of horizontal vergence eye movements has not been specifically addressed. The purpose of this experiment was to determine whether the exaggerated vertical disparity that results from ocular counter-roll affects binocular alignment following convergence from a far to a near target.



## **Methods**

### **Subjects**

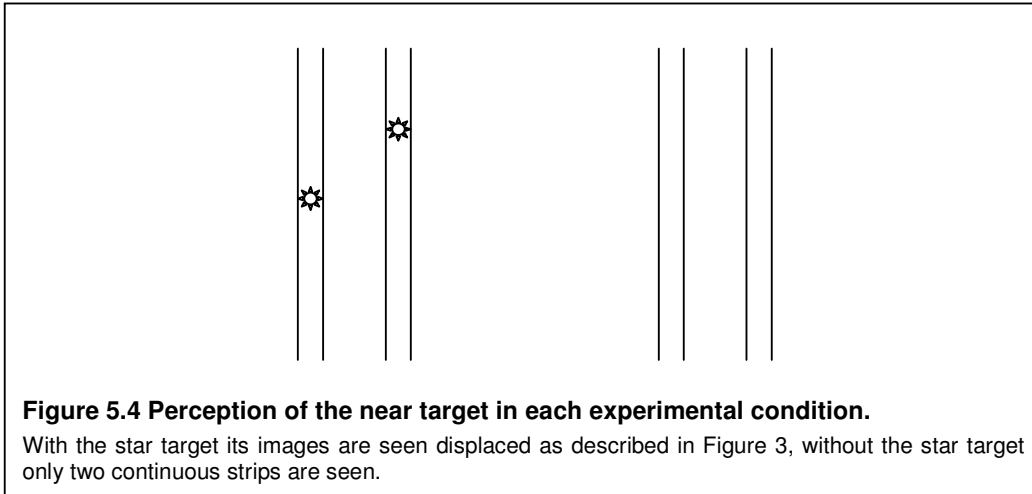
Twelve subjects (aged 18 to 26 years) who met the selection criteria for Chapters 3 and 4 took part in this experiment. Ethical approval was gained from the Ethics Committee of the University of Sydney and all gave informed consent.

### **Procedure**

The video eye movement system described in Chapter 3 was used. In this experiment both horizontal and vertical eye movements were recorded and quantified.

Subjects were seated 200 cm from the far target that was used in Chapters 3 and 4. For this experiment the bite bar was capable of rotating and being fixed to a specific angle using an inclinometer. The position of the chair was adjusted until the subject indicated that the far target was straight ahead, then the shaft of the bite bar was moved up or down so that biting on it would fix the head in this position. The inter-pupillary distance of the eyes, and the vertical distance from the point of rotation of the bite bar device to the lateral canthus of the eyes was measured for each subject.

The near target was positioned 30 cm from the eyes along the midline to stimulate  $10^\circ$  of convergence in a subject with a 62 mm inter-pupillary distance (acknowledging that the eyes were converging  $1.8^\circ$  on the far fixation point 200 cm away). This value of 62 for the inter-pupillary distance was based on the mean value of 62.5mm (st dev 3.1 mm) obtained from 53 similar subjects from previous experiments. The near target consisted of a strip of firm white cardboard (2 cm wide) that was secured above and below the head well outside the subject's visual field, so that, for one condition, only the continuous strip was visible. In the other condition a star (the same as that used for experiments one and two) was attached to this strip in the subjective straight ahead position, confirmed by the subject reporting that the far and near images were horizontally aligned when the head was straight. This position was marked on the reverse side of the white strip, so that the examiner could quickly remove and replace the star target during the experiment. When the subject fixed the far target and tilted the head, the near diplopic images shifted to the opposite side, and, when the star was present, the images also appeared to separate vertically (Figure 5.4).



There was therefore both a normal near fixation target, and one that did not give a visual cue to the straight ahead position or stimulate any vertical vergence. As the purpose of this experiment was to determine whether there was any significant *difference* in the final binocular alignment on the near target between the two conditions (not resulting vergence errors) precise quantification of the vergence demand was not necessary. Calibration was carried out on laterally displaced targets at 200 cm when the head was straight (as described in Chapter 4).

During each recording the subject was instructed to make vergence eye movements from the far to the near target at a rate of approximately 0.5 Hz, using the verbal signaling method used for the previous experiments. For each recording, there were six conditions:

- Head straight, with the star fixation target
- Head straight, without the star fixation target
- Head tilted 15 ° to the right, with the star fixation target
- Head tilted 15 ° to the right, without the star fixation target
- Head tilted 15 ° to the left, with the star fixation target
- Head tilted 15 ° to the left, without the star fixation target

When the star target was not present, the subject was instructed to “look at the white strip and imagine that you are looking straight ahead of you at the star”. The order of the head tilt was varied, and with each tilt the order of presenting the near star target was also varied.

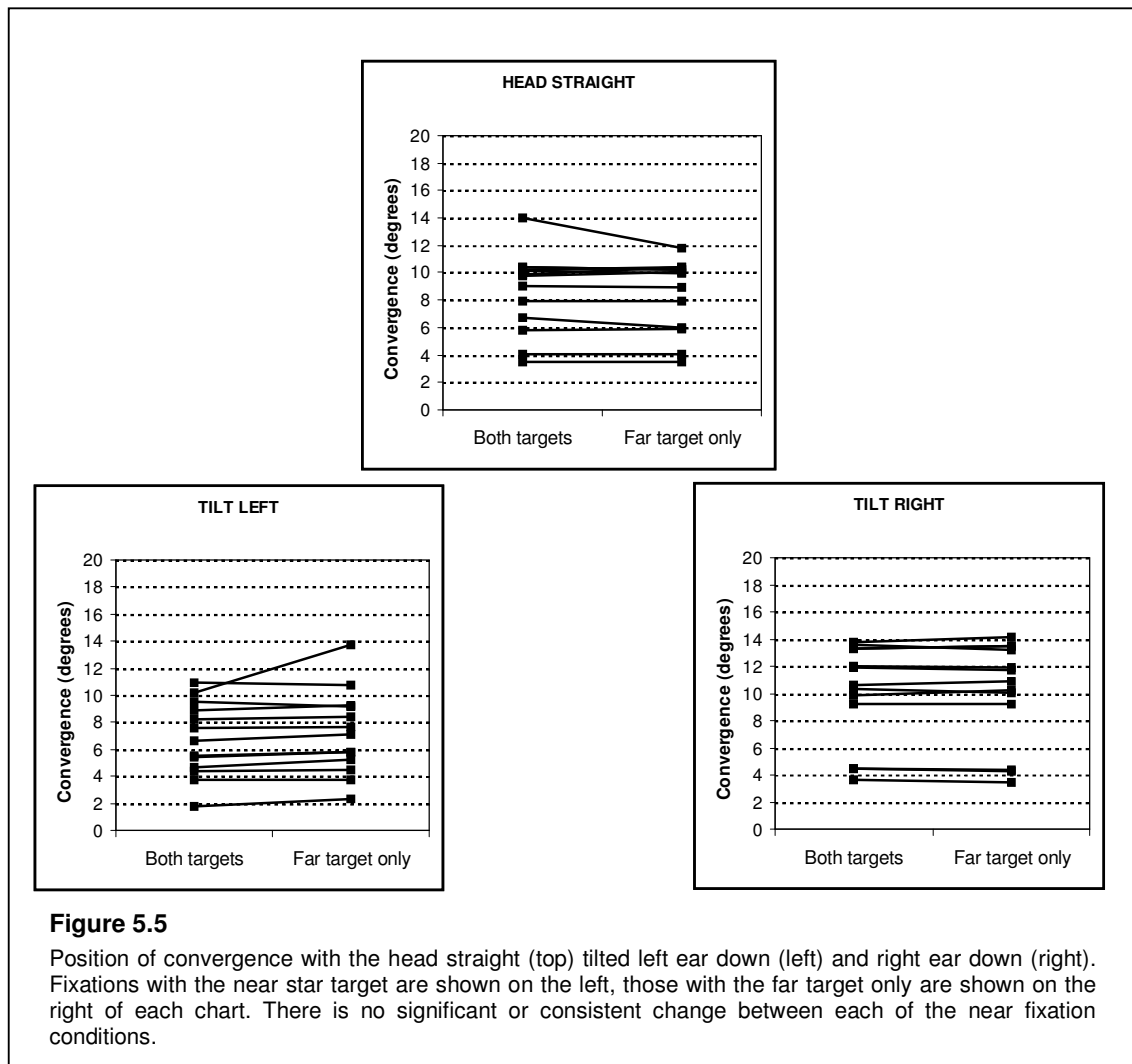
The analysis of the recordings was made using the method described in Chapters 3 and 4 although in this experiment both vertical and horizontal eye movements were analysed.

## Results

The average distance from the rotation point to the bite bar (long axis) was 14.5cm (sd 0.7 cm) and the average inter pupillary distance was 61.4cm (sd 0.4cm).

### Horizontal eye alignment

Figure 5.5 shows the position of convergence on the near target with and without the near fixation target. Several subjects are showing underconvergence which is consistent with the findings from Chapter 3, however with individual differences in the subjects' inter-pupillary distance the absolute value of these measurements may not be precise. Of more importance is the finding that in almost all cases there was no significant or consistent difference in the average angle of convergence, whether or not there was a near foveal fixation target. Raw data is presented in Appendix 5A.



## Vertical eye alignment

The results of this part of the experiment are illustrated in Figure 5.6. Statistical data is presented in Tables 5.1 and 5.2, raw data is presented in Appendix 5B. Unocular vertical movements are presented in positive values if the eye is above the midline, and as negative values if it is below the midline. Vertical vergence is presented as a positive value if the right eye is higher than the left. To control for small conjugate vertical movements that may have occurred if the far and near targets were not precisely aligned vertically, the vertical near position with the head straight and the star fixation target present was base-lined to zero for each eye, and corresponding values during head tilt were adjusted by the same amount. There was a only very small difference of 0.1° for vertical vergence between the two conditions when the head was straight – this was clearly well within the limits for experimental error.

**Table 5.1**  
Vertical alignment (in degrees) for near fixations

	LED	HS	RED
RE both targets	-0.41	0*	-1.61
95% confidence interval	0.93		0.95
RE far target only	0.12	-0.33	-1.86
95% confidence interval	0.87	0.86	1.30
LE both targets	-0.80	0*	-1.12
95% confidence interval	0.79		1.34
LE far target only	0.03	-0.18	-1.13
95% confidence interval	0.75	0.89	1.57

Vertical vergence	LED	HS	RED
Both targets	0.39	0*	-0.49
95% confidence interval	0.66		0.59
Far target only	0.10	-0.15	-0.73
95% confidence interval	0.62	0.29	0.66

\* Baselined data

**Table 5.2**  
t test analysis for the difference between the two fixation conditions (top) the direction of head tilt (middle) and the fixations for the right and left eyes (bottom).

Both targets/Far target only

		LED	RED
RE	F	3.678	0.357
	df	11	11
	p	0.081	0.562
LE	F	11.377	0.001
	df	11	11
	p	<b>0.006</b>	0.975
Vert Vergence	F	2.760	0.001
	p	0.125	0.975
	df	11.000	11.000

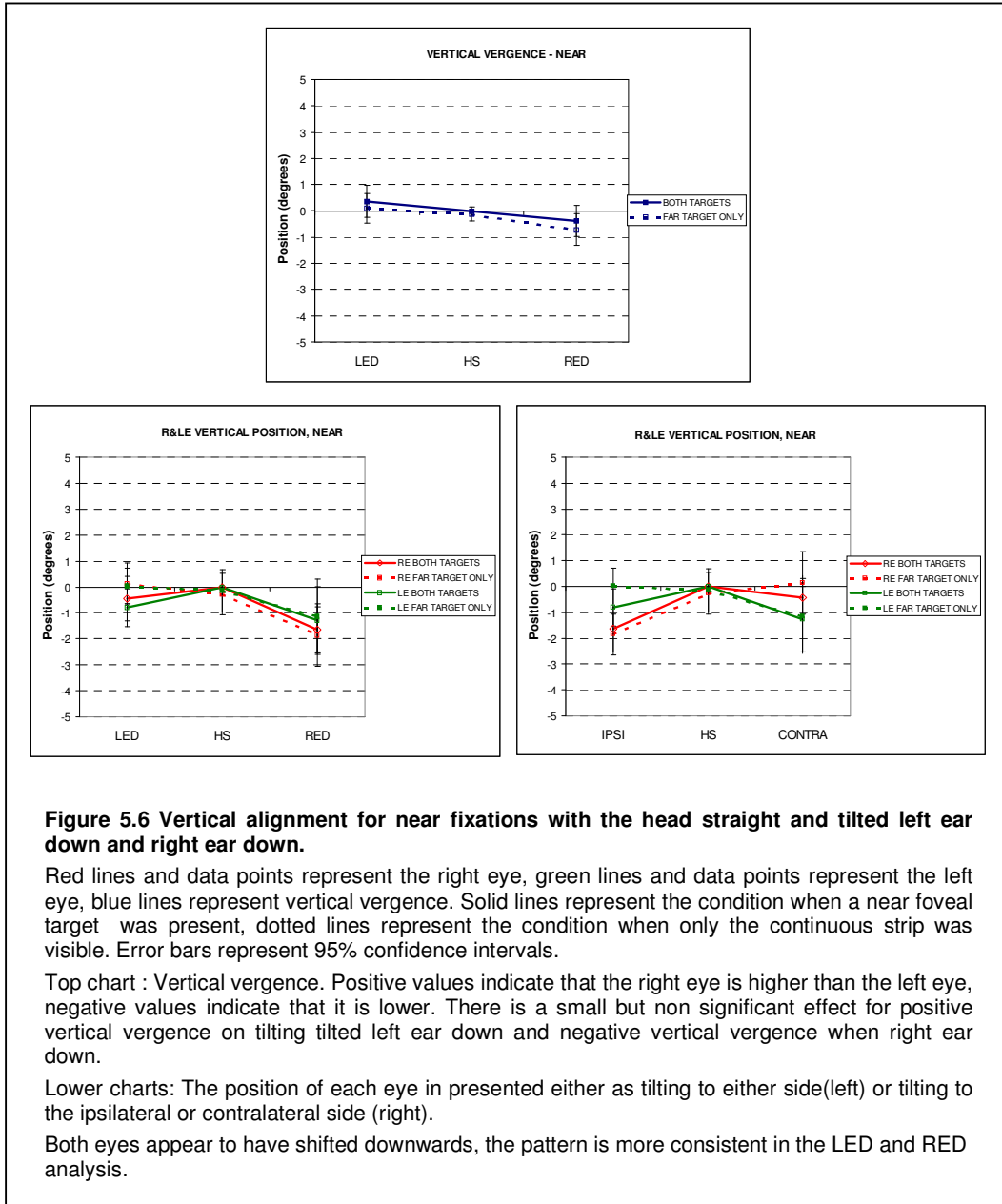
Right / Left Ear Down

		RE	LE	Vergence
Both target	F	6.276	0.149	2.513
	df	11	11	11
	p	<b>0.029</b>	0.707	0.141
Far only	F	10.771	1.602	1.928
	df	11	11	11
	p	<b>0.007</b>	0.232	0.192

Right eye/Left eye

		RED	LED
Both target	F	1.330	2.669
	df	11	11
	p	0.273	0.131
Far only	F	0.094	0.963
	df	11	11
	p	0.764	0.347



It can be seen in Table 5.2 and Figure 5.6 (upper chart) that there is only a very small and statistically insignificant difference in vertical vergence whether there was, or was not, a stimulus to vertical fusion. When considering the position of each eye (lower charts) there seems to be a small effect of positive vertical vergence on left tilt and negative vertical vergence on right tilt in both conditions, however the difference between the right and left eye was not significant at  $p < 0.05$  for either condition.

Figure 5.6 (lower charts) shows the vertical position of the right and left eyes in each condition. Although the right eye tends to be higher on left tilt, and the left eye higher on right tilt the difference between the right and left eyes does not reach significance in any position. There were significant difference between the position of the left eye in the two near target conditions when tilted left ear down (right eye  $F_{1,11}=11.3$ ,  $p=0.006$ ), and the right eye showed a larger downward shift when tilting right ear down than when tilting led both with and without the near target (both targets  $F_{1,11}=6.28$ ,  $p=0.03$ , near target only  $F_{1,11}=10.77$ ,  $p=0.007$ ).

An unexpected finding was that each eye tends to move *down* when the head is tilted, whether or not it is the ipsilateral eye or the contralateral eye. The expectation was that the contralateral eye would move up to fixate and the ipsilateral eye would possibly move slightly down (Figure 5.1). Presenting the same data to indicate eye position during ipsilateral or contralateral tilt shows that the differences appear to be primarily related to the direction of head tilt (LED or RED) rather than the contralateral or ipsilateral eye.

## **Discussion**

These findings indicate that exaggerated vertical disparity of a near target associated with ocular counter-roll does not influence the precision of a convergence movement to this target. The implication of this is that accommodative convergence is the primary stimulus to the initial vergence eye movement, and that final adjustments are made to correct any residual disparity as described by Collewijn<sup>89</sup>. The reduction of ocular counter-roll on convergence<sup>140</sup> and the proximity of the image of the near target to the fovea following the initial convergence would eliminate almost all vertical disparity. Therefore, any pre motor planning for the vergence movement is not influenced by the initial 'incorrect' vertical retinal disparity.

