Spatial perception and progressive addition lenses

Peter Leslie Hendicott

DipAppSc(Optom), MAppSc

School of Optometry
Queensland University of Technology
Brisbane
Australia

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Abstract

Progressive addition lenses (PALs) are an increasingly preferred mode for the correction of presbyopia, gaining an increased share of the prescription lens market. Sales volumes are likely to increase over the next few years, given the increasing cohort of presbyopic patients in the population. This research investigated adaptation to PAL wear, investigating head movement parameters with and without progressive lenses in everyday visual tasks, and examined symptoms of spatial distortions and illusory movement in a crossover wearing trial of three PAL designs. Minimum displacement thresholds in the presence and absence of head movement were also investigated across the lens designs.

Experiment 1 investigated head movements in two common visual tasks, a wordprocessing copy task, and a visual search task designed to replicate a natural environment task such as looking for products on supermarket shelving. Head movement parameters derived from this experiment were used to set head movement amplitude and velocity in the third experiment investigating minimum displacement thresholds across three PAL designs. Head movements were recorded with a Polhemus Inside Track head movement monitoring system which allows real time six degrees of freedom measurement of head position. Head position in azimuth, elevation and roll was extracted from the head movement recorder output, and data for head movement angular extent, average velocity (amplitude/duration) and peak velocity were calculated for horizontal head movements

Results of the first experiment indicate a task dependent effect on head movement peak and average velocity, with both median head movement average and peak velocity being faster in the copy task. Visual task and visual processing demands were also shown to affect the slope of the main sequence of head movement velocity on head movement amplitude, with steeper slope in the copy task. A steeper slope,

indicating a faster head movement velocity for a given head movement amplitude, was found for head movements during the copy task than in the search task. Processing demands within the copy task were also shown to affect the main sequence slopes of velocity on amplitude, with flatter slopes associated with the need for head movement to bring gaze to a specific point. These findings indicate selective control over head movement velocity in response to differing visual processing demands.

In Experiment 2, parameters of head movement amplitude and velocity were assessed in a group of first time PAL wearers. Head movement amplitude, average and peak velocity were calculated from head movement recordings using the search task, as in Experiment 1. Head movements were recorded without PALs, on first wearing a PAL, and after one month of PAL wear to assess adaptation effects. In contrast to existing literature, PAL wear did not alter parameters of head movement amplitude and velocity in a group of first time wearers either on first wearing the lenses or after one month of wear: this is due to task related effects in this experiment compared to previous work. Task demand in this experiment may not have required wearers to use the progressive power corridor to accomplish identification of visual search targets, in contrast to previous studies where experimental conditions were designed to force subjects to use the progressive corridor.

In Experiment 3, minimum displacement thresholds for random dot stimuli were measured in a repeated measures experimental design for a single vision lens as control, and three PAL designs. Thresholds were measured in central vision, and for two locations in the temporal peripheral field, 30° temporal fixation and 10° above and below the horizontal midline. Thresholds were determined with and without the subjects' head moving horizontally in an approximate sinusoidal movement at a frequency of about 0.7 Hz. Minimum displacement thresholds were not significantly affected by PAL design, although thresholds with PALs were higher than with a single vision lens control. Head movement significantly increased minimum displacement threshold across lens designs, by a factor of approximately 1.5 times. Results indicate that the local measures of minimum displacement threshold determined in this experiment are not sensitive to lens design differences. Sensitivity to motion with PAL lenses may be more a global than a localized response.

For Experiment 4, symptoms of spatial distortion and illusory movement were investigated in a crossover wearing trial of three PAL designs, and related to optical characteristics of the lenses. Peripheral back vertex powers of the PALs were measured at two locations in the right temporal zone of the lenses, 15.6 mm temporal to the fitting cross, and 2.7 m above and below the horizontal to the fitting cross. These locations corresponded to the zones of the lenses through which minimum displacement thresholds were measured in the previous experiment. The effect of subjects' self movement on symptoms is able to discriminate between PAL designs, although subjective symptoms alone were not related to the lens design parameters studied. Subjects' preference for one PAL design over the other designs studied in this experiment is inversely related to the effect on subject movement on their symptoms of distortion. An optical parameter, blur strength, derived from the power vector components of the peripheral powers, may indicate preference for particular PAL designs, as higher blur strength values are associated with lower lens preference scores.

Head movement amplitude and velocity are task specific, and are also influenced by visual processing demands within tasks. PALs do not affect head movement amplitude and velocity unless tasks are made demanding or performed in less natural situations designed to influence head movement behaviour. Both head movement and PALs have large effects on minimum displacement thresholds; these effects may be due in part to complexity of the subjects' task within the experiment. Minimum displacement thresholds however were not influenced by PAL design. The most sensitive indicator for subject's preference of PALs was the effect of subjects' self movement on their perception of symptoms, rather than the presence of actual symptoms. Blur strength should be further investigated for its role in PAL acceptance.

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List of abbreviations

AFC: alternative forced choice

ANOVA: analysis of variance

CI: confidence interval

cm: centimetres

D: dioptres

DS: dioptres, spherical power

deg: degrees (of angle)

deg/s: degrees/second

H: horizontal

Hz: hertz

I-Q: interquartile

LED: light emitting diode

LH: lefthand

log: logarithm

logMAR: logarithm of the minimum angle of resolution

min arc: minutes of arc

mm: millimetres

MOCS: method of constant stimuli

ms: milliseconds

PAL: progressive addition lens

pctile: percentile

RH: righthand

s: seconds

sd: standard deviation

sec arc: seconds of arc

tan: tangent (of an angle)

V: vertical

VOR: vestibulo-ocular reflex

Statement of original authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, this thesis contains no material previously published or written by another person except where due reference is made.

Peter L Hendicott

Date:

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Chapter 1 Introduction

Progressive addition lenses (PALs) are an increasingly popular mode of vision correction for presbyopic patients. Industry based data (Table 1.1) indicates that multifocal (PAL) lenses have now overtaken bifocals as the main prescribed mode for multifocal lens designs, with the majority of these designs prescribed to presbyopic patients. Whilst sales by volume for PALs is approximately 4% higher than bifocals, the dollar value of these sales is approximately three times greater.

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Source: Analysis of the Australian eyewear industry, Optical Dispensers and Manufacturers Association and FR Perry and Associates.
Reported in *Australian Optometry, October 2002, p8*

Table 1.1 Prescription lens sales in Australia (value $m = sales value in millions, dollars; volume(m) = sales volume in units, millions; percentage values are percentage of total sales).

Population trends over the next 25 years show a rapidly ageing population, with a significant increase in the number of people over 45 years, the presbyopic age group (Figures 1.1 and 1.2, below, sourced from the Australian Bureau of Statistics).

Demand for PALs can therefore be expected to increase significantly over the next 25 years, presenting the Australian optical industry with the opportunity to improve market share with successful PAL designs. Development of PAL designs since their introduction in the late 1950's has aimed at the development of progressive power surfaces which maximise functional fields of view, and minimise unwanted astigmatism in peripheral zones of the lens, and hence reduce spatial distortions which are apparent to the wearer. This is reviewed in Chapter 2 of this thesis.

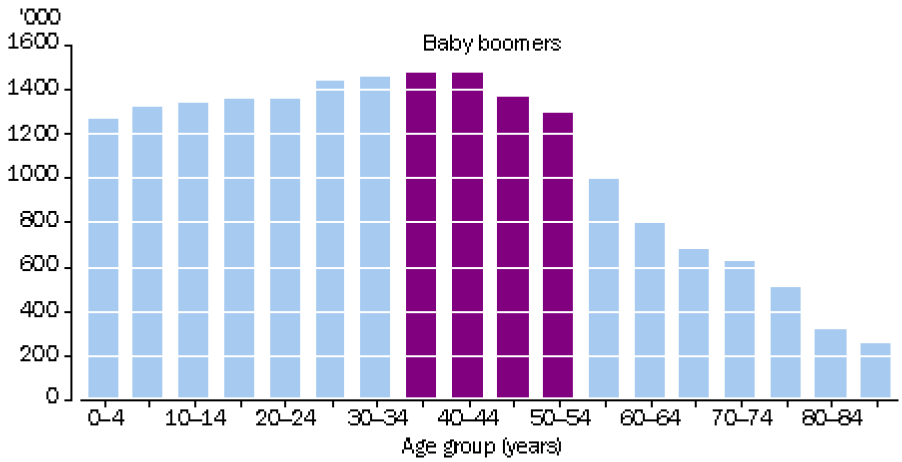

Figure 1.1 Australian population by age group, 2001

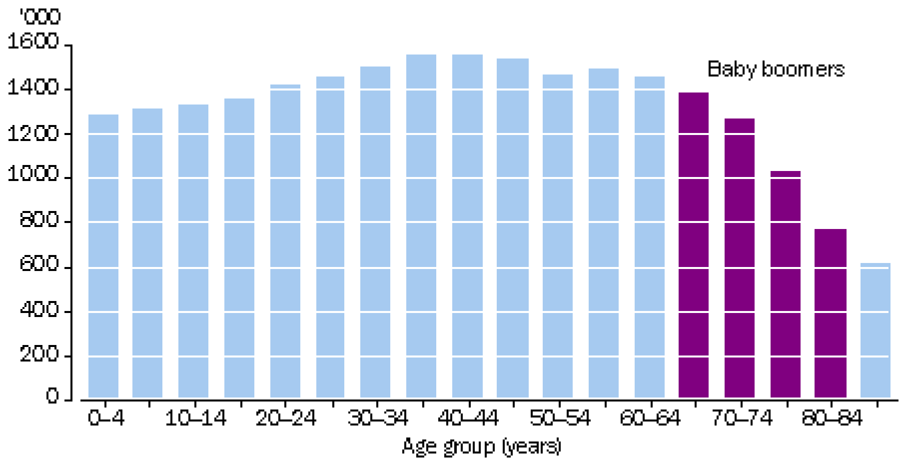

Figure 1.2 Projected Australian population by age group, 2031

The overall goal of this thesis is to identify factors which may allow PAL designers to make more successful lens designs.