This experiment has also shown that the lack of a fixation target does not affect horizontal binocular alignment. When the head was straight there was no difference between horizontal or vertical alignment whether there was, or was not a stimulus to foveal fixation. This finding is consistent with that of Cooper, Feldman and Eichler<sup>141</sup> who showed that an annular peripheral provides a stronger stimulus to fusion than a central stimulus. Although the continuous strip stimulus in the current experiment was not annular, the strong vertical stimuli provided by the edges of the bar probably provided a sufficient stimulus for an accurate convergence movement.

An unexpected finding from this experiment was the vertical alignment of the eyes on head tilt. Tilting the head moves the ipsilateral orbit downwards in relation to an earth fixed target, while the contralateral orbit moves up a small amount (as represented in Figure 5.1). In order to maintain foveal fixation on the target it was predicted that the ipsilateral eye would move up and the contralateral eye would move down (by a much smaller amount) to maintain foveal

fixation. The results did not fit this expectation, in fact there appeared to be a tendency for a 'reverse skew' deviation as the eye on the same side as the tilt was lower (this effect did not reach statistical significance). The downward position of the eyes appeared to be more related to whether the tilt was right ear down or left ear down. Both eyes shifted down more when tilting right than left, this only reached significance for the right eye, ( $F_{1,11} = 6.28$   $p=0.03$  with both targets  $F_{1,11} = 10.77$   $p=0.007$  with the near target only). This suggests that whatever is causing the difference between right and left tilt is affecting each eye and does not alter vertical vergence.

When tilting left ear down the vertical alignment of the left eye was smaller when the foveal fixation target was absent ( $F_{1,11} = 11.38$   $p=0.006$ ). This difference could have been due to the lack of any horizontal cues to fusion. However when considering vertical vergence, there was no statistical significance when either the direction of head tilt or the presence of a near target was considered.

These unexpected vertical effects on head tilt suggest that could be due to the dual torsional and vertical actions of the oblique and vertical rectus muscles associated with ocular counter-roll. The design of this experiment did not a further evaluation of this possibility, so this was explored further in Chapter 6.

## Chapter 6

### **The influence of gravity on the accuracy of vergence eye movements during static roll head tilt to earth fixed targets**

#### **Introduction**

The findings from experiment in Chapter 5 showed that during a static roll head tilt to an earth fixed target, there was a downward movement of both eyes, especially for near fixation.

It had been assumed that if a person tilts his or her head to one side while fixing on an earth fixed target the ipsilateral eye would move up and the contralateral eye would move slightly down. The finding of a downward movement was unexpected and suggested that ocular counter-roll during static tilt may influence the vertical alignment of the eyes. The effect of static tilt can be evaluated by comparing eye movements under both upright and supine conditions. When a person is upright, the effect of gravity on the otolith organs will vary depending on whether the head is straight, or tilted to either side. If the same conditions are created, but with the subject supine, gravity will still be acting on the otolith organs, but this will be constant for each of these three head positions. Any difference in binocular alignment between these two conditions can therefore be attributed to otolith induced vestibular eye movements.

Torsion is brought about by the cyclo-vertical muscles, the superior and inferior obliques, and to a lesser extent, the superior and inferior rectus muscles. Contraction of these muscles during head tilt could also result in unwanted vertical movements that may affect the precision of binocular alignment.

Another possible effect of head tilt on the vertical position of the eyes is that of skew deviation, the tendency for the eyes to show a small vertical divergence when the head is tilted, with the eye on the same side as the tilt being higher. This effect has been demonstrated in static conditions<sup>30, 32, 33</sup> indicating that it is at least partly influenced by otolith stimulation. Although a typical skew deviation was not demonstrated in the upright conditions described in Chapter 5, further evaluation of its effect during head tilt to earth fixed targets in upright and supine conditions may provide additional information to assist in understanding the vertical shifts that were found in that experiment.



The following experiment was designed to determine whether the effect of otolith induced torsion contributes to the accuracy of binocular fixation by assessing:

1. The vertical and horizontal position of the eyes with the head straight and tilted to either side under both upright and supine conditions
2. The accuracy of horizontal vergence under each of these conditions.

## **Method**

### **Subjects**

All subjects were young university students between 18 and 25 years of age with ocular motility and visual standards the same as for the previous experiments. Twenty five subjects fitted the required criteria and gave suitable recordings in each condition.

### **Equipment**

The recording system (VidEyO) is outlined in Chapter 3 and horizontal and vertical eye movements were recorded and quantified. As for all experiments in this thesis, assessment was made of the position and accuracy of binocular fixation, the dynamics of the eye movements were not evaluated.

### **Calibration**

The calibration method was the same as that used for the previous two experiments, that is, monocular fixations were made for 5 seconds duration on a two laterally placed targets. However for this experiment targets were set at 160 cm from the subject (see below), with the lateral target placed 28 cm to the temporal side of the central target to induced a 10° movement. As for each of the previous experiments, all calibration fixations were observed on the computer screen and accepted only if they were steady and not affected by blinks.

### **Procedure**

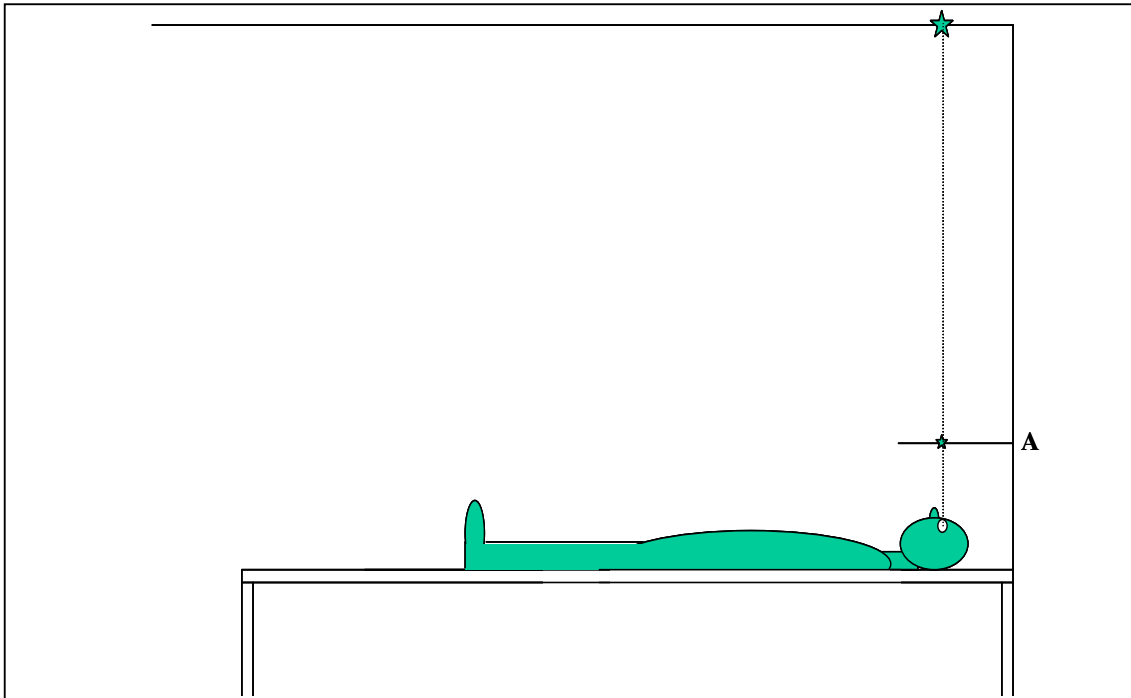
Condition 1: In the first condition the subject was seated upright and the distance from the rotation point of the bite bar to the level of the eyes was measured. The bite bar that could be rotated to specific angles was the same as that used for the previous experiment. The far target that was similar to that used in the previous experiments was placed on the midline on a white screen, 160 cm away. The lateral stars of the same size were placed 14 cm and 28 cm from the midline to subtend angles of 5° (for the experimental protocol) and 10° (for calibration). The near target was another star, the same as that used for the previous experiments. The position of this target was determined subjectively by the subject using physiological diplopia (as described in Chapter 4) by fixing on the far target and aligning the diplopic images of the near target with the inner lateral stars. The height of the near target was adjusted until it was subjectively determined to be level with the far target.

As this experiment involved assessment of the accuracy of binocular alignment, it was necessary to determine the position of the eyes for both far and near fixations that represented bifoveal fixation. This would be very difficult to accurately predict for different subjects, especially during head tilt, so the assumption was made, (as for the first experiment) that monocular fixations on detailed targets represented foveal fixation, and that any variation from these positions under conditions of binocular vision represented a vergence error<sup>93-96</sup>. For this experiment the principle was incorporated into the eye movement recordings, by having the subject first make monocular changes of fixation with each eye, then binocular changes, during each vergence condition. Any difference between the measures of binocular and monocular fixations was considered to be a fixation error and the sum of the right and left eye fixation errors represented vergence errors.

Horizontal and vertical eye movements were recorded while the subject made changes of fixation from the far to the near target at a rate of 0.5 Hz (as for previous experiments). For monocular measurements the examiner covered the other eye with an occluder that was sufficiently large to prevent peripheral fusion. The occluder was then removed to record binocular movements. This condition was very similar to that when a near target was present in the experiment reported in Chapter 5, except that in this case monocular fixations were also measured, and the device to hold the near star was different. Three separate recordings were made, one with the head straight, and the other two with the head tilted 15° to either side. This was achieved by rotating the bite bar as described in Chapter 5. The subject was asked to report diplopia of a fixated target if this occurred.

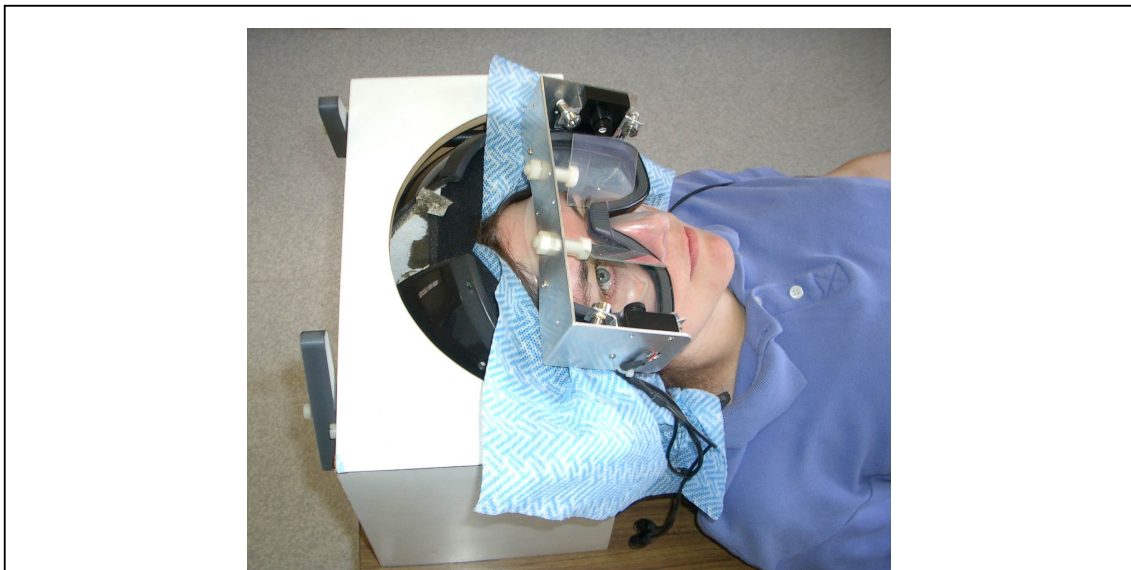
Condition 2: In the second condition the subject lay supine on a bench. A screen, identical to that used in the upright condition, was placed on the ceiling of the laboratory 160cm above the subject (this height of the ceiling from the subject was the reason why 160 cm was used for the far target in the upright condition). The near target was also suspended above the subject and its height adjusted by the examiner using the physiological diplopia method described above (see Figure 6.1).

For this supine condition the head was held firmly in a motor cycle helmet that had been split vertically, but could then be tightened to produce a firm fit. This helmet was encased in a three sided wooden box-like holder (Figure 6.2). Care was taken that the head mounted eye movement device did not touch the sides of this device.



**Figure 6.1 Representation of the supine condition (not to scale).**

The subject lies on a bench, the far target (larger star) is fixed to the ceiling 160 cm away. The near target (smaller star) is on an adjustable rod (A). When the subject is looking at the far star the rod is moved up or down until the diplopic images of the near star are aligned with two lateral stars that subtend  $5^\circ$  for each eye (see text). The head holder and eye movement equipment are not shown.

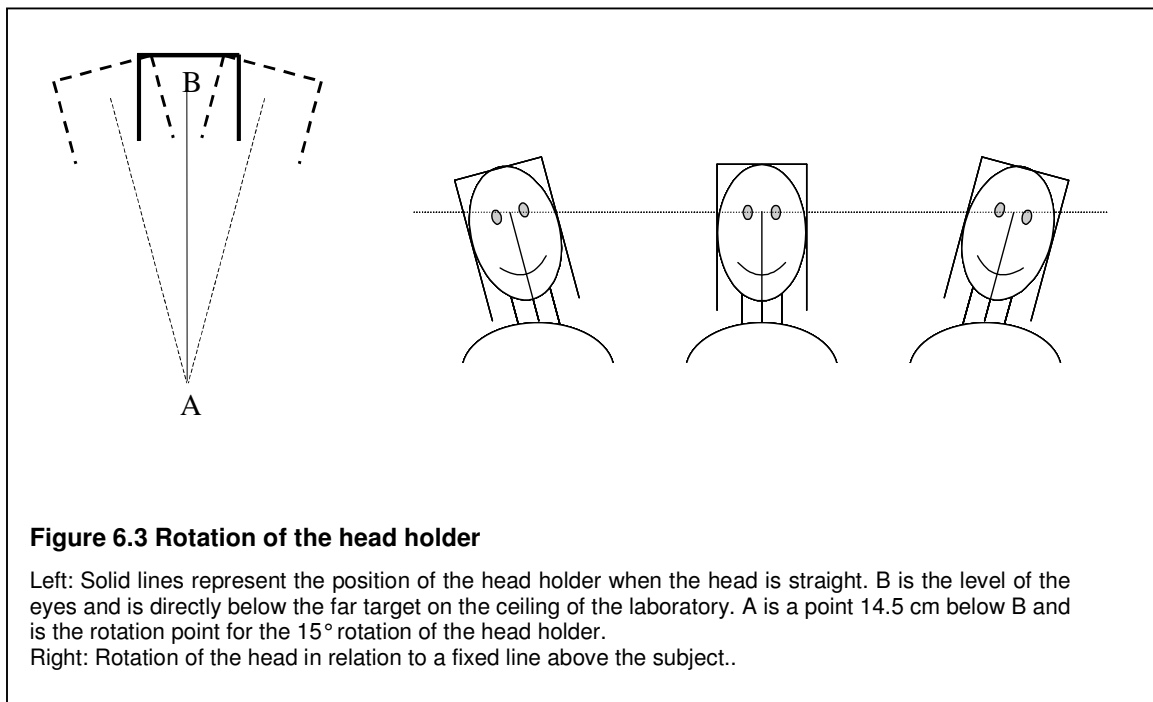


**Figure 6.2 The head holder for the supine condition.**

Head holder for supine testing. The subject's head is in a motor cycle helmet that has been fitted into the box like holder. The helmet has been split vertically but can be tightened by the levers at the back of the box. The box can then be rotated to tilt positions.

Prior to the experiment a plumb line had been used to mark the point on the bench that was directly in line with the far fixation target. A second mark 14.5 cms below this was made to represent the average distance from the rotation point of the bite bar to the eyes (long axis). The value of 14.5 cm had been found from the 13 subjects in Chapter 5 (and confirmed by another six subjects from an unreported pilot study). The outline of the helmet holder was drawn on the bench, firstly with it positioned straight, then with it rotated 15° to either side from the mark that represented the point of rotation. (Figure 6.3).

This enabled the experimenter to position the head in a tilt that was very similar to that in the upright condition. It is acknowledged that the amount of lateral translation would differ for subjects if the length of the long axis was not exactly 14.5 cm, however this difference would be small (the standard deviation from the previous experiment was 0.7 cm) and, in any case would not affect the measurement of vergence errors, as these were calculated from individual differences between the monocular and binocular measurements.



The procedures for calibration and measurement were the same as for the upright condition. The order of upright/supine conditions, and the head position was varied between subjects.

During each recording the subject changed fixation from the far to the near target four times at a rate of approximately 0.5 Hz, as for previous experiments.

### Analysis

The recordings were analysed as described in Chapter 3, although the difference between the binocular and monocular condition was calculated for each eye (right eye and left eye fixation

errors), and the sum of these gave the vergence error. Over-convergence was expressed as positive and under-convergence was expressed as negative. Vertical eye movements were expressed as as positive if the eye was above the midline, and negative if it was below the midline.

Head tilts to the subject's right are described as right ear down (RED) and those to the subject's left are described as left ear down (LED) .

The level of significance was set at  $p < 0.05$

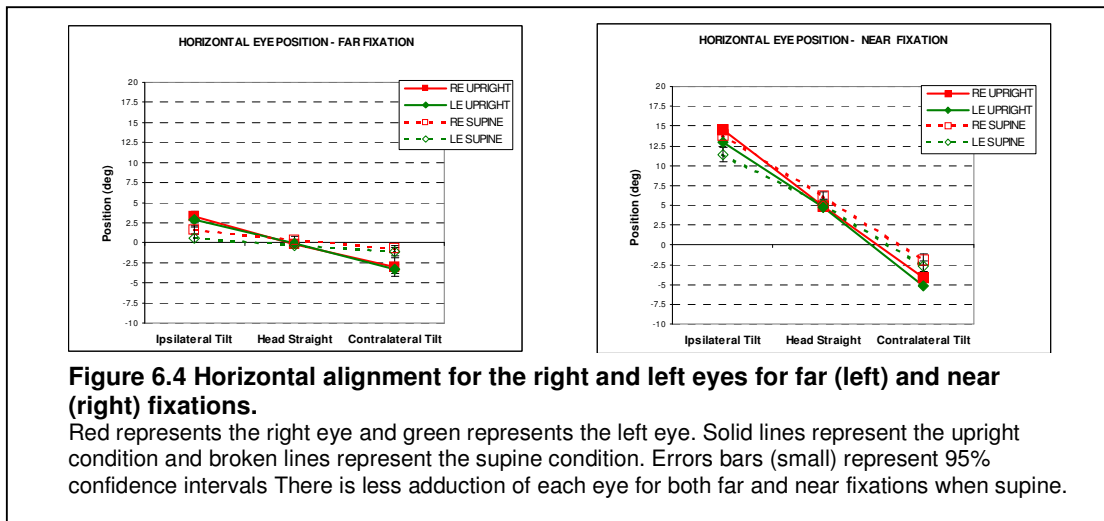
## Results

The mean distance from the point of rotation to the level of the eyes (A-B in Figure 6.3) was 14.6 cm, with a range from 14cm to 16 cm. The average inter-pupillary distance was 62.6mm with a standard deviation of 2.9mm. Of the 25 subjects, the left eye failed at the convergence near point in 22 subjects, two subjects did not show a preference, and in only one subject the right eye consistently failed.

### Horizontal alignment

#### Horizontal position

Figure 6.4 shows the horizontal position of each eye during binocular viewing. Data from condition 1 (upright) are shown as a continuous line, those from condition 2 (supine) are shown as a broken line, Mean values for these data (in arc minutes) are shown in Table 6.1 along with the results of a t test for any significant differences between the upright and supine conditions Table 6.2). Raw data are presented in Appendix 6A..



It can be seen that there are small but significant differences between the upright and supine conditions. There is a smaller lateral shift of each eye to fixate for both far and near when supine. These reach statistical significance for each eye (particularly the right) in many positions. Significant differences in vergence occur for near fixations with the head straight and tilted RED, and for far fixations with the head straight (Near: Head straight  $F_{1,24} = 28.16$   $p = 0.000$ , RED  $F_{1,24} = 10.83$   $p = 0.003$ . Far: Head straight  $F_{1,24} = 5.04$   $p = 0.034$ ).

**Table 6.1**

Horizontal position (in degrees) of each eye in each condition (Head straight, tilt to same side (ipsilateral), and tilt to opposite side (contralateral tilt)).

		UPRIGHT			SUPINE		
		Ipsilateral Tilt	Head Straight	Contralateral Tilt	Ipsilateral Tilt	Head Straight	Contralateral Tilt
<b>Right Eye</b>							
Far fixation	Mean	3.26	-0.25	-3.06	1.61	0.36	-0.77
	St Dev	1.58	1.06	2.93	1.29	1.01	1.17
Near Fixation	Mean	14.51	4.92	-4.12	13.87	6.20	-1.90
	St Dev	1.52	0.97	2.92	2.35	1.31	1.82
<b>Left Eye</b>							
Far fixation	Mean	2.91	-0.07	-3.25	0.56	-0.32	-1.09
	St Dev	2.34	0.64	1.38	1.31	1.20	1.32
Near Fixation	Mean	12.96	4.78	-5.12	11.39	5.07	-2.71
	St Dev	2.72	0.99	1.26	2.18	1.70	1.78

**Table 6.2**

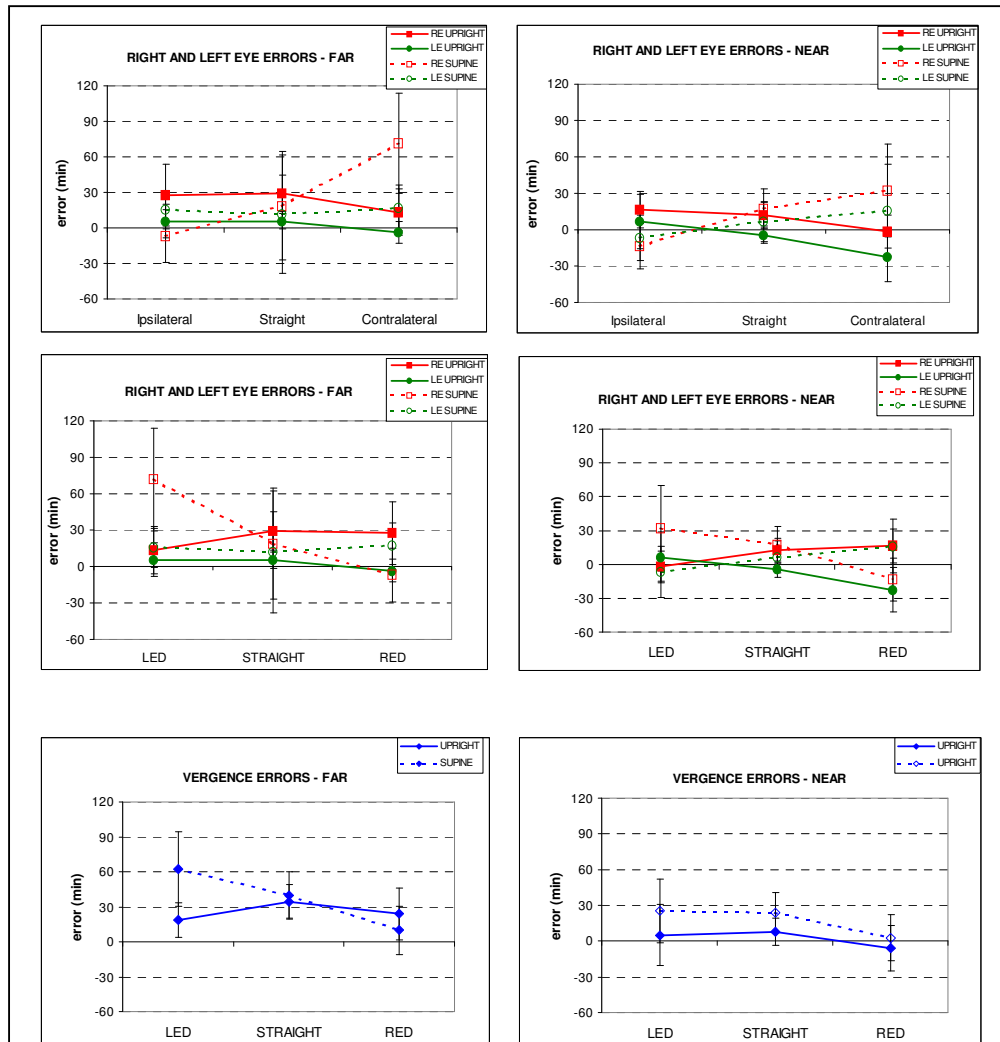
Difference between the horizontal position of the eyes (Students t test) in the upright and supine conditions for near and far fixations. There are highly significant difference in monocular fixations in many positions, but significant errors in vergence occur for near fixations with the head straight and tilted RED, and for far fixations with the head straight.

NEAR		Right eye	Left eye	Vergence
Head straight	F	16.702	0.869	28.164
	df	24	24	24
	p	<b>0.000</b>	0.361	<b>0.000</b>
LED	F	8.397	5.793	1.196
	df	24	24	24
	p	<b>0.008</b>	0.024	0.285
RED	F	2.091	32.697	10.832
	df	24	24	24
	p	0.161	<b>0.000</b>	<b>0.003</b>

FAR		Right eye	Left eye	Vergence
Head straight	F	7.057	0.851	5.041
	df	24	24	24
	p	<b>0.014</b>	0.365	<b>0.034</b>
LED	F	12.853	20.028	0.042
	df	24	24	24
	p	<b>0.001</b>	<b>0.000</b>	0.840
RED	F	19.653	49.920	3.555
	df	24	24	24
	p	<b>0.000</b>	<b>0.000</b>	0.072

## Horizontal errors

Summaries of horizontal fixation errors of each eye and resulting vergence errors are illustrated in Figure 6.5 and Table 6.3. Raw data and individual charts are presented in Appendix 6B. The upper two charts in Figure 6.5 show monocular fixation errors for each eye depending on whether the tilt was to the ipsilateral or contralateral side. The lower four charts show the fixation errors for each eye, and resulting vergence errors depending on whether the tilt was right ear down or left ear down.



**Figure 6.5 Monocular fixation errors and vergence errors when upright and supine.**

Red represents the right eye and green represents the left eye, blue represents vergence. Solid lines represent the upright condition and broken lines represent the supine condition. Error bars represent 95% confidence intervals.

A: Monocular fixation errors for each eye depending on whether the tilt was to the ipsilateral or contralateral side. B: Monocular fixation errors for each eye depending on whether the tilt was left ear down (LED) or right ear down (RED). C: Vergence errors: these increase on tilting LED, this appears to be due primarily to over-convergence of the right eye.

**Table 6.3**

Student's t test for the differences between horizontal monocular fixation errors and binocular vergence errors depending on whether the subject was upright or supine (top and) middle) or whether the tilt was right or left ear down (bottom)

**UPRIGHT/SUPINE**

NEAR		Right eye	Left eye	Vergence
Head straight	F	0.655	1.538	3.243
	df	24	24	24
	p	0.426	0.227	0.084
LED	F	2.807	0.828	1.404
	df	24	24	24
	p	0.107	0.372	0.248
RED	F	6.247	6.155	0.228
	DF	24	24	24
	p	<b>0.020</b>	<b>0.021</b>	0.638

FAR		Right eye	Left eye	Vergence
Head straight	F	0.252	0.057	0.386
	df	24	24	24
	p	0.620	0.814	0.540
LED	F	6.259	0.876	6.296
	df	24	24	24
	p	<b>0.020</b>	0.359	<b>0.019</b>
RED	F	3.632	3.869	0.394
	df	24	24	24
	p	0.069	0.061	0.536

**RED/LED**

		Right eye	Left eye	Vergence
Upright Near	F	3.746	4.070	0.477
	df	24	24	24
	p	0.065	<b>0.055</b>	0.496
Upright Far	F	1.580	1.952	0.289
	df	24	24	24
	p	0.221	0.175	0.596
Supine Near	F	5.364	1.786	2.554
	df	24	24	24
	p	<b>0.029</b>	0.194	0.123
Supine Far	F	10.536	0.029	7.789
	df	24	24	24
	p	<b>0.003</b>	0.866	<b>0.010</b>

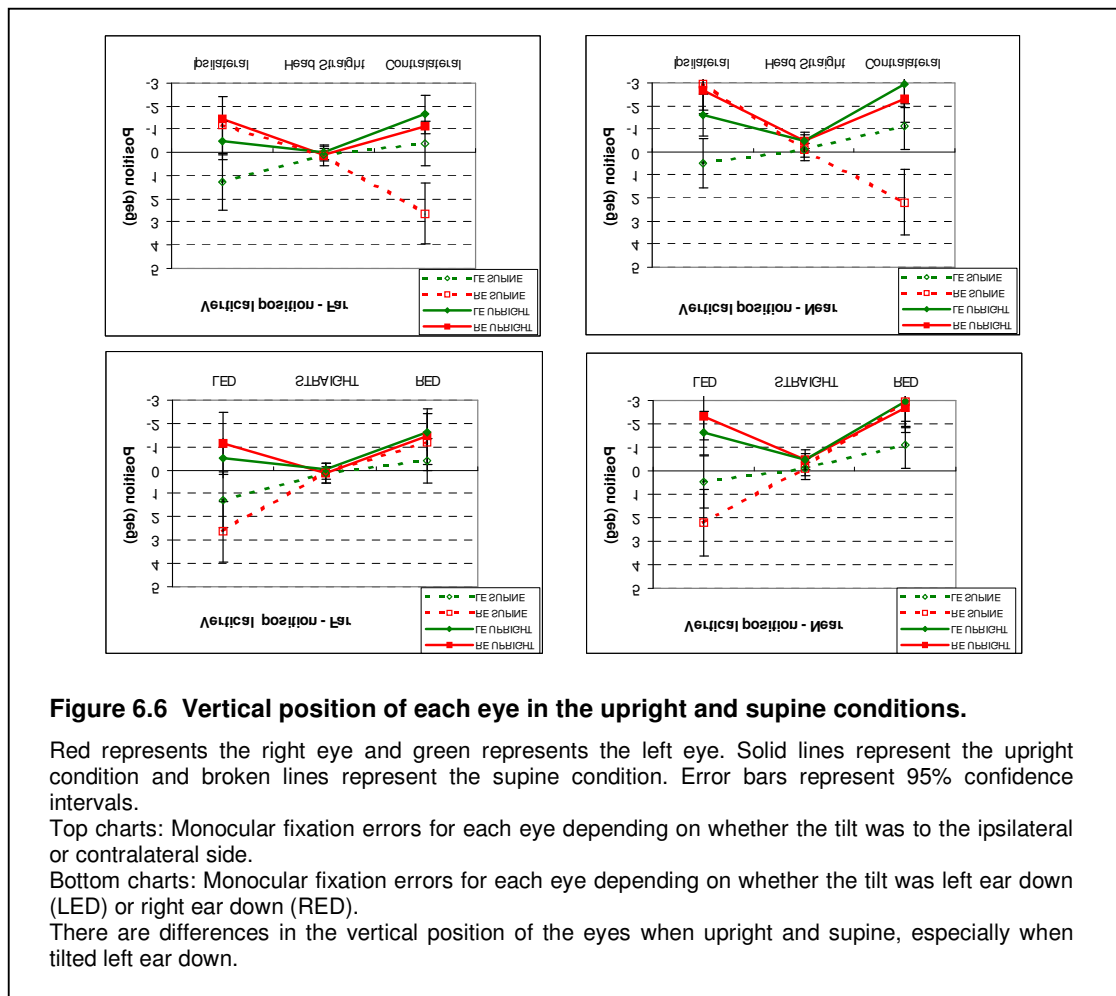
These data show that while there are horizontal monocular fixation errors on tilting to the right and left, the only significant difference in vergence errors between the upright and supine conditions occurred for far fixation when and tilting left ear down ( $F_{1,24} = 6.3$ ,  $p = 0.02$ ).



Figure 6.5 shows that this was due to failure of the right eye to diverge sufficiently. This effect is also shown by the significant differences in vergence errors for far fixations between tilting right ear down and left ear down ( $F_{1,24} = 7.8, p = 0.01$ ). This appears to be caused by over-convergence of the right eye. There is a similar pattern for near fixations, but this does not reach statistical significance.

### Vertical alignment

The vertical position of each eye during binocular vision is shown in Figures 6.6, and Table 6.4. Raw data are presented in Appendix 6C. There are clear differences in the position of eyes between the upright and supine conditions when the head is tilted, but not when the head is straight. Two different t tests were carried out depending on whether the tilt was to the ipsilateral or contralateral side, or whether it was with the head tilted right ear down or left ear down. The results are shown in Table 6.5, where it can be seen that differences in vertical position are more consistent when the subject is tilted left ear down.



**Table 6.4**  
Vertical alignment of each eye in each tilt condition

		UPRIGHT			SUPINE		
		LED	Straight	RED	LED	Straight	RED
<b>Right Eye</b>							
Far fixation	Mean	-1.14	0.11	-1.44	2.64	0.13	-1.19
	St Dev	2.44	0.56	2.05	3.35	1.07	3.08
Near Fixation	Mean	-2.32	-0.45	-2.67	2.20	-0.08	-2.97
	St Dev	2.58	0.72	2.18	3.62	1.18	3.28
<b>Left Eye</b>							
Far fixation	Mean	-0.50	-0.01	-1.64	1.28	0.11	-0.39
	St Dev	2.11	0.79	2.10	3.07	0.68	2.45
Near Fixation	Mean	-1.62	-0.47	-2.94	0.48	-0.08	-1.10
	St Dev	2.33	1.04	2.66	2.77	0.76	2.56

The results presented in Figure 6.6 confirm the findings from the experiment reported in Chapter 5, in that the eyes tended to move down to fixate when upright with the head tilted. However, this effect changed when the subject was supine, the effect was less when tilted right ear down and both eyes shifted *upwards* when tilted left ear down. Statistical data in Table 6.5 shows that the difference between tilting to either side in both upright and supine conditions was significant for the left eye, and was highly significant ( $p < 0.000$ ) for the right eye when tilted left ear down.