1.1 Outline of the thesis

This thesis investigates aspects of spatial distortion with progressive addition lenses. Initial experiments investigate characteristics of head movement behaviour in two common visual tasks, and this is followed by an investigation into head movement behaviour in first time wearers of PALs. Head movement behaviour is one factor in the successful adaptation of the wearer to a PAL, as these lenses are reported to modify the habitual pattern of head movement of the wearer, due to the restricted functional fields of view of the lenses.

Subsequently, the thesis investigates the effect of PAL wear on motion detection thresholds, as measured by the minimum displacement threshold (Chapter 3), in a clinical wearing trial of three different PAL designs. This experiment is structured as a crossover wearer trial of the lens designs. Minimum displacement thresholds are assessed in two conditions, with the head static, and with the head moving; head movement amplitude and velocity are based on the results of the earlier experiments on head movements.

Running in parallel with the clinical trial of PAL designs and motion threshold detection, wearers of the PAL designs completed questionnaires to elicit symptoms of spatial distortion and illusory movement ('swim"), also factors which influence successful adaptation to a PAL. These symptoms of distortion and illusory movement are related to aspects of the optical design of the PALs.

1.2 Structure of the thesis

This thesis reviews the optical characteristics of progressive addition lenses (Chapter 2), and discusses aspects of motion detection with particular reference to apparent motion and random dot stimuli (Chapter 3).

Literature regarding head movement and its effect on visual functions, and relationships to PAL wear are reviewed in Chapter 4. Chapter 5 discusses the vestibulo-ocular reflex (VOR), which is allied to head movement and serves to stabilise vision in the presence of head movement.

Experimental methods are described in Chapter 6 for experiments investigating head movement, and Chapter 9 for experiments measuring minimum displacement thresholds. Chapter 11 describes experimental methods for the clinical wearing trial, where subjects recorded symptoms of spatial distortions resulting in the calculation of scores for spatial distortion and lens preference; methods for determining the optical characteristics of the PAL designs studied are also described.

Experimental results for the investigation of head movement behaviour in common visual tasks are discussed in Chapter 7; results for experiments investigating head movement behaviour in first time wearers of PALs are discussed in Chapter 8. Experimental results for motion thresholds in the PAL wear crossover trial are discussed in Chapter 10. Chapter 12 presents a discussion of the optical design of the PALs studied, together with their wearers' subjective ratings of distortion.

An overview of findings and conclusions is presented in Chapter 13.

1.4 Aims

This thesis aims:

1. to establish parameters of head movement amplitude and velocity in commonly undertaken visual tasks. This will add to the existing literature describing head movement behaviour in such tasks as reading, visual search, and locomotion.
2. to investigate and establish parameters of head movement amplitude and velocity in first time wearers of PALs during a common visual task. Head movement behaviour with PALs has previously been studied under experimental conditions designed to elicit head movement; the present experiment evaluates head movement behaviour in a natural task environment.
3. to test the hypothesis that PAL wear increases motion detection threshold in the peripheral visual field, and that the motion detection threshold is a measure of visual function sensitive to differences in PAL design
4. to test the hypothesis that symptoms of spatial distortion and illusory movement relate to optical factors of the PAL design
5. to establish a method to differentiate PAL designs that is readily usable in clinical practice.

Chapter 2 Progressive addition lenses: optical factors

2.1 Progressive lenses: an introduction

The concepts of progressive power lens surfaces were first patented in 1907 by Aves (Sullivan and Fowler 1988). Progressive addition lenses (PALs) however were first used for the correction of presbyopia in the 1950's (Maitenaz 1966), and have gained in popularity since then. The lenses are characterised by a gradual increase in power from the lower boundary of the distance viewing zone of the lens to the upper boundary of the near vision zone of the lens (Atchison 1987, Sheedy et al. 1987). Atchison (1987) further suggested the lenses can be thought of as consisting of 4 zones: the distance zone, near zone, the intermediate power progression and the lateral peripheral zones of the lenses. The aspheric front surfaces of PAL designs, necessary to produce surface power variation through the visual zones of the lenses, additionally cause lateral areas of the lenses to have unwanted astigmatism and distortions (Atchison 1987). Sullivan and Fowler (1988) and Fowler (1998) presented reviews of the patent literature describing the development of methods by which lens designers have produced variable power lens surfaces. Their reviews indicated that the major direction of PAL development has been towards techniques aimed at reducing or eliminating surface astigmatism, thus reducing peripheral distortions.

2.2 Optical factors and progressive lenses

2.2.1 Peripheral astigmatism

Producing the progressive power curves on the lens surface causes the production of unwanted and unavoidable aberrations in the peripheral zones of the lenses (Atchison 1987, Atchison and Kris 1993). These aberrations are due to the asphericity of the front surface. This produces variable amounts of cylindrical refractive power at variable axes (Simonet, Paineau and Lapointe 1986, Sheedy et al. 1987, Atchison 1987, Fowler and Sullivan 1989) and prism power contours which may differ between lens pairs (Atchison and Brown 1989, Atchison and Kris 1993). These power effects can produce sensations of distortion, or apparent motion of the visual field (“swim”, see Section 4.3), when the head is moved. These factors may influence visual adaptation to the lenses.

Fisher (1997) also indicated that the peripheral astigmatic power variations can limit the field of view of the near vision zone by restricting the area through which vision is possible without noticeable blur. This is a factor in adaptation for many patients. Fisher (1997) studied the relationship between surface astigmatic contours and subjective estimates of unacceptable lateral blur in near vision for eleven subjects with six different PAL designs. Subjects were required to estimate the lateral limits of clear and comfortable vision without head movement. Eye position was recorded at this limit, and this was extrapolated to distance from centre on the surface of the PAL to determine the astigmatic contour at the point of noticeable blur. Fisher found that the 1.00 dioptre (D) astigmatic contour corresponded to the limits of clear and comfortable vision. Other estimates of astigmatism able to be tolerated by the visual system are 0.3 D (Maitenaz 1974), 0.5 D (Davis 1978) and 1.00 D (Shinohara and Okazaki 1995). The 1.00 D contour limit is commonly used by lens manufacturers to delineate the functional width of the progression and near zones in their lenses (Jalie 1997). This limit is somewhat arbitrary, as blur thresholds depend on a number of factors such as pupil size, target luminance and target contrast. Additionally, lateral limits of clear and comfortable vision at near are affected by the reduction of the effective power of the near addition outside the reading zone of the PAL.

The astigmatic cylindrical powers induced by the front surface of the PAL can be considerable. A number of studies have established astigmatic contour lines for the front surface of various PAL designs. Astigmatic power contours ranging from 2.00 D to 5.00 D can be found in the lateral peripheral zones of PALs (Simonet, Paineau and Lapointe 1986, Sheedy et al. 1987, Atchison and Kris 1993). Higher degrees of astigmatic error are found in the more peripheral areas of the lenses, within 30-40 degrees of the distance optical centre (Sheedy et al. 1987). Significant astigmatic powers can still be found within surface areas closer to the distance optical centre. Sheedy et al. (1987), in studying astigmatic contours in 10 commonly used lenses available at that time in the US market, measured spherical equivalent power, astigmatic power and axis every 3° horizontally and vertically on the lens surface using a Humphrey Lens Analyser. They found unwanted cylindrical power ranging from 1.50 D to 3.50 D across the lenses level with the distance centre in this sample of lenses. Atchison and Kris (1993), using a similar method, showed cylindrical powers between 3 D and 4 D within a 25 millimetre (mm) distance laterally and inferiorly from the distance centre. Astigmatic powers of this magnitude may be sufficient to induce meridional magnification differences when objects are viewed through these areas of the lenses, producing spatial distortions. Sullivan and Fowler (1989a), in their study evaluating grating visual acuity in PALs, found that the axis of the peripheral astigmatism was between 30 and 150 degrees in the temporal portion of the lenses, and more oblique between either 30 and 60 degrees or between 120 and 150 degrees on the nasal zone of each lens for the three lens designs they tested. Simonet, Paineau and Lapointe (1986), Sheedy et al. (1987) and Atchison and Kris (1993) also found variability in the axis of the resultant astigmatism in peripheral zones of PALs. For objects viewed to the side through PALs with this distribution of axis directions, increased spatial distortions would be found due to the different blur and magnification effects of the astigmatic powers as the wearer would be viewing through lateral peripheral zones of the lens with asymmetric astigmatic powers.