**Table 6.5**  
Student's t test analysis of the differences in the vertical alignment of each eye between the upright and supine conditions

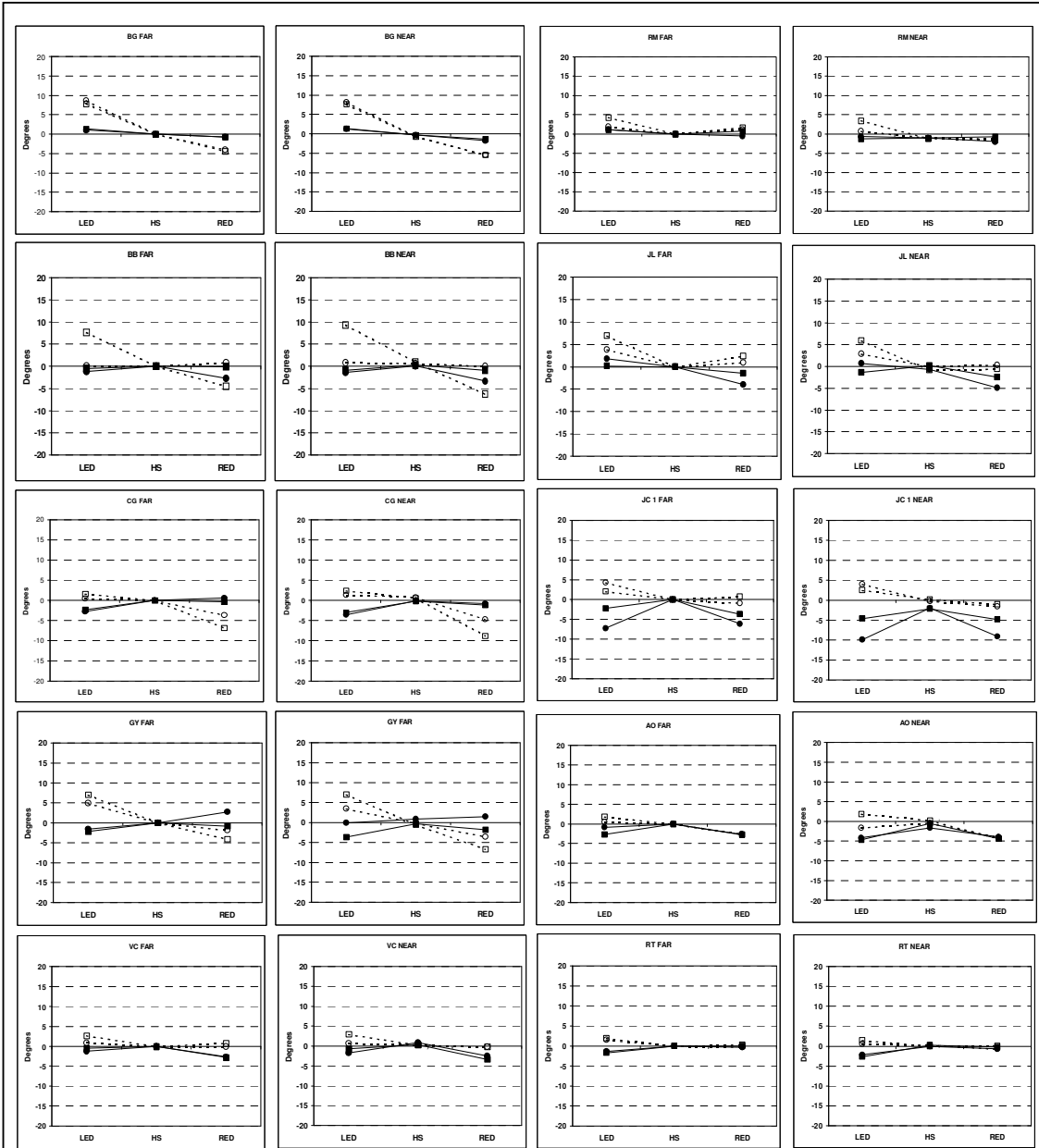
NEAR		Right eye	Left eye
Head straight	F	2.041	3.353
	df	24	24
	p	0.166	0.080
LED	F	27.377	8.323
	df	24	24
	p	<b>0.000</b>	<b>0.008</b>
RED	F	2.041	6.718
	df	24	24
	p	0.166	<b>0.016</b>
FAR		Right eye	Left eye
Head straight	F	0.016	0.367
	df	24	24
	p	0.899	0.551
LED	F	25.180	5.458
	df	24	24
	p	<b>0.000</b>	<b>0.028</b>
RED	F	0.016	4.038
	df	24	24
	p	0.899	0.056

Individual charts are presented in Figures 6.7(A) to 6.7(C) where they have been classified by the change from the upright to supine position. The charts for an individual for far and near fixations are generally very similar. In Figure 6.7(A) (ten subjects) there is little shift of the eyes on head tilt when upright, or the eyes move down slightly. However, when supine, one or usually both eyes move up when tilted left ear down and are close to, or below the midline when tilted right ear down. This is similar to the pattern found for the pooled data. In Figure 6.7(B), for seven subjects the pattern tends to be symmetrical, with the eyes moving down when upright and moving up when supine. In three subjects there is a small effect of the eyes moving down more when supine than when upright. In Figure 6.7(C) (five subjects) there is very little shift in either condition.

#### Skew deviation

If the difference between the monocular and binocular vertical fixations is considered (vertical errors) Table 6.5 shows that, once again, the left ear down position becomes relevant, in that the left eye errors are significantly more hypertropic when supine than when upright.

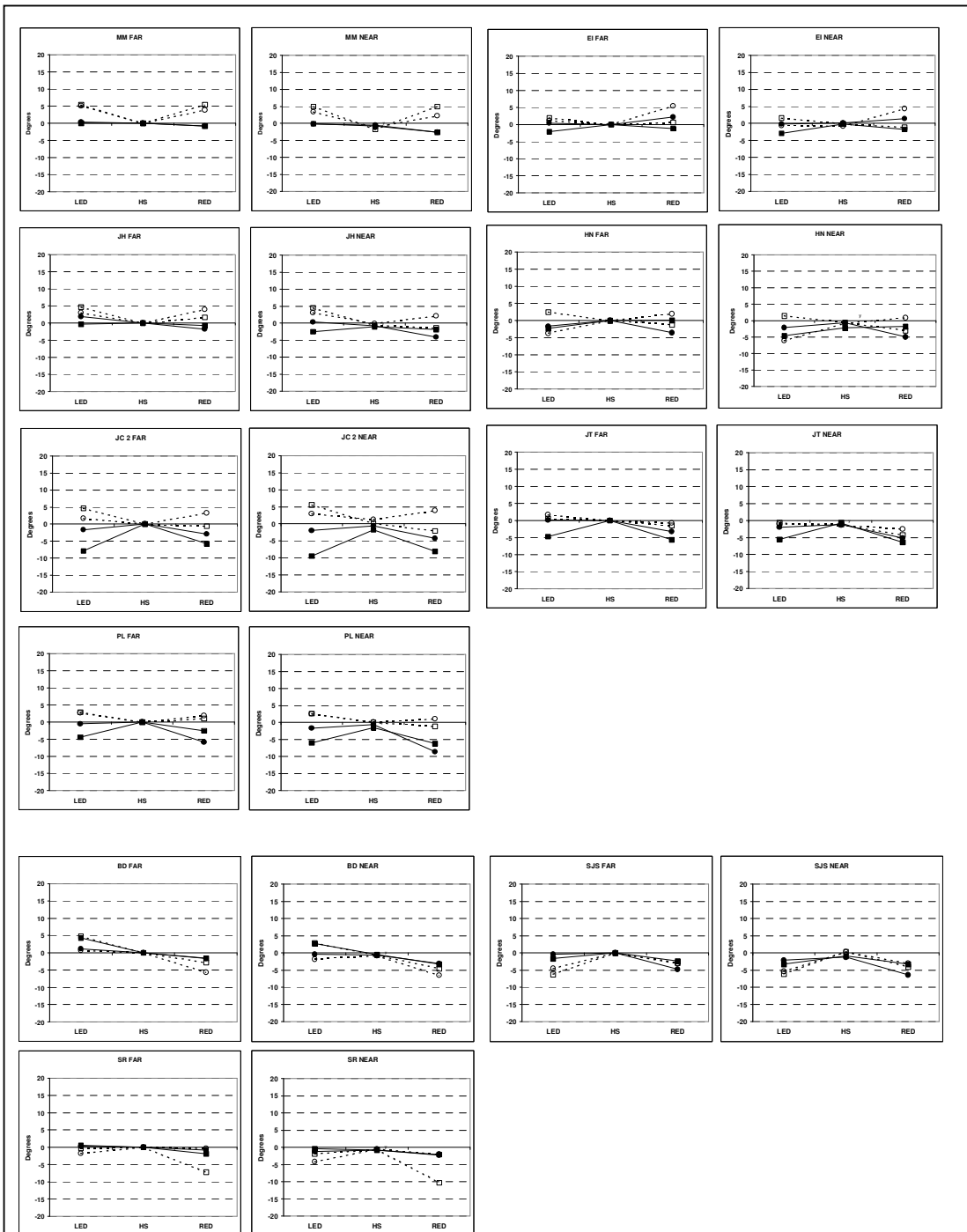
When upright, six of the twenty five subjects showed a skew deviation only on tilting to the right (the right eye higher than the left), another six showed this only on tilting to the left (left eye higher than the right) and six had a bilateral skew deviation. However, some of these differences were very small. The pooled data shown in Figure 6.6 and Table 6.6 illustrate this tendency for a skew deviation, especially when tilting left ear down, but the difference between the right and the left eye was only significantly different when tilting left ear down and for near fixations ( $F_{1,24} = 0.48$ ,  $p = 0.04$ ). However, the reverse effect, of the ipsilateral eye being lower on head tilt when the subject was supine, was highly significant when tilting left ear down for both far and near fixations (far:  $F_{1,24} = 8.6$ ,  $p = 0.001$ , near:  $F_{1,24} = 17.24$ ,  $p < 0.000$ ) and for near fixations when tilting right ear down (far:  $F_{1,24} = 13.72$ ,  $p = 0.001$ ).



**Figure 6.7(A) Individual charts: the vertical alignment of each eye. (Category 1)**

The solid lines represent the upright condition and the dotted lines represent the supine condition. Square data points represent the right eye, circles represent the left eye.

In these subjects there was little shift of the eyes on head tilt when upright, or the eyes moved down slightly. When supine, one or both eyes moved up when tilted left ear down and are close to, or below the midline when tilted right ear down.

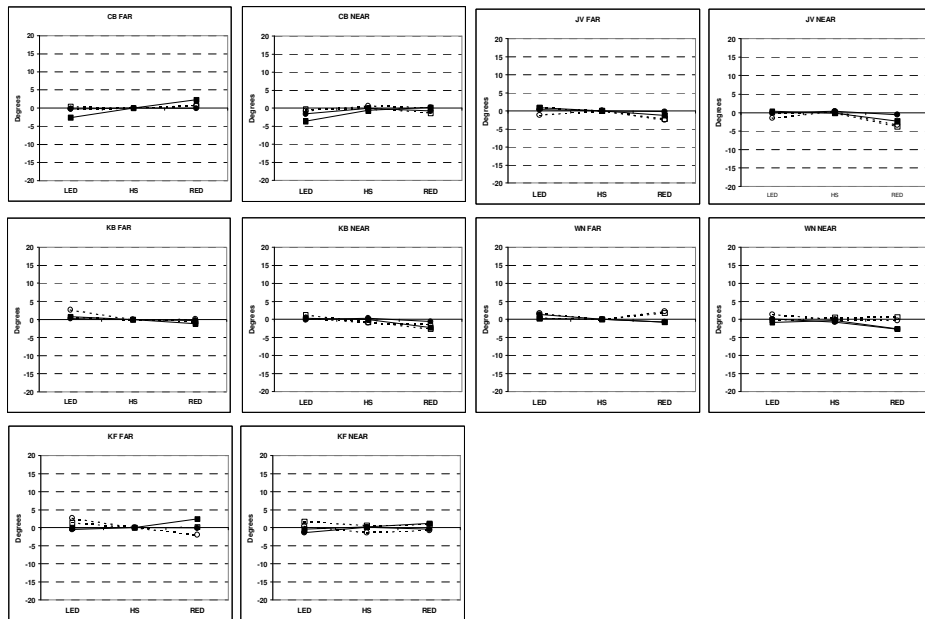


**Figure 6.7(B) Individual charts: the vertical alignment of each eye (Categories 2 & 3).**

The solid lines represent the upright condition and the dotted lines represent the supine condition. Square data points represent the right eye, circles represent the left eye.

Top seven subjects (category 2): there is a symmetrical tendency for both to move down when upright and up when supine.

Bottom three subjects (category 3): there is a small effect of the eyes moving down more when supine than when upright.



**Figure 6.7(C) Individual charts: the vertical alignment of each eye (Category 4).**

The solid lines represent the upright condition and the dotted lines represent the supine condition. Square data points represent the right eye, circles represent the left eye. In these subjects there was little or no vertical shift when upright or supine

**Table 6.5**

Student's t test for the differences between vertical monocular fixation errors depending on whether the subject was upright or supine (left) or whether the tilt was right or left ear down (right)

UPRIGHT/SUPINE		RE	LE
NEAR	Head straight	F 0.22	0.90
		df 24	24
		p 0.64	0.35
LED	Head straight	F 0.44	7.06
		df 24	24
		p 0.51	<b>0.01</b>
RED	Head straight	F 3.70	0.58
		df 24	24
		p 0.07	0.45
<hr/>			
FAR		Right eye	Left eye
Head straight		F 0.00	0.86
		df 24	24
		p 0.96	0.36
LED		F 0.00	3.18
		df 24	24
		p 0.99	0.09
RED		F 0.76	0.05
		df 24	24
		p 0.39	0.82

UPRIGHT		Right eye	Left eye
UP NEAR		F 4.12	1.18
		df 24	24
		p 0.05	0.29
UP FAR		F 0.19	0.10
		df 24.00	24.00
		p 0.67	0.76

SUPINE		Right eye	Left eye
UP NEAR		F 0.93	6.95
		df 24	24
		p 0.34	<b>0.01</b>
UP FAR		F 1.88	8.13
		df 24	24
		p 0.18	<b>0.01</b>

**Table 6.6**

Student's t test for the differences between the vertical position of each eye when upright and supine. Significant differences indicate a positive skew deviation when upright and a negative skew deviation supine (see Figure 4.6).

RE/LE

NEAR		Upright	Supine
Head straight	F	0.01	0.00
	df	24	24
	p	0.93	1.00
LED	F	4.79	17.24
	df	24	24
	p	<b>0.04</b>	<b>0.000</b>
RED	F	0.67	13.72
	df	24	24
	p	0.42	<b>0.001</b>

FAR		Right eye	Left eye
Head straight	F	0.53	0.01
	df	24	24
	p	0.47	0.94
LED	F	3.00	8.60
	df	24	24
	p	0.10	<b>0.01</b>
RED	F	0.30	2.46
	df	24	24
	p	0.59	0.13

## **Discussion**

There were several findings from this experiment.

The data for inter-pupillary distance, the length of the long axis and the eye that failed on convergence were consistent with previous experiments.

Although there are individual differences between subjects, pooled analysis of the 25 subjects show that there are significant differences in both horizontal and vertical binocular alignment of the eyes between the upright and supine conditions when the head was tilted. These seem to be dependent on the direction of head tilt, in that the differences were more likely to occur when the head was tilted left ear down. The only position where significant horizontal vergence errors occurred (tilting left ear down, when supine) was the same as that where most significant vertical effects also occurred. This suggests that the increased horizontal vergence errors were a result of the changed vertical alignment of the eyes.

It is possible that these effects were caused by artifacts in the testing situation. The difference in horizontal shift of the eyes to fixate following head tilt could have been caused by different amounts of head rotation, despite the care that was taken to ensure that it was the same in each condition. The largest differences ( $4.5^\circ$ ) occurred when the head was tilted left ear down, for near fixation. However the horizontal *errors* were also larger when tilted left ear down, reaching a significance of  $p=0.02$  ( $F_{1,24}=6.3$ ) for far fixation. As these errors were calculated from a fixed position, it is unlikely that they were caused by small differences in head position.

There were also significant differences in the vertical position of the eyes in each condition, in that the eyes appeared to shift down on head tilt when the subject was upright, confirming the results reported in Chapter 5. This effect was reversed when the subject was supine, especially when tilted left ear down. This upward shift may have also been caused by artifacts, either that the head was not rotated correctly when supine, especially to the left, or that the head holder caused the head mounted eye movement recording device to shift. These are unlikely, for the following reasons:

Rotating the head apparently caused the eyes to move down when the subject was upright. As this final position represents foveal fixation, it implies that the experimental condition caused an initial upright shift of the eyes and a subsequent downward fixation movement. Assuming that this is the 'correct' result, an artifact causing the opposite effect would have to be caused by initially inducing a downward shift of the eyes, either by allowing the subject to tilt the chin down or by causing the head to be pushed down along the Z axis, with a subsequent corrective upward movement. Either of these would have been unlikely – it would



be uncomfortable for the subject to achieve either of these positions when supine, and the firm helmet was designed to prevent any uncontrolled head movement.

Particular care was taken that the head mounted recording device did not touch the sides of the box-like helmet holder, although the straps that held the recording device were, of course, in contact with the inside of the helmet. Movement of the head or the straps independent of the helmet may have caused some artifacts. This was unlikely, firstly because the helmet had been modified to produce a very firm fit, and secondly because this effect would probably occur on head tilt to each side – not just the left.

Vertical fixation errors (the difference between the vertical component of monocular and binocular fixations) were also greatest in the left ear down position. The same logic can be applied as above (for differences in horizontal position) in that as these errors were calculated from a fixed position it is unlikely that they were caused by artifacts in the method used to determine this position.

If the findings were not caused by artifacts, what caused the unexpected vertical alignment on head tilt, and the differences in the upright and supine conditions?

Apart from the downward shift on head tilt when the subject was upright there was also a small effect of vertical divergence, with the eye on the same side as the tilt being higher, and the eye on the opposite side to the tilt being lower, an apparent 'skew deviation'. This has been reported by others during both dynamic<sup>29, 31, 33</sup> and static<sup>30, 32</sup> head tilts in normal subjects. However, this difference did not reach statistical significance apart from the left ear down tilt condition for near fixation ( $F_{1,24}=4.8, p=0.04$ ). (See Table 6.6).

In the supine condition, there were intriguing differences. The downward shift was much reduced when tilted right ear down and became a more pronounced *upward* shift when tilted left ear down. There was also 'reverse' skew (the ipsilateral eye being lower) on tilt to either side.

Several studies have investigated vertical vergence associated with torsional eye movements. Jauregui-Renaud, Faldon, Clarke, Bronstein and Gresty<sup>31, 142</sup> used dynamic roll oscillation of both 0.4 Hz and 1 Hz to demonstrate slow phase positive skew deviations. These occurred when the subject was both upright and supine. At the slower rotation when upright (0.4 Hz) two of the three subjects showed increased skew, suggesting an otolith contribution to the phenomenon. The skew deviation was greater when a fixation target was introduced.

In these experiments subjects were oscillated in darkness (without a fixation target) about earth-horizontal axes oriented at 20° and 40° from the mid sagittal plane. With this laterally

displaced rotation axis there was a significant effect on the slow phase skew deviation. When the axis was displaced to the opposite side of the tilt, both eyes had slow phases downwards, but the ipsilateral eye moved downwards more slowly than the contralateral eye.

The authors postulated that, as the subjects rotated about an axis with nose 40° to one side then semicircular canal activation of the right posterior canal and left anterior canal would cause stimulation of specific extraocular muscles. When there was a roll to the right shoulder, the primary vestibular projections would be to the right superior oblique and the left inferior rectus muscles. This would produce the required laevotorsion of each eye. However, due to the anatomically different muscle axes of the oblique and rectus muscles, the left inferior rectus would have a greater depressing effect than the right superior oblique, producing asymmetrical depression (L>R). The similar effect would occur for roll to left shoulder, producing a positive skew and depression of each eye.

Bergamin and Straumann<sup>29</sup> oscillated human subjects about the naso-occipital axis while they fixed targets 1.4 m and 0.25m along the horizontal head-fixed meridian, as well as when the eyes were directed both straight ahead and to the right. They showed that the angular eye velocity included a vertical component (positive skew) that increased with the horizontal eccentricity of the line-of-sight, and also increased for near fixation. There was also a marked gain reduction of the torsional VOR between viewing the far and the near targets.

They hypothesised that during binocular fixation of head-fixed targets in right gaze, if the rotation axis did not coincide with the line of sight but instead stayed parallel with the naso-occipital axis, then ocular counter-roll to the same side would move the fovea mainly upwards unless there was a corrective downward movement to maintain foveal fixation. To support this they demonstrated a small vertical divergence of the eyes (positive skew) on roll to the right during convergence on a target that was aligned with the right eye, however there was little evidence of this during roll tilt for far fixation with the eyes directed to the right

Kori, Schmid-Priscoveanu and Straumann<sup>32</sup> controlled for factors related to lateral shift of the eye (and therefore a possible change in rotation axis) by measuring vertical divergence and ocular counter-roll in normal subjects evoked by whole body position steps about the roll axis of the head, in both upright and supine conditions. Dynamic movements were based on angular velocity vectors measured 120ms after the beginning of rotation and static responses were measured 4s after the beginning of rotation. Similar disconjugate dynamic vertical movements (positive skew) were elicited when upright and supine, but the static vertical divergence was much smaller when supine than when upright. This was consistent with a smaller gain (less than half) of static compared with dynamic ocular counter-roll. From these results the authors concluded that there is no significant increase in vertical divergence from otolith input, possibly due to semicircular canal stimulation having a greater effect on the

vertical rectus muscles and the utricular stimulation having a greater effect on the oblique muscles, as was suggested by Suzuki, Tokumasu and Goto from studies on cats<sup>143</sup>.

The authors postulate that, because the vertical action of the vertical rectus muscles is greater than that of the oblique muscles, when the subject tilts to either side, the ipsilateral intorting superior rectus drives the eye upwards, and the extorting contralateral inferior rectus drives the eye downwards, resulting in vertical divergence.

In most of the above experiments the testing was carried out under primarily dynamic conditions, demonstrating the influence of the semicircular canals on ocular counter-roll and skew deviation. Betts, Curthoys and Todd<sup>30</sup> measured the position of the eyes on static roll tilt (30° to 90°) in normal subjects and demonstrated a consistent positive skew deviation that increased for near fixation.

Although the conditions of the above studies differ from those in the current experiment, they do show results that are consistent with the findings in the upright condition, in that they confirm a positive skew deviation and downward displacement of each eye, both of which increase on convergence.

Enright has shown that prism induced vertical vergence is associated with conjugate cyclotorsion (with the eyes rotating in the same direction as the higher eye) and lateral translation of the eyes<sup>45</sup>. The association between vertical vergence, conjugate torsion and lateral globe translation that Enright's experiment revealed were also present in this experiment and may, in part, explain the consistent pattern of downward shifts of the eyes on tilt when the subject is upright.

There are therefore several possible explanations for the skew deviation and downward displacement of the eyes on head tilt under static conditions using an earth fixed target.

- That skew deviation is simply a vestigial response to a phylogenetically old reflex<sup>10</sup>
- That the downward displacement is due to the need for foveal fixation following the upward displacement of each fovea if the rotation axis is about the naso-occipital axis<sup>29</sup>
- That the positive skew due to the need for foveal fixation following the upward displacement of each fovea if the rotation axis is about the optic axis of the eyes<sup>142</sup>
- That the downward displacement and positive skew it is due to the unequal vertical actions of the extraocular muscles associated with ocular counter-roll and lateral displacement of the eyes<sup>142</sup>.
- That the positive skew is due to the greater vertical actions of the vertical recti over the oblique extraocular muscles during ocular counter-roll<sup>32</sup>.

- That the downward displacement is only apparent due to the eyes rotating around the visual axis rather than the globe's center of rotation as suggested by Jauregui-Renaud et al<sup>142</sup> or possibly due to lateral translation of the globe similar to that found by Enright<sup>45</sup>.

These possibilities are, of course, not exclusive.

If, however, the skew was caused by downward displacement about the naso-occipital axis, when the eye needs to converge to fixate as suggested by Bergamin & Straumann<sup>29</sup>, then this effect should have diminished as the target became aligned with the eye, and reversed when the eye needed to abduct. A correlation between the lateral and vertical positions of the eyes in the current study showed no relationship between the two, *r* values were 0.05 or less under the eight conditions (ipsilateral and contralateral tilt, near and far fixation, when upright and supine). Therefore this explanation, while possibly appropriate under the conditions described by Bergman and Straumann cannot apply to the findings of the current study.

If, however the vertical divergence occurred because of the need to correct for rotation about the optic axis, rather than the visual axis as suggested by Jauregui-Renaud et al<sup>142</sup>, then the effect would be independent of the lateral position of the eye, and would be consistent with the tendency towards vertical divergence that increased for near fixations.

The fourth explanation, that the semicircular canal stimulation caused contraction of specific extra-ocular muscles would not apply under the static conditions of the current experiment. However, a similar explanation can be suggested. As the targets were earth fixed, on head tilt, the eyes would be shifted laterally to fixate, with the ipsilateral eye adducting and the contralateral eye abducting. This would place the intorting superior oblique of the ipsilateral eye and the extorting inferior rectus of the contralateral eye in the positions where they have their greatest vertical actions, causing downward displacement of each eye, but, as the inferior rectus has greater vertical action than the superior oblique, the ipsilateral eye would be relatively higher. This would explain both the downward displacement and tendency to vertical divergence in the current experiment.

Why, then does the apparent opposite (though asymmetrical) effect occur in the supine condition?

The vertical skew deviation under static conditions as reported by Betts et al<sup>30</sup> and Kori<sup>32</sup> was small, with the largest mean values being 1.8°. If the above analysis (based on the different vertical actions of the superior oblique and inferior rectus) is correct, one would predict a much larger vertical divergence than was found by previous research and in the current experiment.

In natural conditions this asymmetry would occur most of the time, as a normal head tilt would usually place the fixation target closer to the primary position of one eye than the other. Given the marked difference between the muscle planes for the superior oblique ( $53^\circ$ ) and the inferior rectus ( $23^\circ$ ) muscles, if both contract unopposed, the mechanical downward action of the inferior rectus would be considerably greater than the downward effect of the superior oblique, giving a much larger skew deviation than the values reported by Betts et al<sup>30</sup> and Kori<sup>32</sup>. If, however, there is a concurrent controlling mechanism, as suggested by Kori, this could be effected by an opposing action of the antagonist muscles, that is, innervation to the superior rectus of the contralateral eye and the inferior oblique of the ipsilateral eye, allowing the skew to be controlled to a smaller amount that could be overcome by vertical fusion or lie within a vertical Panum's area. The vertical vergence range is small, usually no more than  $3^\circ$  in normal subjects, and only small increases can be induced by training<sup>45-48</sup>.

This opposing action would be initiated by the same factors that initiate the ocular counter-roll, that is, vestibular input and, to a lesser extent, proprioception from the neck muscles. In the supine positions only the proprioception from the neck is still present. Actions by the antagonist muscles, the ipsilateral superior rectus and the contralateral inferior oblique would result in unopposed elevation of each eye, but particularly the ipsilateral eye (superior rectus), the effect that was found in this study. This explanation is only partly satisfactory, as the eyes still need to maintain foveal fixation, so that any tendency towards a downward shift would need to be corrected by an upward fixation movement. Another problem with an explanation that is based on extra-ocular muscle actions is that the vertical effects in this study seem to be related to the direction of head tilt and not the position of the eye in the orbit (Figure 6.6).

One explanation for the downward shifts observed in this and the previous experiment could be that the eyes are not rotating around the eye's normal center of rotation. This could be related to the small difference between the visual axis and the optic axis of the eyes (see Figure 1.1) as suggested by Jauregui-Renaud et al<sup>142</sup> who suggested that the eyes may undergo vertical translations in opposite directions when the eyes tort, however in this experiment the eyes moved in the same direction. Another possibility is that the eyes are not rotating about the centre of the globe during tilt. Demer<sup>144</sup> has shown that there is repositioning of the medial and lateral rectus pulleys during convergence when the head is straight. A similar change could occur during head tilt, and/or with lateral translation that may lead to an apparent downward movement of the eyes.

Whatever is the cause of the apparent downward shift when upright, this experiment has shown a reverse effect when supine, especially when tilting left ear down. As the only difference between the two conditions was the effect of gravity on the otolith organs, then this change must be related to the absence of otolith induced ocular counter-roll.

The overall tendency for the eyes to be higher when supine could be explained by an antagonist response that partly overcomes whatever factors cause the eyes to move down on head tilt in normal (upright) conditions. When the subject is supine, the absence of otolith induced counter-roll would remove these factors, but other cues, possibly perceptual, or proprioceptive (from the muscles of the neck) may provide information that the head is tilted, causing an imbalance in this antagonist response and cause the eyes to shift upwards.

The contribution of the neck muscles, especially the sterno-cleido-mastoid muscle (SCM) to ocular torsion is a matter of some controversy. Ott<sup>23</sup> found no difference in OCR in normal human subjects when there was a combined body and head tilt, and when only the trunk was tilted, and concluded that input from the neck muscles did not contribute to the symmetrical OCR of 2.4° to 9.5° that this study revealed.

However, other reports have shown some effect of proprioception from the muscles of the neck, particularly when normal vestibular input is reduced.

Karlberg, Aw, Black, Todd, MacDougall and Halmagyi<sup>27</sup> applied vibration to the SCM muscle and the mastoid bone in subjects with chronic unilateral vestibular defects and found maximum torsion of between 6°-7°. The torsion induced by SCM vibration was significantly larger in subjects who had loss of three semicircular canals compared with those with loss of only two semicircular canals.

de Graaf, Bekkering, Erasmus and Bles<sup>24</sup> found no influence of neck proprioception to subjective horizontal alignment or OCR in normal subjects, however the different results from subjects without labyrinthine function implied that there was a contribution from SCM proprioception.

Von Baumgarten, Kass Vogel and Wetzig<sup>28</sup>, assessed astronauts pre flight and showed that OCR was always larger when there was a lateral head tilt compared with the situation when only the body was tilted (contrary to the findings of Ott). This difference was larger in three out of four crew members after space flight. During flight, stimulation of the neck receptors in weightlessness had a weak effect on ocular torsion but it markedly influenced the perception of the subjective vertical and horizontal.

Hoffstetter-Degen, Wetzig and von Baumgarten<sup>145</sup> used subjective methods (in one subject only) to determine the effect of pure neck receptor stimulation on eye position during space flight and concluded that neck receptors do not contribute to OCR to a measurable extent. However the subjective orientation of a vertical line was perceived correctly in flight. The authors concluded that *“neck receptors on the perception level can fully substitute for the ineffective equilibrium organs of the inner ear within less than 4 days”*.

Guerraz, Luyat, Poquin and Ohlmann<sup>26</sup> had upright blindfolded subjects make adjustments to a tactile rod during head tilt and found that this alignment was rotated a few degrees in the opposite direction to the head tilt. When this task was repeated with the subjects supine this effect of rotation increased significantly, suggesting that tactile perception of orientation is affected by neck afferents.

In a subsequent experiment Guerraz, Blouin and Vercher<sup>25</sup> had blindfolded subjects draw, in the air, a previously seen geometric figure with the head straight or tilted to either side. The task was carried out first when upright, then supine. In each condition the head tilt induced rotations of the drawings, indicating that there is *“a significant contribution of neck afferents in the control of hand motion in space in the absence of vision”*.

Although the findings from these studies are not conclusive they suggest that there is little contribution from SCM proprioception to ocular counter-roll when there is head-on-neck tilt under normal conditions, but, when otolith function is compromised (from vestibular dysfunction, microgravity conditions or when supine) then input from the neck may still provide a stimulus to ocular torsion and/or subjective perceptions of the upright.

Throughout this experiment there was a pattern of statistically significant effects occurring when the head was tilted left ear down, especially when supine. Horizontal vergence errors increased, showing significantly more over-convergence errors for far fixation when supine than when upright ( $F_{1,24} = 6.35$ ,  $p = 0.02$ , Figure 6.6). There were also significantly more over-convergence errors when tilted left ear down than when tilted right ear down ( $F_{1,24} = 7.1$ ,  $p = 0.01$ ). The effect of an upward shift of the eyes when supine was present in many of the twenty five subjects, and this effect was more likely to occur when the tilt was left ear down.

There is little evidence of asymmetry in ocular counter-roll in the literature, although Guerraz, Blouin, and Vercher, in an experiment where blindfolded subjects drew, in space, remembered geometrical figures<sup>25</sup>, reported that the rotation off set was greater when the head was tilted to the right. This effect did not reach statistical significance.

Vogel and Kass<sup>146</sup> measured ocular counter-roll of astronauts pre and post flight in different positions of body tilt and reported asymmetrical effects of OCR gain between body tilt to either side. Two subjects demonstrated this asymmetry before the flight with the higher gain on tilt left ear down, and three subjects exhibited asymmetries after the flight with the higher gain tilting right ear down.

Diamond and Markham<sup>147</sup> tested four subjects who were thought to be resistant to motion sickness in parabolic flight. Three of these subjects showed no significant torsion at zero gravity in either the upright position or when tilted 30 degrees to right or left, but the other subject showed eye torsion toward his left in all positions at zero gravity. This subject became motion sick in this condition. The suggested explanation was that asymmetry of the utricular system may be well compensated in normal gravity, but may become unmasked in unaccustomed gravitational situations.

These reports are consistent with some of the findings of the current study, and suggest that the different effects when upright and supine are not due to artifacts but are related to SCM induced torsion that becomes especially evident when otolith function is reduced. Although there is no clear explanation for the asymmetrical effects that were often found, this asymmetry has also been reported by others, particularly in conditions of reduced otolith function.

### **Summary**

This experiment confirmed the apparent downward shift of the eyes on tilting the head that was reported in Chapter 5, but it also revealed that this shift changes when ocular counter-roll is absent, that is, when the subject was supine. There was also a marked difference in many of the vertical findings when the subject was supine, depending whether the head was tilted right or left ear down. These findings are consistent with other studies where vestibular input is reduced or absent. Horizontal vergence errors also increased when supine and tilting left ear down, suggesting that ocular counter-roll in natural (upright) conditions provides stability for precise vergence eye movements.

In this study the effect of ocular counter-roll was only surmised, there was no direct measurement of torsional eye movements. In order to achieve a better understanding of this phenomenon, a further study that included measurement of horizontal, vertical and torsion eye movements became necessary.