The studies just described were performed a number of years ago, and investigated lens designs that, in the main, are not currently available in the ophthalmic market. Investigations of peripheral astigmatic contours for PALs currently available have not been published, in spite of frequent claims by PAL manufacturers that current lens designs alleviate much of the peripheral astigmatism found in older designs.

Simonet, Paineau and Lapointe (1986) suggested that the swim described by patients wearing PALs is due to either the changes in the amount of astigmatism, or to variations in the axis of the astigmatism in the infero-lateral zones of the lenses. Lens designers have sought to minimise the effect of this astigmatic gradient by positioning the zones of unwanted astigmatism in smaller areas of the infero-lateral zones of the lenses, or by spreading the astigmatic contours over a wider surface area. The first of these design philosophies causes a greater rate of change of astigmatism. These two approaches result in what are termed “hard” and “soft” lens designs (Atchison 1987). Hard designs concentrate the unwanted astigmatism in a smaller surface area; whereas "soft" designs spread the unwanted astigmatic contours over larger areas of the front surface. Soft designs can be considered to allow easier adaptation, particularly in early presbyopia (Jalie 1997). The lower near addition powers prescribed in early presbyopia would result in less peripheral astigmatism, also making adaptation easier.

Variations in the axis of the unwanted astigmatism could induce variable magnification factors. Backus et al. (1999) demonstrated that magnification of the retinal image in either the horizontal or vertical meridian results in a perceived positional shift of targets within the apparent frontoparallel plane. The apparent frontoparallel plane is the spatial region in which targets appear to lie in the same plane when viewed binocularly. Meridional magnification changes skew the position of this plane. This skewing of the plane results in the perception of tilted images in a lateral plane around the vertical. The blur induced by the astigmatic power also serves to reduce the useable field of view of the lenses.

2.2.2 Effects of prismatic power

Spatial perception with PALs may also be affected by prismatic power induced in the periphery of the lenses. Prismatic effects of spectacle lenses are found when the line of sight does not coincide with the axis of the lens (Atchison, Smith and Johnston 1980, Fogt 2000). Prismatic effects increase with increasing distance from the optical centre of the lens, and produce changes in the perceived direction of objects. Fogt and Jones (1996) showed that myopic spectacle wearers underestimate the lateral position of objects by judging positions to be closer to the midline. Tuan and Jones (1997) reported similar results. Fogt and Jones (1996) and Tuan and Jones (1997) considered these perceived positional shifts to be due to a recalibration of extraretinal eye movement information. This may persist for some days, even with training to compensate for the positional errors (Fogt and Henry 1999).

Unlike single power spectacle lenses which show a regular and predictable prism gradient over the lens surface, PALs show a variable prism gradient due to the complexity of the surface. Atchison and Brown (1989) studied differences in prism between pairs of PALs, and found differential prism gradients of up to 5Δ between right and left eye pairs in both horizontal and vertical meridians. Prism disparities of this extent between eyes could induce fusional difficulties for PAL wearers, in addition to causing directional shifts of viewed objects. Atchison and Kris (1993) also demonstrated induced prisms of up to 6Δ in vertical meridians and 5Δ in horizontal meridians of single PALs.

The effect of the peripheral prism gradient in PALs may have a second effect on spatial perception. Prismatic effects also induce curvature distortion where straight lines appear curved or tilted (Pick and Hay 1966, Hay and Pick 1966). Adaptation to this prism induced curvature distortion is dependent on gaze direction (Pick and Hay 1966, Hay and Pick 1966). The visual system adapts to this induced distortion, so that on removal of the prism, there is a negative after-effect where the straight line appears curved in the opposite direction to the curvature induced by the prism. The negative after effect can be used to quantify the amount of distortion induced. In one of the few studies investigating spatial distortion with progressive lenses, this principle has been used by Sullivan and Fowler (1993) to investigate whether adaptation to optically induced curvature distortion differs between successful and non successful PAL wearers. They induced curvature distortion with a 15 Δ plano prism with the base of the prism placed temporally before the right eye with the left eye occluded. After a 10 minute adaptation period, the prism was removed and curvature distortion was measured at 2 minute intervals for 10 minutes using the negative after-effect. No significant difference in adaptation to curvature distortion induced by this single prism was found between successful and non-successful PAL wearers. They concluded that monocular measurement of curvature distortion might not differentiate patient tolerance to PALs. The situation with PALs however is different to that of a single prism lens used monocularly. PALs have variable prism gradients over the lens surface, and the amount of prism on the lens can differ significantly between lens pairs (Atchison and Brown 1989). Evaluation of curvature distortion detection should take place in experimental situations that more closely resemble the distorting effects of PALs.

2.3 PALs: Clinical trials

Many of the studies investigating PALs have reported clinical trials of wearer acceptance of PALs in preference to other lens designs, or to other progressive lenses (Wittenberg 1978, Chapman 1978, Hitzeman and Brookman 1980, Spaulding 1981, Borish and Hitzeman 1983, Augsburger et al. 1984, Hitzeman and Myers 1985, Brookman, Hall and Jensen 1988, Wittenberg et al. 1989, Sullivan and Fowler 1989a, Cho et al. 1991, Bachman 1992, Fowler et al. 1994, Young and Borish 1994, Boroyan et al. 1995). These investigations have generally taken the form of clinical wearer trials with crossover designs where subjects have been asked to determine their preference for one lens design over another. Early studies asked subjects to indicate preference for a PAL design compared to forms of lined multifocals (bifocals or trifocals). As more PAL designs became available, subjects in the clinical trial studies were asked to indicate preference for one PAL design over another. Overall, these clinical studies showed high acceptance by patients for PALs, with acceptance rates up to 86% over these studies. In many of these studies, however, acceptance of the PAL under investigation was assumed if the subject within the trial did not fully reject the lens; acceptance scales in the majority did not include variable scales for acceptance. Often the question asked of the subject was ‘would you buy these lenses?’, to which a positive answer was taken to indicate acceptance.

In general, no predictive factors related to likely success with PALs have been found. Schultz (1983) indicated that hyperopic wearers showed a substantially higher acceptance rate (81.8%) than emmetropes (68.8%) and myopes (63.6%). This difference probably related to the greater necessity for hyperopic presbyopic patients to wear their correction compared to a lesser need for myopic patients to do so, as many myopic patients are able to undertake near tasks without their spectacles. As field of view for near vision was more restrictive in early PAL designs, myopic subjects may well have preferred to read without the PAL, thus influencing the acceptance rate. Also, Schultz’s subject sample shows a larger percentage of hyperopes with higher refractive corrections than of the myopes; the hyperopic subjects would have a greater need to use their refractive correction, a factor which may have influenced the reported acceptance rates. Gender does not appear to influence success rate with PALs (Wittenberg 1978, Borish et al. 1980, Spaulding 1981, Borish and Hitzeman 1983, Hitzeman and Myers 1985, Brookman, Hall and Jensen 1988, Wittenberg et al. 1989). Wittenberg (1978) suggested that patients with higher cylindrical refractive errors had a higher rate of acceptance of PALs; this suggestion was not supported by Sullivan and Fowler (1989b) who found no influence on success with PALs for mean spherical or cylindrical power.

PALs therefore are a highly successful mode of vision correction, although some patients report inability to adapt to the lenses due to distortions or to restrictions placed upon clear fields of vision due to the lens design. Young and Borish (1994), in their multicentre practice survey of 1700 patients, indicated failure of 10% of wearers to adapt to the PAL under study after 4 weeks. They also found that the majority of the failures could be attributed to problems involved with fitting of the lenses. This conclusion was based on their observation that the majority of failures to adapt came from a small number of sites in the survey, suggesting that fitting skills of the practitioners were the cause of the adaptation failures. This is in contrast to a study reported by Sullivan and Fowler (1990), who investigated patient tolerance to dispensing anomalies in both successful and unsuccessful PAL wearers. Accuracy of lens fitting (powers and centration) was compared in the two groups. They found no significant differences in dispensing accuracy between the two groups, and suggested other causes such as adaptation to optical distortions created by the lens design or differences in psychological makeup of the patient or lifestyle differences may differentiate the two subject populations.

The experiments in this thesis will investigate subjective visual performance with three different progressive lens designs, worn in a cross over clinical trial by the same subjects, and relate symptoms of spatial distortion to optical characteristics of the lenses. The PAL designs will all be dispensed to the same spectacle prescription and fitting characteristics, thus controlling for dispensing errors.

Chapter 3 Apparent Motion

The perception of motion can be generated by observation of an object which continually changes its position in the visual field relative to the observer. The perception of motion can also be generated by the response to two stationary stimuli, the phenomenon of apparent motion (Anstis 1970, 1978, 1980) or phi (Wertheimer 1912, cited in Nakayama 1985). Movement can be seen in response to two stationary stimuli if they are presented sequentially in time and at two separate locations (Barlow and Levick 1965, Anstis 1970, 1978, 1980, Biederman-Thorson, Thorson and Lange 1971, Nakayama and Tyler 1981, Lappin and Bell 1976, Braddick 1974). Perception of motion is also generated if stimuli are presented alternately to one eye (Julesz 1971), and also dichoptically, where one stimulus is presented to one eye and the next to the other (Nakayama 1985).