## Chapter 7

### **The influence of OCR on the accuracy of horizontal binocular alignment for far and near fixation during roll head tilt.**

#### **Introduction**

The experiment in Chapter 6 showed that when subjects were upright and had a static roll head tilt to an earth fixed target (right ear down or left ear down), there was frequently a downward movement of each eye. This effect was larger for near than for far fixations. However this result changed when the subject was supine. The downward shift on tilting right ear down was reduced, and an upward shift occurred when tilting left ear down. Horizontal vergence errors increased when tilting left ear down. These results suggest that the torsion associated with ocular counter-roll may influence the vertical alignment of the eyes and contribute to the precision of horizontal vergence eye movements.

Ocular torsion had not been directly measured in the previous head tilt experiments and its influence on horizontal and vertical eye movements could only be surmised. Horizontal and vertical movements only had been assessed in these experiments for three reasons:

- i. The overall objective of the thesis was to assess the accuracy of horizontal vergence eye movements under conditions as natural as possible. The video eye movement system that was used in these experiments is able to assess torsion by using polar cross correlation of grey level distributions around the iris, but this requires the use of pilocarpine nitrate eye drops. These act upon the ciliary muscle to constrict the pupils and prevent radial dilation of landmarks on the iris. The increased convexity of the lens that the pilocarpine nitrate induces would also affect vergence through a reduced need to accommodate, and would reduce the natural conditions of the experiments.
- ii. Most of the subjects were first year psychology students who were required to take part in approved research within the Department of Psychology. This process permitted general measures of horizontal and vertical eye movements on a relatively large number of subjects but was not suitable for the time consuming exact measurements of ocular torsion.
- iii. The VidEyeO system was originally designed to assess torsion for use with the eye at, or close to, the primary position. The infra red illumination needed to provide good contrast of the iral striations tended to induce shadows that affected the integrity of the image of the pupil

when the eye moved away from the primary position by about more than about 15°. For the experiments where measurement of torsion was not required, this illumination could be modified to give the best contrast of the pupil for horizontal and vertical shifts of up to 30°.

However, given the results from the previous experiment (Chapter 6) it was decided to repeat the experiment on a limited number of subjects using a modified system that permitted the exact measurement of torsional eye movements, and created an environment where some of the inevitable differences between the upright and supine conditions in Experiment 4 were removed.

In the following experiment, six subjects were assessed with a modified system that permitted measurement of horizontal, vertical and torsional eye movements during changes of binocular fixation during roll head tilt from far to near earth fixed targets, in both upright and supine conditions. This provided the data to determine the influence of ocular counter-roll on the accuracy of horizontal binocular alignment during head tilt.

## **Methods**

### **Subjects**

Six subjects (three male, three female) between the ages of 20 and 34 were tested. All subjects had normal ocular muscle balance and a convergence near point of 6cms or better, and visual acuity of 6/6 (equivalent) at the distance of the far target

### **Measurement**

The video eye movement system used was similar to that described in Chapter 3, however, for exact measures the eye movement recording device was attached to individual thermo plastic masks to prevent movement of the device during recording sessions (Figure 7.1). This permitted the additional measurement of torsional eye movements using polar cross correlation of grey level distributions around the iris, with compensation for geometric distortion. The sampling rate was approximately 25 Hz and the resolution was approximately  $1^{148, 104, 105}$ . Modification was made to this system by positioning the infra-red light source below and slightly temporal to the pupil when the eye was in the primary position. This position could be adjusted until satisfactory images were obtained for moderate horizontal and vertical eye movements. At the beginning of each test, a baseline recording was made of each eye monocularly in all three dimensions while subjects fixated a laser spot target on the midline at eye level 200cm away for 60 seconds. Video recordings were made of each eye separately during the experiments and were analysed off line.



**Figure 7.1 The recording device**

The recording device is attached to an individual thermoplastic mask for each subject. Video cameras are placed above the eyes. Two half silvered "hot mirrors" reflect the infra-red image of the eye to the cameras that are mounted above each eye. Each eye is illuminated from below, by two InfraRed LED emitters that are invisible to the subject, whilst infra red pass filters on the camera lenses prevented ambient light from affecting the image

### **Pitch chair**

Subjects were strapped into a chair that was fixed to a frame that could be driven by an electric motor to rotate backwards 90° so that the subject remained in a seated position but on his/her back. (Although the subject was not lying flat the word 'supine' will be used for this condition in the experiment - it is defined as "*Lying on the back, or with the face upward; -- opposed to prone*" in the Webster's Medical Desk Dictionary<sup>149</sup>.) Two straps 5cm wide were attached to the frame of the apparatus at approximately the mid level of the scapulae and were passed over the shoulders, crossed in front of the torso and fixed under the seat of the chair. Another strap was passed over the lap and fixed under the seat of the chair. A central shaft of the frame could be rotated laterally to a predetermined amount using an inclinometer for the upright condition, and by lining up an indicator on this shaft to pre-determined marks on the apparatus for the supine condition. A bite bar and an adjustable padded head support were attached to the shaft. As neither the seat of the chair nor the point of rotation of the central shaft were able to be adjusted vertically, the size of the long axis of head tilt differed depending on the height of each subject (Figure 7.2).

Two types of laser targets, with lenses that resulted in a cross hair line pattern were initially used for both far and near fixation. Two were earth fixed and did not move when the subject was tilted. The other two were head fixed and varied with the height of the subject. The positions of these head fixed targets were noted when the head was upright, then were switched off and the earth fixed targets (far and near) were moved to the corresponding positions to become the targets for the tilt conditions. This meant that the earth fixed targets could be positioned at the straight ahead position for both upright and supine conditions, regardless of the different heights of the subjects.

## Procedure

The far target was positioned on a white screen, 200 cm from the subject, similar to that used for each of the previous experiments. For this experiment the centre star was removed and the laser cross was projected onto a faint vertical line on the midline of the screen that was precisely in line with the middle shaft of the chair. The vertical position of the laser cross was adjusted until the subject confirmed that it was subjectively straight ahead. Two lateral stars were positioned 35 cm on either side of the midline to induce a 10° lateral eye movement for calibration purposes only. The near target consisted of a white vertical bar, 2 cm wide, onto which the second laser target could be projected. This was positioned 30 cm from the eyes along the midline to stimulate 10° of convergence in a subject with a 62 mm inter-pupillary distance (acknowledging that the eyes were converging 1.8° on the far fixation point 200 cm away). As for previous experiments, small differences in inter-pupillary distance would not affect measurements of vergence errors, as these errors were calculated from this fixed position. The vertical position of the near laser target was adjusted until it was subjectively determined to be at the same level as the far target. Calibration was carried out by having the subject fix with each eye separately on the far central cross for five seconds, and then the laterally placed star.

When the subject was rotated backwards to the supine position a second screen, identical to that for the upright condition, was positioned directly above the subject and at the same distance, and the far and near laser targets were positioned the same as for the upright condition.

The same assumption was made as for previous experiments, that monocular fixations on detailed targets at both near and far represented foveal fixation, and that any variation from these positions under conditions of *binocular* vision represented a vergence error<sup>93-96</sup>. The subject first made monocular changes of fixation with each eye, then binocular changes, during each test condition. Any difference between the combined measures of horizontal binocular and monocular fixations was interpreted as a vergence error.

Eye movements during four vergence changes at 0.5 Hz were made when upright, as described in Chapter 6. To produce a head tilt the bite bar was slowly rotated 15° to the right or left and the same procedure of testing was followed. After each change in head position the subject was left for 60 seconds to allow any semicircular canal input produced by the deceleration during roll-tilt to dissipate before recordings were made<sup>150</sup>. For all subjects, recordings were first made when upright, then supine, but the order of head position during each condition was varied. Separate calibrations and recordings were made for the upright and supine conditions.



**Figure 7.2 Rotation of the pitch chair**

The subject is rotated backwards from the upright position (top) to the supine condition (bottom).

As separate video recordings were made of each eye, during this procedure a 'blank' in the recording was made before each vergence condition to ensure synchronisation of the videos during the off line processing. As for the previous experiments, the standard error of the mean value for each of the four fixations for each condition was very small, so the mean value was used for further statistical analysis.

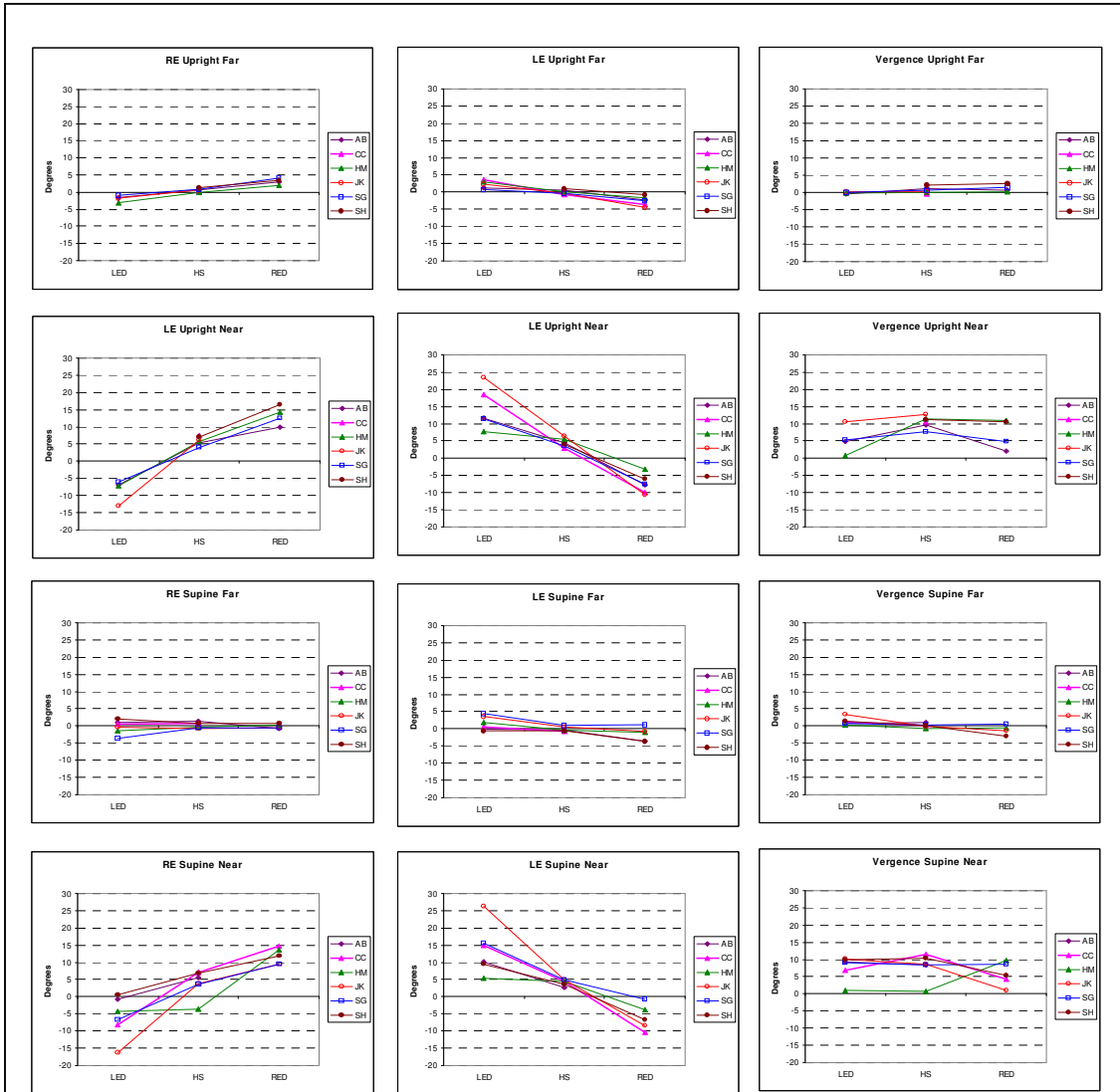
All procedures were in accord with international conventions and were approved by the University of Sydney Human Ethics Committee, and all subjects gave informed written consent and were free to withdraw at any time.

## **Results**

Recordings were obtained from all subjects; however, for some subjects the video image in some positions was unsatisfactory due to shadows affecting the image of the pupil. This usually occurred on head tilt when the ipsilateral eye had to make a large nasal-ward shift to converge. For this reason, some data points are missing on the Figures and Tables displayed.

### **Horizontal alignment**

The horizontal alignment of each eye, and resulting horizontal vergence for each subject are shown in Figure 7.3. Subject HM did not make a convergence movement to the near target on left tilt when upright, nor on left tilt or with the head straight when supine, he simply made a conjugate shift to fix with the left eye only (without diplopia). This data was not included in the further analysis of vergence errors.

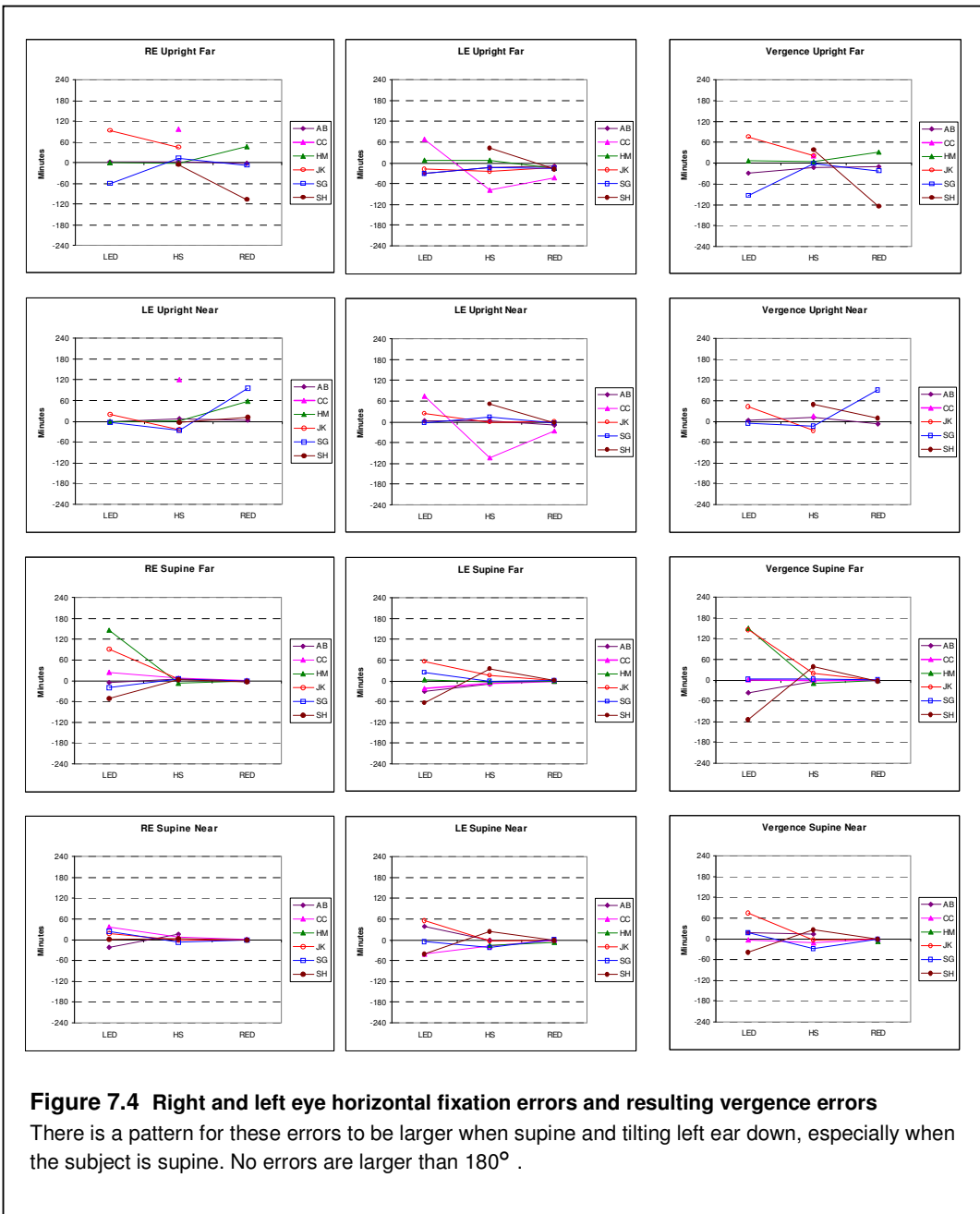


**Figure 7.3 The horizontal position of each eye (in degrees) and the resulting vergence position for each of the six subjects.**

There are individual variations in the position of the eyes on head tilt – this was probably due to the different lengths of the long axis in individual subjects as a result of their different heights. Likewise some of the differences in the amount of convergence could be explained by differences in their inter-pupillary distances.

Combined errors of horizontal vergence are shown in Figure 7.4. All are within 125' when upright and 180' when supine, these values are consistent with the errors found in the previous experiments.

These are consistently greater when tilting to the left, particularly for far fixations, and are consistent with the findings from Experiment 4.