3.1 Random dot stimuli

Random dot stimuli were introduced by Julesz (1971), and utilized for the investigation of stereopis, where two patterns of dots are identical except for an area of dots within the pattern which is laterally displaced in one pattern with respect to the other, producing an image in depth when viewed stereoscopically due to the disparity induced by the lateral separation. If, on the other hand, the random dot pairs are presented alternatively, the displaced region appears to oscillate back and forth, in apparent motion (Anstis 1970, Julesz 1971). For motion to be apparent, the visual system has to compare a series of successive patterns to allow it to extract information about change in position (Braddick 1974) – the issue of correspondence between points which was highlighted by Anstis (1970, 1978).

Braddick (1974) investigated the perception of apparent motion as a function of displacement of the two stimuli using random dot stimuli. He found that the maximum displacement of stimuli that allowed perception of apparent motion was 15 min of arc, with this limit dependent upon the size of the displacement in visual angle rather than as a function of the number of dots. Braddick (1974) also found the perception of apparent motion did not occur when the stimuli were presented dichoptically, which is in contrast to studies using sequentially flashed stimuli such as dots, where apparent motion is perceived with greater displacement than Braddick found with random dot stimuli. Braddick (1974) proposed two processes underlying apparent motion, a short range process responding to elements of patterns, where corresponding points separated spatially and temporally must be matched in the presence of numerous false matches and for short interstimulus intervals; and a long range process responsive to contour or form movement, and which can operate at wider separation of targets and greater interstimulus intervals (classical apparent motion (Wertheimer 1912)). Braddick (1974) suggested this short range process operated for displacements less than about 15 min arc, and for interstimulus intervals less than 100 msec.

In contrast, Lappin and Bell (1976), while also recognizing apparent motion with random dot stimuli is mediated by a process distinct from that of classical apparent motion, suggested that the limit for correct identification of apparent motion is influenced by the size of the displacement in terms of the number of dots, as opposed to the retinal angle of displacement as suggested by Braddick (1974). Lappin and Bell (1976) considered this to be due to varying dot (or pixel) densities in Braddick's experiment, where Braddick (1974) used stimuli of equal retinal angle and changed pixel numbers to get varying displacements. Baker and Braddick (1982) investigated these differing points of view, and quantified displacement limits by firstly varying pixel (dot) spacing (and hence displacement in terms of angle, as displacement were generated by moving a number of pixel spaces), secondly by maintaining a constant number of pixels in the display and hence varying pixel density, and lastly by varying the area of the stimulus. Baker and Braddick (1982) found the limit for short-range apparent motion was determined by the retinal angle of the displacement and not the number of pixels across which the stimulus is displaced as suggested by Lappin and Bell (1976). Baker and Braddick (1982) also indicated that the number of dots in the stimulus has little effect on the limit of short-range apparent motion.

These experiments of Braddick (1974), Lappin and Bell (1976) and Baker and Braddick (1982) have all measured the maximum displacement of random dot stimuli that can still elicit the perception of apparent motion, the maximum displacement threshold, d_{max} (Nakayama 1985, Baker and Braddick 1985). The perception of motion can also be generated with a minimum displacement of the stimuli, termed the minimum displacement threshold, d_{min} (Baker and Braddick 1985, Nakayama and Tyler 1981, Nakayama 1985). To determine minimum displacement threshold, separation of motion information from information about position is necessary (Nakayama and Tyler 1981, Nakayama 1985) – the example used by Nakayama (1985) relates to the minute hand of a clock: if observed long enough, an observer realizes it has moved, but is this due to perception of the movement, or has movement been inferred due to a change in position? Thus position cues can affect the perception of motion.

Nakayama and Tyler (1981) investigated whether motion sensitivity can be isolated from position sensitivity, using random dot stimuli, which they considered would contain no position specific cues, and a moving line stimulus which they expected would induce both motion and position sensitive cues. They also tested position sensitivity by using a single static line stimulus, where the observer was required to detect a deviation from straightness. Their results are illustrated in Figure 3.1 below.

Figure 3.1 indicates that motion detection with the random dot grating is determined by the velocity of the stimulus (left hand graph), as peak velocity of the oscillating points in the random dot grating increases in proportion to the temporal frequency, e.g. peak velocity of a 1 Hz oscillating motion is 10 times that of a 0.1Hz oscillation, for the same amplitude of oscillation. In the right hand figure, this function is essentially flat in the temporal frequency range 0.1 – 1 Hz, showing that position information, generated by the movement of the line, determines the thresholds, rather than velocity of the stimulus as for the random dot stimuli.

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Figure 3.1 Results of Nakayama and Tyler 1981: left hand (their Fig 3) shows motion threshold amplitude against temporal frequency for a random dot stimulus, right hand (their Fig 4) shows threshold against temporal frequency for a single line stimulus, for two observers. Note flatness of slope between 0.1 – 1 Hz range in right hand graph (from Nakayama K, Tyler C. Vision Research 1981 21: 427-433).

Nakayama and Tyler (1981) also showed that where position cues are reduced, such as in conditions where hyperacuity (Westheimer and McKee 1978) is poor, motion threshold was determined by velocity; where positions cues were present, thresholds were determined by displacement, rather than velocity. Nakayama and Tyler (1981) conclude that random dot stimuli can isolate motion sensitive mechanisms from position sensitive mechanisms. Nakayama and Silverman (1984) also showed that maximum displacement threshold increases with increasing velocity.

3.2 Other factors affecting displacement thresholds

3.2.1 Spatial frequency

A number of studies have outlined dependence of the maximum displacement threshold on spatial frequency of the random dot stimuli. Chang and Julesz (1983) have measured d_{max} for symmetrically filtered low-pass, medium-pass and high-pass random dot stimuli. Threshold for d_{max} was 18 min arc for the low-pass stimulus, for unfiltered stimuli d_{max} was 12.5 min arc, for medium-pass filtered stimuli d_{max} was 8.3 min arc, and was 5 min arc for high-pass filtered stimuli; indicating the maximum displacement threshold is dependent upon spatial frequency of the stimulus. Subsequently, Chang and Julesz (1985) showed that when spatial frequencies of spatially filtered random dot stimuli were below 4 cycles/degree, d_{max} was inversely proportional to increasing frequency. At frequencies above 4 cycles/deg, d_{max} remained constant. Cleary and Braddick (1985, 1990a) also showed that d_{max} is inversely proportional to the frequency of narrow band stimuli, becoming approximately constant when expressed as a number of cycles of the stimulus frequency. They found this relationship to hold over a wider range of spatial frequencies, from 0.66 to 10.66 cycles/degree. Boulton and Baker (1991), using stimuli consisting of micropatterns developed from Gabor patches, showed that d_{max} is dependent on spatial frequency of the stimulus but is independent of stimulus size. They also demonstrated that d_{max} depends on the lowest spatial frequency in the stimulus. Studies with sinusoidal gratings as apparent motion stimuli have given similar results (Turano and Pantle 1985, Nakayama and Silverman 1985). Cleary and Braddick (1990 ab) indicate that this inverse scaling of d_{max} with spatial frequency is consistent with a number of models of the motion sensor, with greater performance with low-pass filtered displays determined by motion sensors tuned to low spatial frequencies. These models (Adelson and Bergen 1985, van Santen and Sperling 1985, Watson and Ahumada 1985) suggest that each directionally selective sensor operates within a spatial band-pass channel. Motion detectors sensitive to low-pass frequency filtered stimuli explains the increase in d_{max} found with low-pass filtered stimuli (Chang and Julesz 1983, 1985, Cleary and Braddick 1990 ab) and also the lack of effect of optical blur on larger displacements found by Barton et al. (1996).

3.2.2 Eccentricity

Baker and Braddick (1985) used random dot stimuli to investigate thresholds for minimum and maximum displacement at different eccentricities. Stimuli were scaled for eccentricity, with stimulus size increasing as eccentricity increased – ie for a stimulus to be presented at 10º eccentricity, stimulus size (20º) was twice the eccentricity. Minimum displacement thresholds (d_{min}) increased by a factor of 2 to 4 in four subjects at 10º eccentricity compared to central targets (0.4º eccentricity).

They indicate that the minimum displacement threshold shows an increase with eccentricity consistent with the variation of cortical magnification with eccentricity. For their four subjects, minimum displacement thresholds at 10º eccentricity ranged from 80 to 200 sec arc, with a stimulus size of 20 x 20º. Conversely, d_{max} increased linearly with increasing eccentricity, increasing from approximately 7-10 min arc at 1° eccentricity to 80-100 min arc at 10° eccentricity.

Peripheral motion detection thresholds equate to foveal measures when stimuli are scaled according to the cortical magnification factor (McKee and Nakayama 1984, Koenderink et al. 1985, van de Grind et al. 1983). Using random dot stimuli, van de Grind et al. (1983) calculated signal to noise ratios as a determinant of stimulus velocity, and showed that minimum motion detection performance was roughly invariant across the temporal visual field to a 48º eccentricity, when stimuli were scaled to obtain equivalent cortical sizes and velocities. McKee and Nakayama (1984) showed that the target size necessary to produce the lowest differential motion threshold (analogous to minimum displacement threshold as used in the experiments in this thesis) is large, ranging from 1º at the fovea to 20º at 40º eccentricity. When they normalized thresholds for differential motion sensitivity against the fovea, differential motion threshold was linearly related to eccentricity. McKee and Nakayama (1984) also show that velocity discrimination, expressed as the Weber fraction $\Delta V/V$, is similar at the fovea and the peripheral retina to 40° eccentricity. Orban et al. (1985), also assessed just noticeable differences in velocity in the peripheral field, and showed a U-shaped function described velocity discrimination, with the shape of the curve dependent upon contrast of the stimulus and on eccentricity scaling, in agreement with McKee and Nakayama (1984).

Displacement thresholds are dependent upon eccentricity, with thresholds increasing as eccentricity increases. Spatial scaling of the stimuli in accordance with the cortical magnification factor however shows, for minimum displacement threshold, performance in the peripheral retina is equivalent to that of the fovea.

3.3 Relationship to the experiments in this thesis

This thesis investigates motion detection by examining minimum displacement thresholds in central vision and in two locations in the peripheral visual field, at 30° temporal and 10° above and below the horizontal meridian (Chapter 9 and 10). Random dot stimuli are used in these experiments, as these stimuli eliminate position dependent clues (Nakayama and Tyler 1981). Stimuli will be broad band, and not spatially filtered, to allow responses from both low-pass and high-pass detectors. Blur induced by the peripheral zones of the PAL should reduce the high frequency component of the stimulus compared to the single vision lens control. This may increase displacement threshold with PAL lenses compared with the single vision lens control.

Chapter 4 Head movements

Head movements generally do not contribute to changes in gaze within a range of 20 - 30° across fixation, in either humans (Bartz 1966, Gresty 1974, Guitton and Volle 1987) or animals (Tomlinson and Bahra 1986 ab, Phillips et al. 1995, Freedman and Sparks 1997). Bahill, Adler and Stark (1975) assessed the extent of saccadic eye movements in a natural environment in three subjects using electrooculography and found that the majority of saccadic eye movements were smaller than 15º. These findings indicate that to change gaze, changes are made by eye movement and then by a combination of head and eye movement if the gaze shift is larger than approximately 20º. This holds true where the visual field is essentially unrestricted, as in the case of single vision lenses. A different situation holds for PALs, where the limits of clear vision are constrained by the design of the PAL, particularly for near and intermediate vision (see also Section 4.3). Fisher (1997) demonstrated that the boundary of subjectively clear vision at near is limited by the astigmatic contours of the lens. To adapt successfully to PALs may necessitate a change in head (and/or eye-head) movement behaviour.

4.1 Head movement and PALs

Jones et al. (1982), in studying head movement with PALs compared to bifocals in four subjects, found increased head movements when reading with PALs compared to bifocals, and that this difference persisted after months of adaptation to the PAL. Head movements in this case represent the need for head movement to increase the clear field of view when reading. They also suggested that individuals prefer not to make head movements when reading. Afandor and Aitsebaomo (1982) studied the range of eye movement possible with PALs before head movement occurred. Their study used monitoring of eye movements for light stimuli placed at 2° intervals. Eye movement recording continued until a head movement exceeding 2° was detected. They found that the range of eye movement occurring without head movement at near was approximately 13.5°. This was found for both PAL wearers and subjects without correction. Afandor and Aitsebaomo (1982) also found that some subjects showed eye movement ranges of 20° before head movement commenced.

Conversely, some of their subjects showed a smaller range of eye movement, with a 10° range of eye movement prior to any head movement. Afandor and Aitsebaomo labelled the first group "eye movers" and the second "head movers". They found that all the "eye movers" in their study preferred the PAL under study which had the wider near field of view.

In a related study, Aitsebaomo and Afandor (1982) further investigated the area in which changes in gaze are reported to occur without head movement (above) by investigating eye movements occurring with change in target position within ± 14º of fixation for both points of light and letter targets. They found that the "dead zone", where head movement is unlikely to occur, was about ±6° for points of light and ±11° for letters, substantially less than that suggested by previous authors (Bartz 1966, Gresty 1974). Stahl (1999) also demonstrated a zone of "eye only" gaze shifts to light emitting diode targets, with the "eye-only" range being 35.8 ± 31.9°, representing a wide variation in eye and head movement behaviour. Afandor, Aitsebaomo and Gertsman (1986) investigated head and eye movements within a 28° field in presbyopic subjects wearing 3 types of bifocal and a PAL. They found that the relative contributions of eye and head movements were 71% and 24% respectively for changes in gaze for near tasks within this 28° field.

Guillon, Maissa and Barlow (1999, 2000) report an investigation of head and eye movements with an unspecified PAL design and single vision lenses. Head and eye movements were monitored for distance, intermediate and near vision while subjects were required to read text presented in a variety of columnar and row formats. The extent of vertical and horizontal head movement was significantly greater when wearing the PAL than for single vision lens wear at distance and near. No significant difference was found for the two lens designs for intermediate fixation distances, although a similar trend was apparent in the data. Horizontal eye movement amplitude was also significantly greater for near vision with PAL wear than with single vision lens wear.

Ali et al. (2000) and Ciuffreda et al. (2001) also compared eye and head movements during reading with PALs and single vision lenses. Two PAL designs were investigated, one with a wide intermediate zone, the second with a narrow intermediate zone design. Reading targets were presented at 60 cm, with reading material in a standard text format and with sentences alternately spaced at 20° either side of the midline to induce head and eye movement. Increased vertical and horizontal head movement amplitude was found for both PAL designs compared to single vision lenses, and for the narrow zone PAL compared to the wide zone PAL. The number of words per minute read was lowest for both reading tasks with the narrow zone PAL, and the number of fixations and regressive fixations/100 words was minimally higher with the narrow zone PAL. Mean data of 10 subjects are presented in these conference reports, without statistical analysis of the data. A fatigue effect on the measurement of eye movement parameters during reading has been found by Hendicott (1996), for six 60 second periods of eye movement recording during reading. The studies of Ali et al. (2000) and Ciuffreda et al. (2001) do not indicate the time taken to complete the experimental protocol, so this may be a factor in the results found. Whether there was control for an order effect is also not apparent. An earlier study (Katz, Ciuffreda and Viglucci 1984) compared reading rate, reading comprehension and recorded eye movements in seven subjects wearing flat-top bifocals and a PAL. Reading eye movements were recorded for reading tasks at 40 and 57 cm, using paragraphs that subtended less than 14°. Reading parameters were assessed before and after a month of adaptation to the lens designs. No significant difference in performance between the two lenses was found for the reading measures. One difference between this study and the later studies of Ali et al. (2000) and Ciuffreda et al. (2001) is that Katz et al. (1984) recorded eye movements with the head stabilised by a chin rest, a requirement of the available technology at that time for eye movement recording. Fields of view for reading also differ between the two studies, which may account for some differences in results.

Preston and Bullimore (1998) showed that the degree of head movement in reading with PALs is dependent upon print size, with 6 point print resulting in twice the amplitude of head movement found when reading with 10 point print. Preston and Bullimore (1998) also studied the effect of PAL near zone width, and found near zone width had no influence on the amplitude of head movement with reading.

4.2 Adaptation and PALs

In a number of reports of the same experiments, Gauthier et al. (1987, 1989, 1991) and Obrecht et al. (1987) described a series of investigations which demonstrated the effect of reduced peripheral fields on head movement with lenses. They artificially reduced the clear field of view of lenses by applying gel to create blur, or by using a central slit aperture on the lens surface. With these restrictions to peripheral vision, time taken to correctly identify peripherally placed targets increased, and a head movement approximately equal to the eccentricity of the target took place.

Extrapolating these findings to PAL wear, in making head and eye movements to view eccentrically, head movements would occur earlier in the gaze shift, with increased head movement velocity compared to when no lenses are worn. This is necessary because of the reduced field of clear vision in the progressive lens. Head movement becomes necessary to allow clear vision to be maintained within the progressive power zones of the lenses. Gauthier et al. (1987) stated that this adaptation takes place within a few days to a few weeks. Pedrono, Obrecht and Stark (1987) showed that when first fitted with PALs, a wearer learns a new eye-head movement strategy to reduce the time taken to find the zone of clear vision. This requires changes of VOR gain (see Chapter 5), earlier onset of head movement and an increase in head movement velocity.

Gauthier et al. (1989) and Pedrono, Obrecht and Stark (1987) additionally pointed out that with progressive lenses, ideal VOR responses necessitate distinct gain values for each zone of the lenses or for each direction of gaze. Shelhamer, Robinson and Tan (1992) suggested that context cues may determine which gain setting to use, and that it is possible to retain multiple sets of VOR gain settings. For progressive lenses, context cues for the differing VOR gain settings for different viewing zones or gaze directions may be the eye movement response to fusional disparity, or perhaps variable rates of retinal slip, induced by the prismatic contours of the lenses.