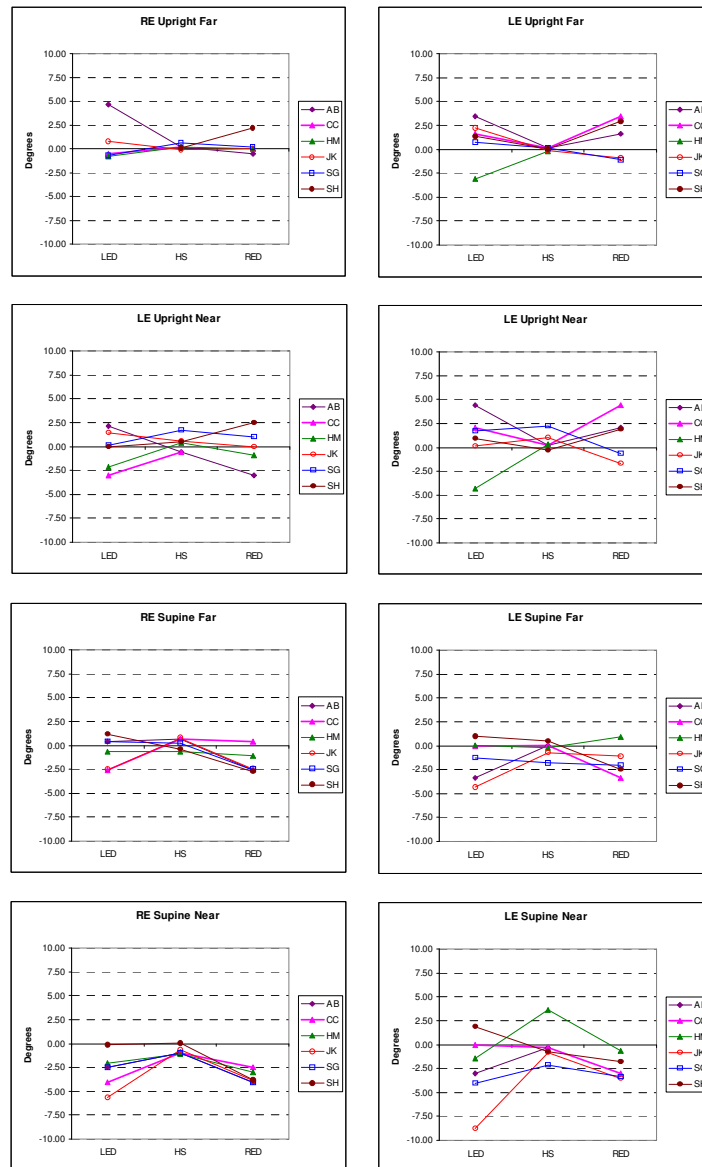


### Vertical alignment

The vertical position of each eye under all conditions is shown in Figure 7.5. Positive values indicate that the eye was higher, negative values show that it was lower. It can be seen that there is a vertical shift of the eyes on head tilt but this is idiosyncratic. Although for near there is a tendency for the eyes to move down, a pattern that was noted in Chapters 5 and 6, this does not differ when supine, if anything, the downward shift is more consistent when the subject is supine. This finding differs from the combined results from Chapter 6, but it could be due to the small number of subjects in this experiment. Individual subjects from that



experiment gave results similar to those from this experiment. Three of the six subjects (CC, HM, SG) did show a downward shift for each eye for near fixation.



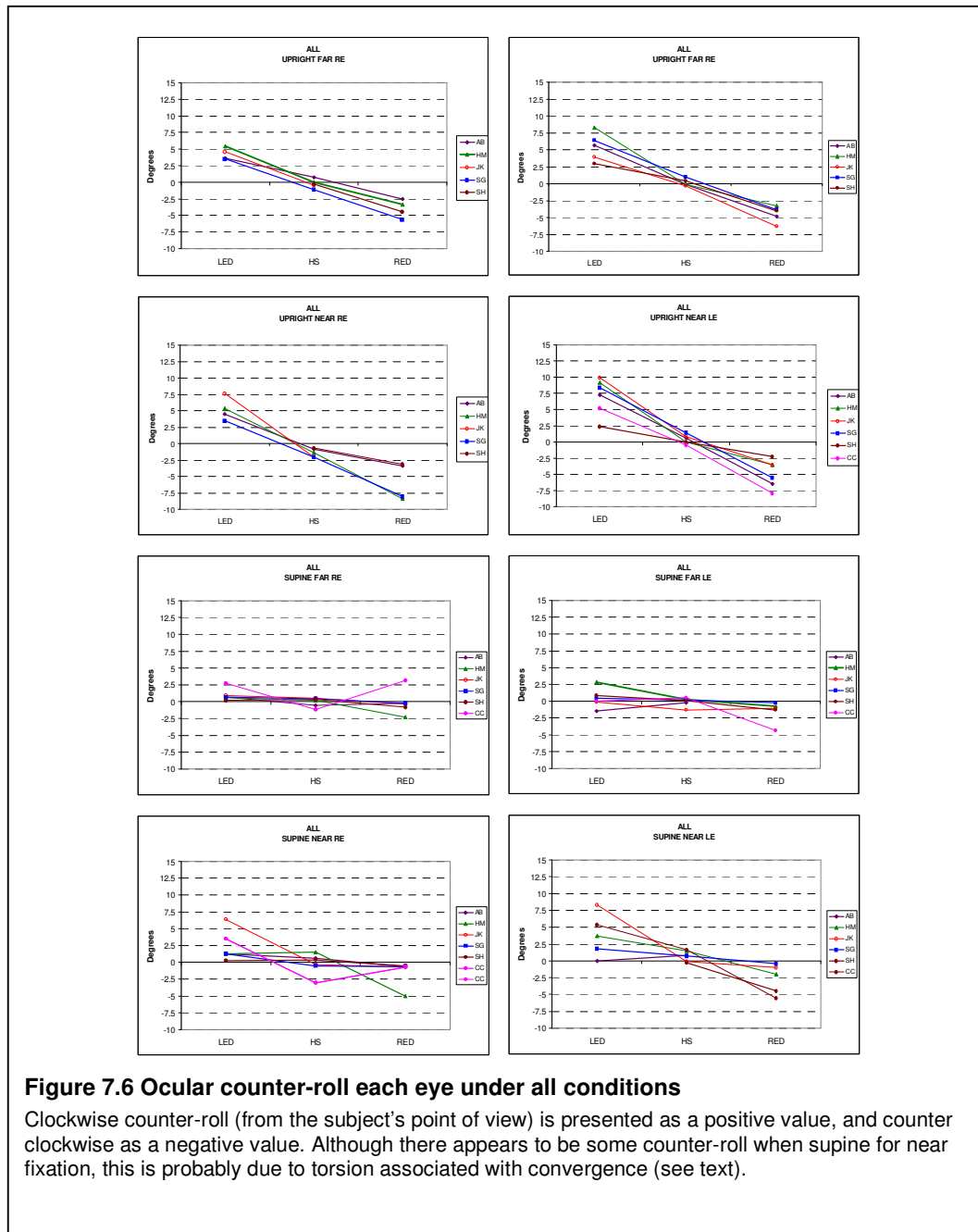
**Figure 7.5 The vertical position of each eye under all conditions**

Positive values indicate that the eye was above the midline, negative values show that it was lower. It can be seen that there is a vertical shift of the eyes on head tilt but this is idiosyncratic.

### Ocular Counter-roll – Far fixations.

The results from all subjects combined are shown in the top charts of Figure 7.6. Clockwise counter-roll (from the subject's point of view) is presented as a positive value, and counter clockwise as a negative value.

For far fixation when upright, the data are fairly consistent, showing the expected positive rotation on tilting left ear down and negative rotation on tilting right ear down. Most values are between 3° to 5°. In the supine condition are were small torsional movements on head tilt, usually less than 2°, however for subject CC this reached 4.9° on tilting right ear down.



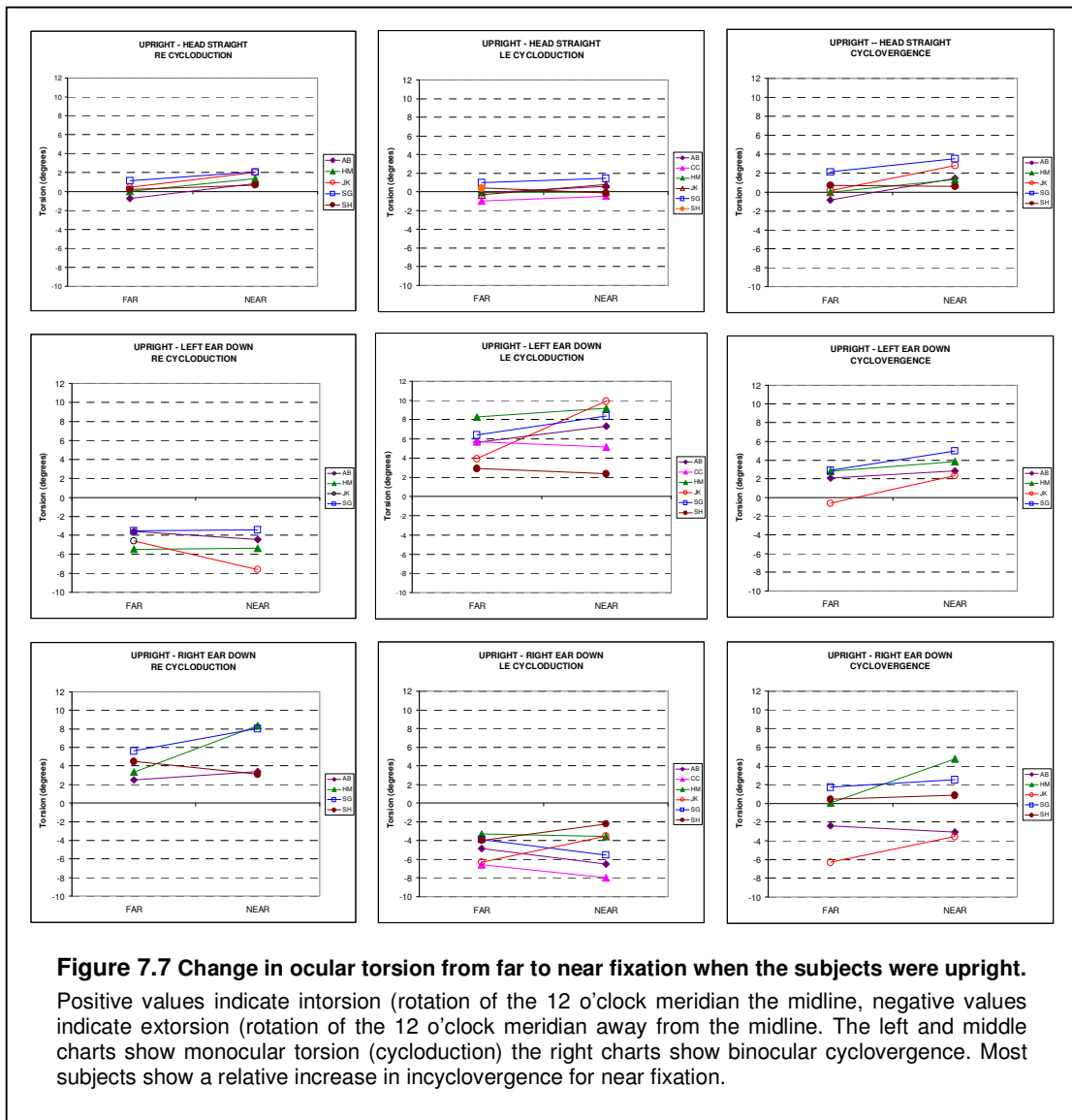
**Figure 7.6 Ocular counter-roll each eye under all conditions**

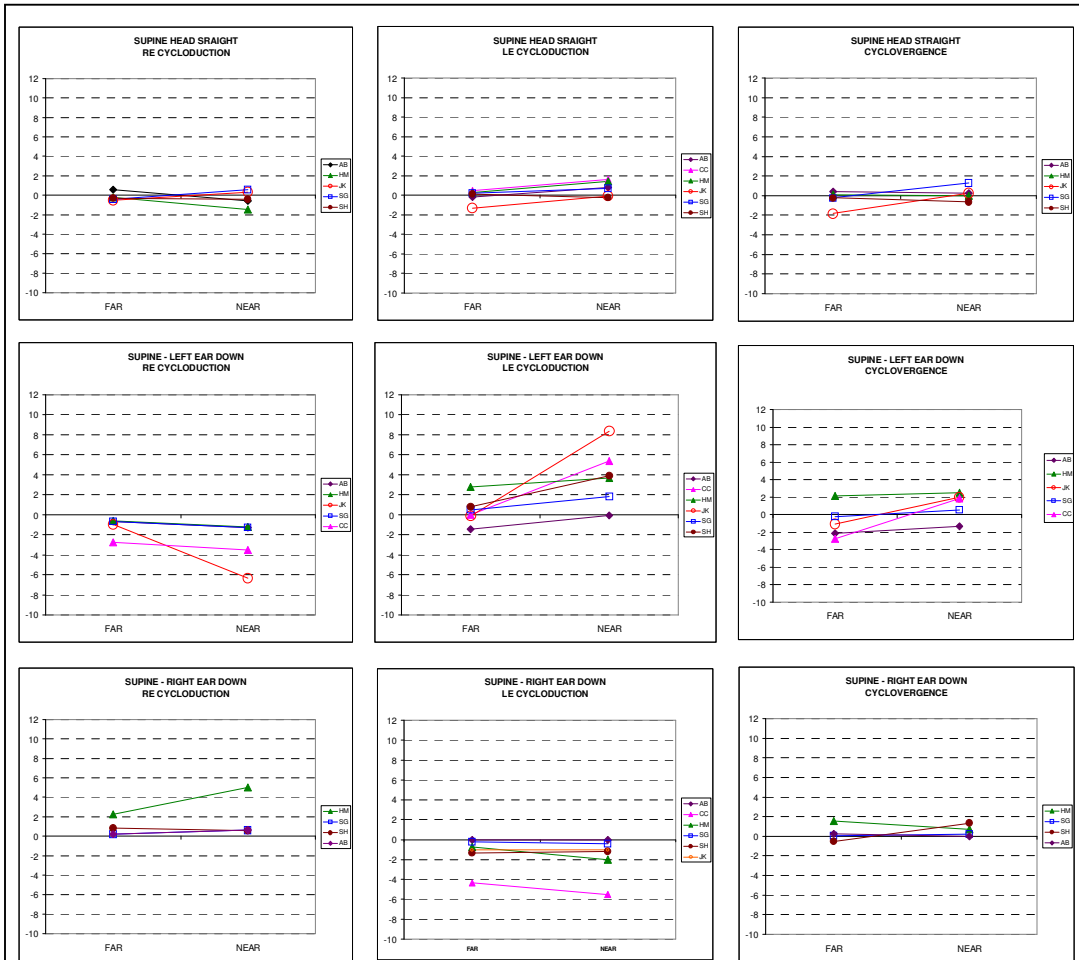
Clockwise counter-roll (from the subject's point of view) is presented as a positive value, and counter clockwise as a negative value. Although there appears to be some counter-roll when supine for near fixation, this is probably due to torsion associated with convergence (see text).

### Change in torsion – Near fixations

When the subjects were upright (top two charts of Figure 7.6) there is approximately 5° of ocular counter-roll for far fixations when tilting to either side. For near fixations there appears to be a positive shift in torsion for the right eye and a small negative shift for the left eye. When the subject was supine (bottom two charts of Figure 7.6) significant torsion occurred for near fixations, especially on tilting left ear down.

To examine this further, the data from the right eye were adjusted so that intorsion (monocular rotation of the 12 o'clock meridian of the eye towards the midline) is expressed as a positive value, and extorsion (monocular rotation of the 12 o'clock meridian away from the midline) is illustrated in Figure 7.7.





**Figure 7.8 Change in ocular torsion from far to near fixation when the subjects were supine with the head straight (top) tilted left ear down (middle) and tilted right ear down (bottom)**

Positive values indicate intorsion (rotation of the 12 o'clock meridian the midline, negative values indicate extorsion (rotation of the 12 o'clock meridian away from the midline. The left and center charts show monocular torsion (cycloduction) the right charts show binocular cyclovergence. There is a moderate increase in incyclovergence for near fixation with the head straight and tilted left ear down but not when tilted right ear down

Figure 7.7 shows that when the subjects were upright with the head straight there was a consistent small intorsion of each eye on convergence for almost all subjects, resulting in incyclovergence ranging from 0.6° (subject SH) to 3.5° (subject SG). This incyclovergence occurred when tilting right ear down and left ear down. However, it was due almost entirely to intorsion of the ipsilateral eye, the eye that had the greatest lateral shift. There was little change in the contralateral eye. A similar effect is apparent in only two subjects (SG, JK) when supine (Figure 7.8). Data showing the change in torsion from far to near fixation is presented in Table 7.1, where positive values (bold) represent a relative increase in intorsion. The values for the contralateral eye that makes a small abducting movement are generally very small.

When supine, this effect was consistent for all subjects in the tilt conditions except for subject SH, where there was a very small (0.14°) increase in intorsion of the left eye on convergence when tilted right ear down.