4.3 “Swim” and PALs

“Swim”, the perception of image distortion or movement in the peripheral field, is a factor in the acceptance of, and adaptation to, PALs. The issue of what constitutes “swim”, or illusory movement, is not well established. Earlier studies investigating success rates of PALs compared to other modes of correction indicate distortions as a factor, but these distortions are ill defined (Borish et al. 1980, Brookman et al.1988, Wittenberg et al. 1989, Gresset 1991). Gordon and Benjamin (2006) describe symptoms of peripheral distortions as waviness, dizziness or a swimming sensation; these symptoms are thought to be due to the peripheral astigmatism and prismatic effects of the lenses. Whilst swim is a major cause of the approximate 10% failure rate in adapting to PALs, there were no studies investigating the measurement of swim until those of Selenow et al. (2000 a,b). They reported an initial study of a method to quantify swim (Selenow et al. 2000a), and subsequently investigated swim in two different PAL designs (Selenow et al. 2000b).

Subjects were presented with a single line on the midline of a computer monitor. This was randomly presented off vertical, and subjects were required to adjust the position of the line until they perceived it to be vertical. The error from true vertical was recorded, and the mean of 4 trials was used in data analysis. The alignment task was performed with the subject looking straight ahead, and with the head rotated to the left or right. It is unclear whether this task was performed monocularly or binocularly in either investigation. In comparing the error from true vertical obtained when wearing single vision lenses as opposed to a PAL, there was a significant effect of lens type when the subject had their head turned left or right (Selenow et al. 2000a). Mean alignment error was 68.7 min when the head was turned left, and 81 min when the head was turned right with the PALs, compared to 19 min in left head turn and 7.78 min in right head turn with the single vision lenses. No difference was found between lens designs for error from true vertical when the subject was looking straight ahead.

In the second study, thirty presbyopic subjects wore two different PAL designs that differed in the amount of peripheral astigmatism (Selenow et al. 2000b). A similar orientation task was used, with a line and a grid target. Measurements were taken with the subject looking straight ahead and in 45° left head rotation with gaze directed straight ahead. The average alignment error was significantly less for the PAL with the lesser peripheral astigmatism. Selenow et al. (2000 a,b) considered that this orientation alignment task is able to assess swim in PALs, and reported it is positively correlated with subjective ratings of swim.

Selenow et al. (2000a,b) have used an orientation discrimination task to investigate swim. Orientation discrimination thresholds are asymmetric in the nasal and temporal retinae (Paradiso and Carney 1988). Orientation thresholds are not significantly affected by induced blur, at least centrally (Vogels et al. 1984). When the cortical magnification factor (Drasdo 1977, Rovamo and Virsu 1979) is considered, just noticeable differences in orientation are constant from 0 to 10° retinal eccentricity (Orban et al. 1984). The mechanism producing greater error from true vertical in the experiments of Selenow et al. (2000 a,b) is unclear. Estimates of slant in binocular conditions depend on horizontal and vertical size ratios (Backus et al. 1999); these may be altered by the astigmatic contours of the PALs creating the perceived misalignment found by the subjects of Selenow et al. (2000 a,b).

Additionally, the experiments of Selenow et al. represent a static viewing condition, whereas normal PAL wear occurs in a dynamic situation of head and body movement. The experiments described in this thesis set out to investigate whether PAL wear affects the detection of motion. Motion detection thresholds will be assessed in the presence and absence of head movement. Head movement will invoke vestibular responses, and the effect of head movement on motion thresholds will be determined in peripheral vision. The effect of PAL front surface astigmatic gradient on motion detection threshold with and without head movement will be investigated for three PAL designs with different astigmatic gradients in a clinical trial. Parameters for head movements will be determined from investigation of head movement amplitude and velocity for common visual tasks. Specific symptoms of spatial distortions will be sought by symptoms questionnaires.

4.4 Velocity of head movement

Bahill et al. (1975) have used the term 'main sequence' to describe the relationship between saccadic eye movement amplitude and velocity. The term 'main sequence' originates in astronomy, where it is used to describe the linear relationship between brightness of a star and its temperature. For saccadic eye movements, peak velocity and amplitude show a linear relationship where velocity increases linearly with increasing amplitude until velocity reaches a value beyond which it increases little (termed 'soft saturation'). Applied to head movements, Stark et al. (1980) and Zangmeister et al. (1981) also demonstrated a linear relationship between peak velocity and amplitude of head movement, although the asymptotic 'soft saturation' found with saccadic eye movement peak velocity did not occur with the peak velocity of head movement.

Measures of the peak (maximal) velocity of head movements have been made under a number of differing experimental conditions. Stark et al. (1980) measured the peak velocity of head movement over a 90° range, using a helmet-mounted rod linked to a potentiometer. Torsional head movement resulted in a varying voltage signal through the potentiometer. They found peak velocity of head movement ranging from around 8 deg/s to 150 deg/s (from inspection of their graphed data). Zangmeister et al. (1981), using a similar experimental protocol, showed peak head movement velocities ranging from 10 deg/s to 150 deg/s. Uemura et al. (1980) found the maximal velocity of head movement to range from approximately 20 deg/s to 80 deg/s over a head movement angular range of 10° to 50° (from inspection of their graphed data). Gresty (1974) has noted peak head movement velocities of 25 deg/s to 220 deg/s for gaze shifts to either continuous or flashed targets. Ron et al. (1993), for successively flashed targets of varying offsets, recorded peak head movement velocities of 100 – 200 deg/s for 50° target displacements.

These studies all used helmet mounted mechanical systems linked to potentiometer driven electronic systems to record head position. They have also used saccadic like gaze shifts to fixation targets which were light sources. More recently, Epelboim et al. (1995a, 1995b, 1997) and Epelboim (1998) presented a series of reports on gaze shift dynamics in sequential looking tasks, all based on the same data set. Head position in their experiment was recorded by detecting arrival time of acoustic signals, generated by a sound emitter mounted on a helmet worn by the subject, to 4 microphones set at the corners of a room. Subjects were required to either look at a series of targets presented in random sequence, or to look at and touch the randomly presented targets. Head movement speeds recorded in their experiment are analogous to the measure of average velocity of head movement presented in this thesis. Whilst Epelboim et al. (1995a, 1995b, 1997) and Epelboim (1998) indicate that the task demand affected the gaze shift dynamics, speeds of head movement they recorded ranged from 3 deg/s to 25 deg/s for gaze shift amplitudes between 5° and 45° for their 4 subjects for both tasks in their experiment.

Han et al. (2003b), investigated head movement and eye movement velocities in reading tasks with different PAL designs, and recorded the peak velocity of head movement during return sweep saccades in reading using an electromagnetic recording system They found peak head movement velocities ranging from 12 ± 1.04 deg/s to 75 ± 6.24 deg/s for the steplike head movements occurring in conjunction with the return sweep saccade in reading. Head movement velocity and amplitude also demonstrated a main sequence relationship.

Similarity in head movement peak velocity between studies with differing experimental protocols and task demands probably reflects nervous system control, anatomical restriction over maximal muscle responses and physical limitations in the generation of head movement via the muscles of the neck.

4.4.1 Velocity inter-relationships

The eye movement literature shows that the two expressions of velocity, average (mean) and peak, as used in this thesis in relation to head movement, are linearly related when saccadic eye movements are considered (Inchingolo et al. 1987, Lebedev at al. 1996). Becker (1989) reported the ratio of average velocity to peak velocity for saccadic eye movements of between 5° and 60° to be within the range of 0.52 to 0.72. Inchingolo et al. (1987) and Becker (1989) also report a strong correlation between mean and peak velocity of saccadic eye movements of 0.98 or greater. Pelisson and Prablanc (1988), who investigated velocity profiles of centripetal versus centrifugal saccadic eye movements, showed a ratio of maximum (peak) over mean (average) velocity of 1.6 ± 0.1. This was constant over a range of eye movement from 0 to 30°, and was also not affected by initial eye position (central or eccentric in the orbit). Both mean and peak velocities of centripetal saccades (directed to the primary position) were however significantly faster than velocities of centrifugal saccades (those starting from the primary position). Harwood et al. (1999) recorded saccadic eye movements over a range of amplitudes, using an infra-red limbal reflection monitoring system, and found the ratio of peak to mean velocity (which they termed 'Q') to be roughly constant for differing amplitudes, with values for 'Q' ranging from 1.54 to 1.8. Harwood et al. (1999) used red circular laser spots, subtending 4 min of arc as fixation targets, whereas Pelisson and Prablanc (1988) used small numbers (10 min of arc) and an electoroculographic recording method. Despite these differences, these two studies returned similar results. The ratio of peak to average velocities account for the interdependency between peak velocity, average velocity (i.e. amplitude of saccade/duration of saccade). As this ratio is constant for saccadic eye movements over a range of saccade amplitudes, it would represent optimal control of the timing of eye movement.

This ratio of peak to average velocity for head movement has not previously been reported, and is investigated in this thesis for head movements occurring during two common visual tasks. If peak and average velocity of head movement also show a constant ratio, as exists for saccadic eye movement, any effect of PAL wear on the velocity profile of head movement may be evident in this relationship. This is considered in the second experiment in the thesis, where the angular velocity profile of head movements in first time wearers of PAL lenses is investigated.

Chapter 5 The vestibulo-ocular reflex (VOR)

This reflex mechanism is driven by the vestibular system acting together with the visual system, and produces eye movements approximately equal in velocity and opposite to the direction of head movements in order to maintain a stable image on the retina (Sharpe and Johnston 1993). The VOR is an adaptive reflex (see Section 5.4) and can be affected by a number of factors, including head movement and spectacle wear (see Section 5.5). In the case of PALs, the VOR may be a factor in successful adaptation to PALs. Whilst not directly assessed in experiments within this thesis, experimental conditions for the experiments investigating motion detection with PALs (Chapters 9 and 10) were set so that this reflex needed to be in play during the experiment, as it would be in normal viewing conditions.

5.1 The vestibular apparatus

The vestibular apparatus is located above and lateral to the cochlea of the ear, and lies in the bony labyrinthine space within the temporal bone of the base of the skull (Waxman 1996). The vestibular labyrinth consists of the utricle and saccule, the sensory organs of the static labyrinth, and the three semicircular canals located orthogonal to each other, the sensory organs of the kinetic labyrinth.

Each semicircular canal ends in an enlarged ampulla, which contains hair cells within a receptor area called the crista ampullaris (Waxman 1996, Fitzgerald 1996). The hair cells within the crista penetrate into a gelatinous membrane called the cupula. The static labyrinth is responsible for information regarding head position in space, primarily signalling head position relative to the position of the trunk, and also responds to linear acceleration of the head in horizontal and vertical directions. The kinetic labyrinth provides information for compensatory movements of the eyes in response to head movement, the vestibulo-ocular reflex (Waxman 1996, Fitzgerald 1996).

When considering the semicircular canals, head acceleration causes movement of endolymph fluid within the semicircular canals, opposite to the direction of head movement. Melvill Jones (1993) demonstrated that the resultant mechanical force on the cupula membrane of the vestibular organs induced by fluid displacement is proportionate to the angular velocity of head movement. Reflex pathways for the VOR involve the vestibular ganglion, the vestibular nuclei, lateral gaze centres and the oculomotor nuclei (Waxman 1996).

5.2 Experimental measures of the VOR

The VOR is typically measured in terms of its gain, expressed as the ratio of eye velocity/head velocity (Shelhamer, Robinson and Tan 1992). In order to preserve maximal visual acuity, the VOR gain approximates -1.0 in the light (Gauthier et al. 1987, Sharpe and Johnston 1993), so that eye movement velocity compensates for head movement velocity in distance fixation. To experimentally measure vestibulo-ocular responses, methods to create head rotation are necessary. Head rotation can be produced by whole body rotation, with subjects seated in rotating chairs or on rotating platforms (e.g. Demer et al. 1987, Gresty, Bronstein and Barratt 1987, Vercher and Gauthier 1990-91, Shelhamer, Robinson and Tan 1992, Demer 1992, Barnes 1993, Demer 1994). Alternatively, head movement can be controlled by helmet mounted mechanical systems (e.g. Hine and Thorn 1987, Tabak and Collewijn 1994, 1995, Collewijn and Smeets 1999). Recording of head and eye positions commonly occurs by search-coil techniques (e.g. Collewijn et al. 1983, Paige 1994, Fetter et al. 1994). A sensory magnetic coil is mounted on the head (e.g. Demer and Viirre 1996, Collewijn and Smeets 2000) to record head position, and a scleral search coil (Robinson 1963) may be fitted to the eye to monitor eye position. Alternate methods of monitoring head and eye positions include mechanical systems for head movement (Gauthier 1984, Takahashi 1989) and pupil tracking (Moore et al. 1999), electrooculography (Hine and Thorn 1987, Gresty, Bronstein and Barratt 1987), and infrared limbal reflection monitoring (Barnes 1983) for eye position measures. More recently, electromagnetic field systems for the monitoring of head position have been developed (Preston and Bullimore 1999, Pope et al. 2001, Han et al. 2003ab).

5.2.1 Near fixation and the VOR

Owing to the difference in position of the centres for eye rotation and head rotation, the VOR has to operate at a gain higher than 1.0 for near fixation (Viirre et al. 1986), whereas in distance fixation this relative positional displacement of the centres of rotation is negligible. Viirre et al. (1986) demonstrated a doubling of the gain of the VOR for near fixation in monkeys. They also demonstrated different gain settings for each eye in lateral fixation for near objects, and similar VOR gain in each eye for distance fixation. VOR gain therefore appears to be mediated by near fixation, or vergence. Hine and Thorn (1987) showed that VOR gain was increased in an inverse proportion to fixation distance, with VOR gain showing a statistically significant increase from around 1.08 at a fixation distance of 180 cm to 1.55 at a 22 cm fixation distance in five subjects. This effect was also maintained with imaginary targets in darkness. A similar increase in VOR gain for near fixation has been demonstrated by Biguer and Prablanc (1981), who report a VOR gain of 2.0 for a near fixation distance of 20 cm. In a subsequent experiment, Hine and Thorn (1987) showed that monocular viewing disrupted the linkage between fixation distance and VOR gain in darkness, with monocular viewing showing a lesser rate of change in VOR gain with decreasing fixation distance than did binocular viewing. This suggests that VOR gain is influenced by binocular signals of proximity, such as convergence. In a third experiment (Hine and Thorn 1987), change in accommodation induced by positive or negative power (1.75 D) spectacle lenses did not alter VOR gain measured in darkness, whereas VOR gain was altered for near fixation distances by the wearing of 5 Δ base in or base out prisms in front of each eye. As a result, Hine and Thorn (1987) concluded that the degree of convergence is the critical factor in determining VOR gain settings for near fixation. Paige (1989, 1991), Paige and Tomko (1991) and Paige et al. (1998) reached similar conclusions.

5.3 The VOR with head movement

VOR gain is dependent on the frequency of head movement, whether the head movement is due to passive rotation or active rotation. Hine and Thorn (1987) showed decreased gain for 20° horizontal head rotations paced by a metronome at frequencies of 1.0, 1.3 and 1.75 Hz, irrespective of fixation distance. VOR gain further decreased when subjects oscillated their heads as fast as possible, which equated to a frequency approximating 4 Hz. The decrease in gain was largest for nearer fixation distances, with gain at 1.0 Hz at 22 cm being 1.8, reducing to 1.3 at 4 Hz; gain for distant targets (200 cm) reduced from 1.05 to 0.9 as head rotation frequency increased from 1 Hz to 4 Hz. Hirvonen et al. (1997) measured VOR gain for a target at 140 cm in the presence of horizontal head rotations of approximately ±10° in five frequency ranges: 0.5 – 1Hz, 1-2 Hz, 2-3 Hz, 3-4 Hz and 4-5 Hz. Gain decreased from 1.05 at 0.5–1.0 Hz to 0.78 at 4-5 Hz, a result comparable to that of Hine and Thorn (1987). Additionally, Hirvonen et al. (1997) reported that head movement frequency of 5 Hz could be reached by 74% of the subjects for the 10º amplitude of head movement, and a 4 Hz head rotation frequency was reached by 94% of subjects for head movements of this amplitude.

Grossman et al. (1988, 1989) also showed VOR gains of approximately 1.0 for both the horizontal and vertical VOR during normal everyday activities such as walking or running while fixating on a distant object. During these activities, VOR gain remained around 1.0 for frequencies of head movement ranging from 1 to 10 Hz (Grossman et al. 1989). Demer and Viirre (1996) showed VOR gains around 1.0 for standing and walking, for VOR measures made both in the dark and light with a distant fixation target. Gains for VOR whilst running decreased to about 0.75. Grossman et al. (1988) measured head rotation frequencies for walking, running and voluntary head shaking. They found the 10th to 90th percentile range for voluntary horizontal head shaking to range from around 1 Hz to 5 Hz. Demer and Viirre (1996) used experimental speeds for walking and running consistent with those found by Grossman et al. (1988). Crane and Demer (1997) found similar values for VOR gain when standing, walking or running. Crane and Demer (1997) also indicated that the horizontal and vertical velocity of images on the retina was < 4 deg/s for targets beyond 4m. This is similar to the retinal image speed of 4 deg/s during head rotations of 0.25 to 5 Hz found by Steinman and Collewijn (1980) when investigating eye position (and hence retinal image position), head movement and vergence in 4 subjects. Steinman and Collewijn also found vergence change, or the change in retinal image position between the two eyes, was in the order of 3 deg/s. All their subjects reported their vision remained clear and single during the experiment.

Studies investigating stereopsis in the presence of head movement (Westheimer and McKee 1978, Patterson and Fox 1984, Steinman et al. 1985) show stereopsis is unaffected by head movement of frequencies up to 2 Hz. Westheimer and McKee (1975) showed that Landolt C and vernier acuities were not affected by retinal image speeds up to 2-3 deg/s, a result confirmed by Barnes and Smith (1981) who showed visual acuity to be relatively unaffected by retinal image movement speeds of 2 to 4 deg/s.