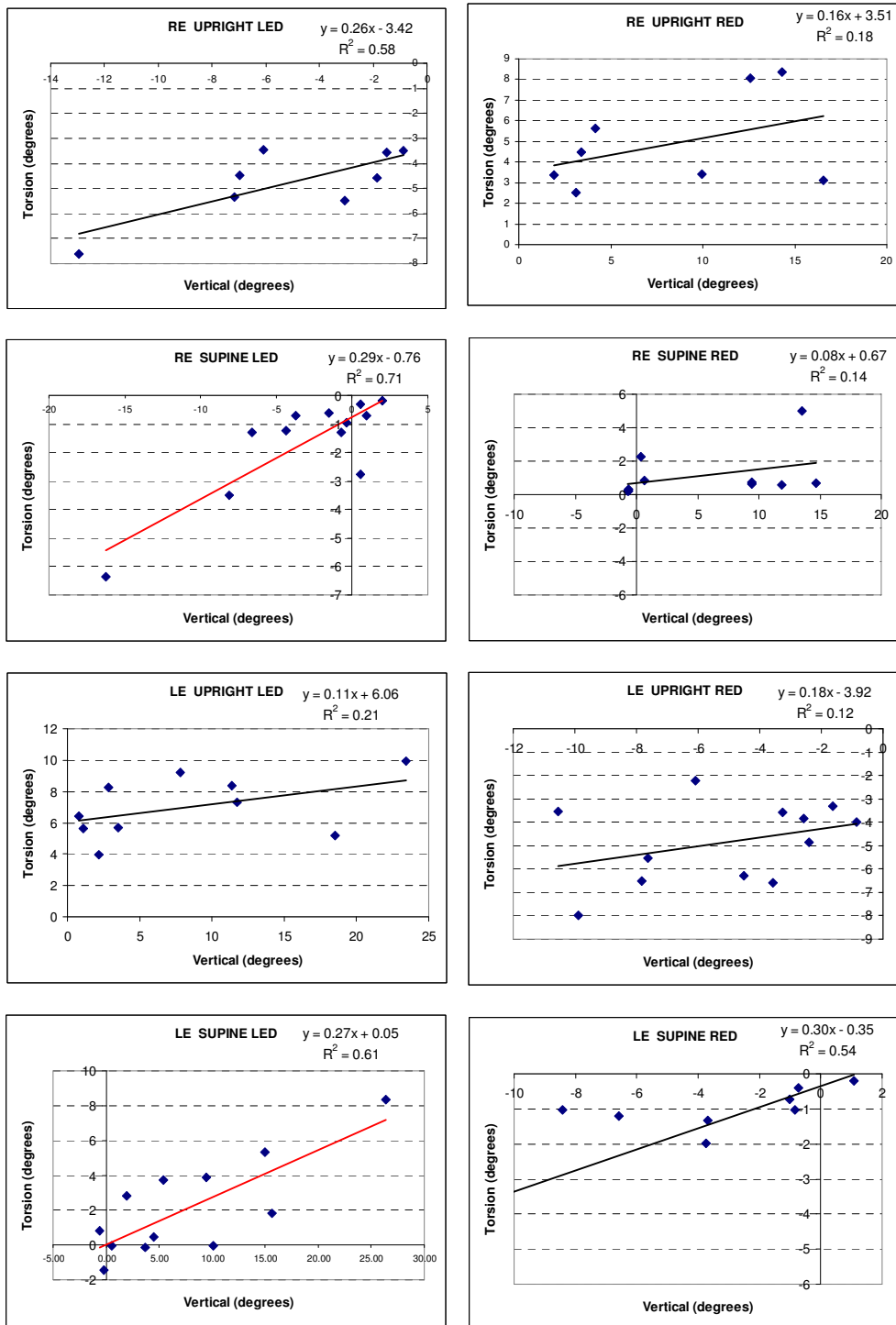
**Table 7.1 Relative change in torsion from far to near fixation.**

Positive values, representing increased intorsion, are shown as bold. In most cases there is increased intorsion for each eye, resulting in a moderate incyclovergence, especially when the subjects were upright. When the head was tilted most of this increase in intorsion occurred with the ipsilateral eye, resulting in incyclovergence..

	UPRIGHT		SUPINE		UPRIGHT	SUPINE
	Right eye	Left eye	Right eye	Left eye	Cyclovergence	
<b>Head straight</b>						
AB	<b>1.61</b>	<b>0.69</b>	-1.163	<b>1.00</b>	<b>2.29</b>	-0.17
CC		<b>0.54</b>	<b>1.92</b>	<b>1.12</b>		<b>3.04</b>
HM	<b>1.32</b>	<b>0.02</b>	-1.29	<b>1.14</b>	<b>1.34</b>	-0.15
JK	<b>1.57</b>	<b>1.11</b>	<b>0.81</b>	<b>1.23</b>	<b>2.68</b>	<b>2.04</b>
SG	<b>0.39</b>	<b>2.45</b>	<b>0.32</b>	<b>0.50</b>	<b>2.84</b>	0.82
SH	<b>0.45</b>	-0.52	-0.05	-0.35	-0.08	-0.41
<b>Right Ear Down</b>						
AB	<b>0.92</b>	-1.63	<b>0.41</b>		-0.71	
CC		-1.37	<b>3.87</b>	-1.17		<b>2.70</b>
HM	<b>5.00</b>	-0.29	<b>2.75</b>	-1.25	<b>4.71</b>	<b>1.50</b>
JK		<b>2.77</b>	<b>0.41</b>			
SG	<b>2.44</b>	-1.66	<b>0.51</b>	-0.21	0.78	<b>0.30</b>
SH	-1.37	<b>1.77</b>	-0.25	<b>0.14</b>	0.40	-0.11
<b>Left Ear Down</b>						
AB	-0.90	<b>1.68</b>	-0.60	<b>1.39</b>	<b>0.77</b>	<b>0.80</b>
CC		-0.54		<b>5.37</b>		
HM	<b>0.13</b>	<b>0.92</b>	-0.61	<b>0.91</b>	<b>1.05</b>	<b>0.30</b>
JK	-3.02	<b>5.98</b>	-5.39	<b>8.48</b>	<b>2.96</b>	<b>3.09</b>
SG	-0.84	<b>1.99</b>	-1.45	<b>1.32</b>	<b>1.16</b>	-0.13
SH		-0.54	-0.10	<b>3.06</b>	-0.54	<b>2.96</b>

These results suggest that the torsion associated with head tilt for near fixations is not caused primarily by ocular counter-roll, but is influenced the lateral position of the eye in the orbit, as the eye becomes more adducted, intorsion increases.

The results from Chapter 6 suggested that the vertical position of the eyes may be related to ocular torsion. To examine this further, values for monocular torsion for both far and near positions were correlated with the vertical position of each eye. The results are shown in Figure 7.9. These show positive correlations for all conditions, but particularly for the supine conditions. The strongest correlations occurred in the tilt left ear down position when supine with the right eye showing the highest correlation. More data would be required to make definitive statements about this relationship, however the apparent strong correlations when tilted left ear down are consistent with other findings from this, and the previous experiment.



**Figure 7.9 Correlations between the monocular vertical (X axis) and the torsional (Y axis) position of each eye in each head position.**

Far and near data has been pooled. The association is strongest when the subjects were supine and tilted left ear down (red trendline).

## **Discussion**

### **Horizontal alignment**

The horizontal alignment of the eyes when upright was consistent with the previous experiments, although in this experiment there was more variation between subjects, probably due to the differences in the length of the long axis resulting from the different heights of the subjects. The ipsilateral eye adducted between 10° and 24° whilst the contralateral eye abducted between 3° to 10°, producing between 5° to 10° of convergence. Results were similar when supine. Vergence errors were greatest when supine and tilting left ear down, and were greater for far fixation, confirming the finding from Chapter 6.

The vertical position of the eyes was also similar to the findings from Chapter 6, in that the eyes tended to move down on head tilt, although the tendency for this to change to an upward shift when supine was not apparent. This may have been due to the small numbers in this experiment. It is unlikely to have been due to the differences in the testing apparatus between the two experiments as the up/down shift was relative to the straight ahead position – differences in the subjects' heights or the determination of the target positions would not have affected this relationship.

### **Torsion**

#### **Ocular counter-roll**

The direction of ocular counter-roll for far fixation when upright was consistent with expectations, there was a conjugate clockwise rotation on tilting left ear down and a counter-clockwise rotation when tilting right ear down (from the subject's point of view). The amount of torsion was more than the 10% compensation reported by Collewijn for static tilts<sup>22</sup>. However it is consistent with Ott<sup>23</sup> who demonstrated symmetrical OCR from 2.4 to 9.5 degrees following head and body tilt to either side. Other factors that may have increased the response may have been the asymmetrical nature of eye alignment in this experiment and the addition of proprioception input from the neck muscles. Ott<sup>23</sup> did not find that trunk tilt induced any significant change in torsional eye position, but others<sup>25-28</sup> have suggested that there is a small additional effect on OCR when there is a head rotation in relation to the torso.

The finding of incyclovergence on convergence is not consistent with other studies that have usually demonstrated a temporal rotation of Listings plane during convergence, resulting in extorsion of the eyes for downward gaze and intorsion on upward gaze. This phenomenon holds for both static fixation on near and distant targets<sup>1-8</sup>, and during the fast and slow phases of torsional vestibular nystagmus<sup>29, 36</sup>..

Porrill, Ivins and Frisby<sup>6</sup> demonstrated increasing changes in near cyclovergence at viewing elevations of 0° to +/- 15° and +/- 30°. Recordings were made as subjects followed a moving fixation target inwards and outwards along the line-of-sight of the right eye. Although there

were significant differences between subjects in that study for monocular torsion and cyclovergence, the cyclovergence was much less variable, measuring around 5° of cyclovergence (incyclovergence on elevation, excyclovergence on depression) at vertical positions of +/- 30°. These values are consistent with those of Mok<sup>5</sup> who found an average change of 5° between gaze angles of 30° in elevation and depression when subjects fixed targets on an isovergence surface.

Mays, Zhang, Thorstad, and Gamlin<sup>3</sup> demonstrated in monkeys that decreased trochlear unit activity (implying relaxation of the superior oblique muscle) was associated with convergence, and that the size of this decrease varied systematically with ocular elevation. In one monkey eye torsion was also measured, and consistent excyclotorsion was found to be associated with convergence. More recently Demer, Kono and Wright<sup>144</sup> using Magnetic Resonance Imaging on one subject during ocular convergence along the visual axis, found that the inferior oblique muscle exhibited significant contractile thickening that was associated with extorsion of the eye.

Some of these studies<sup>151, 144, 2, 6</sup> report that exclovergence occurs on convergence when looking straight ahead along the horizontal plane of the eyes, however Minken and Van Gisbergen<sup>152</sup> define the primary position of gaze as the “*intermediate zone where no torsion occurs*”. The implication of this is that the intermediate zone may be a position of slight elevation or depression of the eyes, not the necessarily the straight ahead position with relation to head fixed coordinates. Therefore, for individual subjects the type and amount of cyclovergence in this straight ahead position may vary. Allen and Carter<sup>1</sup> found values of 0.8° to 4.08° of excyclotorsion in 15 subjects and 3.2 of incyclotorsion in one subject. Two subjects showed no torsion at all.

What then may explain the almost consistent incyclovergence that was found in this experiment?

Firstly, although the sum of torsion in each eye indicated incyclovergence, this was usually the result of increased intorsion of the ipsilateral eye that was making a large adducting movement. The eye that was close to being aligned was more likely to extort, a finding consistent with that of Porrill et al<sup>6</sup>, Ivins, Porrill and Frisby<sup>2</sup> and Demer et al<sup>144</sup>. This can be seen in Figures 7.6 and 7.7 where the eye that is close to being aligned (Left Ear Down, RE cycloduction, and Right Ear Down, LE cycloduction) usually became more extorted. However this change was less than that of the intorsion of the ipsilateral eye, resulting in binocular incyclovergence.

Secondly, whilst most of the above studies confirm that extorsion occurs on convergence when the subject is looking down and intorsion occurs when looking up, Minken implies that



the null point may not be the precise horizontal midline<sup>152</sup>. For some subjects in or extorsion may occur in the straight ahead position. Thirdly, while care was taken to ensure that the far and near targets were horizontally aligned, the gaze angle may still have been one of depression. However as Porrill et al<sup>6</sup> only found differences of around 5° of torsion from straight ahead to 30° of elevation or depression, it is unlikely that small shifts in vertical gaze would result in the significant intorsion that was found in this experiment.

#### Torsion – Vertical interactions

The analysis of any interaction between torsion and vertical eye movements showed that the strongest correlations were found when tilting left ear down when supine, where the R<sup>2</sup> value was 0.84 for the right eye and 0.78 for the left eye. There was a similar correlation for the left eye when tilting right ear down when supine. As there was little association between these two factors when the subject was upright, then association is unlikely to be directly related to the change in torsion associated with ocular counter-roll.

Chapter 6 showed that when subjects were supine both eyes were positioned higher than when the subjects were upright. This was particularly evident for the contralateral eye - the right eye was higher on tilt left ear down and the left eye was higher on tilt right ear down. This is consistent with the above close association between torsion and vertical position.

An interpretation of these findings could be that normally, there is a tendency for the torsion associated with ocular counter-roll to produce unwanted downward vertical eye movements from the ipsilateral superior oblique muscle and the contralateral inferior rectus muscle (see Chapter 6). This could be partly overcome by antagonist responses of the ipsilateral eye inferior oblique and the contralateral superior rectus. However, in the absence of ocular counter-roll, proprioceptive cues to the fact that the head is tilted may still stimulate this antagonist action. This vertical imbalance of binocular alignment would also affect the accuracy of horizontal vergence eye movements, producing more vergence errors.

Another consistent finding from each of the three experiments that involved a head tilt has been that more misalignments, both horizontal and vertical, occurred when tilting left ear down, especially in 'compromised' conditions (no foveal target, absence of OCR). This was a surprising and unexpected finding but the different designs of all three experiments make it unlikely that it is due to chance or artifacts in the testing or analysis of the experiments. One possible explanation could be that when tilting left ear down the left eye has to make the larger convergence movement, and, as the left eye is usually the one more likely to fail on convergence, this results in more vergence errors. However this is unlikely. Chapter 4 showed that more vergence errors occurred when the eyes were shifted to the left – in this position the right eye needed to converge the most. Also, the results from this experiment

suggest that it is the vertical misalignment, associated with torsion, that is the primary cause for the errors of vergence. If proprioception from the muscles of the neck provides cues to head tilt (as discussed in Chapter 6), then differences in the stretch receptors of opposing sterno-cleido-mastoid muscles may initiate different responses depending on the side of the tilt. There is some evidence that asymmetries of torsion associated with head tilt can occur<sup>147, 25, 153</sup> as was discussed in Chapter 6. This is a more satisfactory explanation, as asymmetries in muscles of the body are more likely than asymmetries in extraocular muscles or their neural control.

### **Summary**

This experiment has confirmed many of the findings from Chapters 4 and 5, in that tilting the head is more likely to result in horizontal vergence errors, especially when supine. It has also confirmed the findings from Chapter 6 that there is a change in the vertical position of the eyes when ocular counter-roll is absent, particularly when the head is tilted left ear down. This change in vertical alignment is also more likely to result in horizontal vergence errors. The additional component of this experiment, the simultaneous measurement of horizontal, vertical and torsional position of the eyes, has suggested that the change in torsion associated with convergence may be at least partly due to the amount of lateral excursion required by each eye.

In particular, though, this experiment has provided some evidence that there may be a stronger relationship between the vertical and torsional position of the eye when the head is tilted in the absence of otolith input. This suggests that this vestibular input may, in normal conditions, help to overcome the vertical action of the extraocular muscles that bring about ocular counter-roll. The consistent finding of a changed effect when tilting left eye down was unexpected but could be explained by differences in proprioceptive input from the muscles of the neck.

## CONCLUSION

The original purpose of this series of experiments was to investigate horizontal vergence errors in 'natural' conditions, that is, in a normal visual environment. The requirement to use a bite bar was to be the only departure from this objective, this meant that any findings could only relate to static conditions.

The first two experiments followed this objective, and showed that errors of up to 2°, without diplopia, are common in subjects with normal binocular vision. Occasional errors of up to 5° can occur, but they are only rarely larger than 3°. The accuracy of convergence and divergence is affected by both the size of vergence change and the rate of change (Chapter 3) and whether the movement is symmetrical or asymmetrical (Chapter 4). Binocular alignment following a divergence movement is often less accurate than following convergence (an observation noted by Judd in 1907!).

One of the main aims of Chapter 5 was to determine whether the retinal location of the images of a near target following ocular counter-roll would affect the accuracy of a convergence movement to this target. The results clearly showed that this was not the case, but they did reveal an unexpected finding, the vertical shift of the eyes on head tilt was quite contrary to expectations. Both eyes appeared to have shifted down as a result of the tilt although it had been predicted that the eye ipsilateral to the shift would move up, and the contralateral eye would move down, but only slightly.

The final two experiments investigated this effect further, and the results largely confirmed this finding. However the conditions that the subjects had to put up with went far beyond what could be called 'natural'. These involved lying prone with the head encased in a motor cycle helmet while converging from a target on the ceiling to another suspended just above the nose, or wearing a thermoplastic mask with pilocarpine nitrate eye drops, and being strapped to a chair that rotated backwards until the subject was both seated but lying backwards. This, and the additional assessment of vertical and torsional eye movements necessitated changing the planned title of the thesis from "Objective assessment of vergence errors in natural conditions to "Binocular alignment and vergence errors in free space".

The subsequent analysis of vertical and torsional alignment revealed another unexpected result, that binocular alignment can differ depending on the direction of head tilt. Tilting left ear down frequently produced a different vertical alignment that appeared to influence horizontal vergence. This effect was much greater when the subject was supine. This could be due to unequal proprioceptive input from the sterno-cleido-mastoid muscles of the neck to ocular counter-roll that is particularly evident in the absence of otolith induced ocular counter-roll, associated with a vertical antagonist response that controls for unwanted vertical eye movements during torsion. Further investigation of this effect will require a major study, and the conclusions on this matter can only be tentative.

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