This suggests the VOR system is tuned to work efficiently in maintaining stable vision for head movement within a frequency range up to 5 Hz and for retinal image velocities under 4 deg/s. This is supported by Demer and Crane (1998) who indicate that the VOR appears to be adapted to stabilise gaze during head movements that occur during natural activities.

5.4 Adaptation of the VOR

The vestibulo-ocular reflex also demonstrates plasticity owing to its ability to adapt to changed circumstances. In part, this plasticity is inherent in natural growth, as the VOR system needs to be able to cope with increase in the separation of the eyes caused by changing head size with growth (Ciuffreda and Tannen 1995). Horizontal eye movements resulting from the VOR have been investigated in children 9-12 years of age compared to adults (Herman, Maulucci and Stuyck 1982). Compared to adults, Herman , Maulucci and Stuyck (1982) found children showed an inability to suppress the VOR with a target moving in synchrony with the head, but had adult like increase in VOR gain in the presence of a fixed target. They considered this to be due to maturational lag in the development of extra-retinal processes interacting with adult-like retinal and vestibular mechanisms. In contrast, adults use both extra-retinal and retinal signals to modify the VOR.

Modifications of visual input alter the VOR response and produce adaptive changes in VOR gain. A number of studies have utilised magnifying or reducing spectacles and reversing prisms to alter visual input, demonstrating adaptive effects in the VOR. Gonshor and Melvill Jones (1976) used prisms to produce left to right reversal of the visual field, necessitating a shift of VOR gain from -1 to +1 to allow for visual stability. They reported a decrease in VOR gain to 77% of its initial value after 16 minutes tracking with an inverted retinal image produced by prism spectacles. After a week of continued exposure to this lateral inversion of retinal images, VOR gain decreased to 25% of the initial value. Inversion of the VOR gain commenced after 2 weeks of wear.

Gauthier and Robinson (1975) used 2x telescopic spectacles to alter VOR gain, as measured in darkness. After 5 days of continual wear, VOR gain had increased to 1.24 from its initial value of 0.81. Gauthier and Robinson (1975) also had their subjects estimate the apparent position of a stationary earth-fixed target before and after a head rotation in the dark. The target was initially viewed, then extinguished, the head was then rotated, and then the target re-illuminated. With the telescopic spectacles, the stationary target appeared to have moved relative to space. This is consistent with the subjects thinking they had moved through an angle larger than the actual head rotation, thus expecting to see the target in a more displaced position than it really was. Gauthier and Robinson (1975) suggested this adaptation of both the reflex VOR and perceptual responses indicated there must have been a general recalibration of the central nervous system response to the altered vestibular input.

The time course of adaptation to magnifying or reducing spectacles has been demonstrated in monkeys (Miles and Eighmy 1980). Miles and Eighmy (1980) used telescopic spectacles that magnified by 2X or minimised by 0.5X in each of three monkeys. These spectacles would require a doubling or halving of the VOR gain respectively. Adaptation to magnifying spectacles occurred progressively over a 3 day period, with VOR gain increasing to a value of 1.6 after 3 days, and reaching 1.7 after 7 days. Recovery of the VOR to baseline occurred in approximately 2 days. Wearing 0.5X minifying spectacles caused a reduction in VOR gain to 0.7 within 1-2 days, and a similar rate of recovery (Figure 5.1).

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Figure 5.1 Time course of VOR adaptation in monkeys. Different symbols represent different animals (from Miles and Eighmy, J Neurophysiol 1980; 43:1406-1425)

The effect of magnification on VOR adaptation has also been investigated in humans (Demer et al. 1987, Demer et al. 1989, Demer et al. 1990, Paige and Sargent 1991, Demer 1992, Demer and Amjadi 1993, Demer and Viirre 1996, Crane and Demer 1997, Demer and Crane 1998, Crane and Demer 2000). As in the animal study of Miles and Eighmy (1980), magnifying spectacles cause an increase in VOR gain, although VOR gain increase is less than the value of magnification in all studies. The extent of VOR adaptation with magnifying spectacles depends on head movement frequency (Paige and Sargent 1991) and age (Demer 1994). Older subjects showed less VOR gain increase with 1.9X or 4X magnifying spectacles than younger subjects for sinusoidal head movement with frequencies of 0.5 to 2 Hz (Demer 1994). Differences in VOR gain between the two groups were less for higher frequencies of head rotation. Paige and Sargent (1991) demonstrated an increase in VOR gain with 2X magnifying spectacles across a frequency range of sinusoidal rotations of 0.025 to 4 Hz. They showed that the extent of VOR gain enhancement was frequency dependent, with a 44% increase in VOR gain at a head rotation frequency of 0.025Hz, declining to a minimum gain enhancement of 19% at 4Hz. VOR gain increase due to the magnifying spectacles also reduced as peak head velocity increased. Paige and Sargent (1991) suggested that there might be an amplitude and velocity dependent limitation to VOR plasticity.

5.5 VOR adaptation and spectacle wear

A similar, albeit less marked, adaptation of the VOR is also seen with prescription spectacles, where alteration in the VOR takes place within a few minutes in response to the small changes in magnification (Collewijn, Martins and Steinman 1983, Cannon et al. 1985). Due to the prismatic displacement occurring with spectacle lenses, a person with myopia and corrective spectacle lenses requires less VOR gain for a given angle of head rotation (Collewijn, Martins and Steinman 1983). Conversely, a hyperopic patient would require an increased VOR gain for the same angular rotation of the head. Collewijn, Martins and Steinman (1983) estimated the change required to be about 3% per dioptre of spectacle correction. Cannon et al. (1985) assessed the ratio of in-darkness VOR gain with spectacles to baseline (no spectacles or with contact lenses) VOR gain for a range of refractive corrections. They termed this ratio the normalised VOR gain. They showed a magnification factor for spectacle lenses of approximately 2.5%/dioptre, in agreement with the Collewijn, Martins and Steinman (1983) estimate. The results of Cannon et al. (1985) are illustrated in Figure 5.2, where the normalised gain is shown on the *y*-axis, and spectacle correction is shown on the *x*-axis; error bars represent 95% confidence intervals.

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Figure 5.2 Normalised VOR gain as a function of refractive correction in dioptres. (from Cannon et al. Acta Otolaryngol 1985; 100:81-8)

VOR gains and adaptation rates were investigated by Collewijn, Martins and Steinman (1983) in a series of experiments where their 5 subjects wore their existing spectacle corrections for baseline measures of VOR gain in dark and light conditions. Spectacle corrections were then changed for a negative or positive spectacle correction of 5D; contact lenses were changed to spectacle lenses in one subject. Anisometropia was also induced by using a –5D lens in one eye and a +5D lens in the other in two of the subjects. The changes in spectacle correction and over- or under-corrections resulted in magnification changes ranging from –21% (minification) to +36% (magnification) across all subjects. Both the nominal gain, expressed as the ratio of eye rotation to head rotation, and effective gain, where nominal gain is divided by the magnification factor resulting from the refractive change, were calculated. Data were presented for individual subjects for the time course of gain adaptation. The results showed that adaptation to the changes in magnification induced occurred within a time frame of 4-20 minutes, despite the presence of blur induced by the adjusted spectacle corrections. Visual field was also restricted during the experiment to a 4.7° field containing a large fixation target, with the remaining field masked. As adaptation of the VOR occurred with this restricted field, Collewijn, Martins and Steinman (1983) considered that stimulation of the peripheral retina is unnecessary for fast adaptation of the VOR. Studies of VOR adaptation with telescopic spectacles (Demer et al. 1989) showed that the unmagnified visual field peripheral to the telescopic spectacles field reduces the VOR gain produced by telescopic spectacles when peripheral field is masked. This implies that peripheral retinal feedback mechanisms do play a part in modulating the VOR as a result of altered visual input, in contrast to the suggestion of Collewijn, Martins and Steinman (1983).

The studies of Collewijn, Martins and Steinman (1983) and Cannon et al. (1985) also used single vision lenses, where prismatic and magnification affects are regular across the lens surface. Progressive lenses, however, have a variable prism and magnification gradient across the lens, and large amounts of horizontal and vertical prismatic power (Atchison and Brown 1989). Adapting to wearing PALs would therefore necessitate the development of a variable VOR gain readjustment for different areas of the lens surface, as suggested by Gauthier et al. (1989). Shelhamer, Robinson and Tan (1992) indicate that humans can establish multiple sets of VOR gain information, allowing for the wearing or non-wearing of spectacles, for example. Some wearers, however, may not successfully develop these multiple VOR settings, and experience spatial distortions with PALs. VOR adaptation has also been shown to lessen with age (Paige 1992, Baloh, Jacobsen and Socotch 1993, Paige 1994, Goebel et al. 1994, Demer 1994), which may influence adaptation of the VOR with progressive lenses as PAL wearers are usually in older age groups.

Retinal slip, the motion of images on the retina due to a difference between eye movement velocity and target velocity, is thought to be the basic stimulus responsible for adaptive modification of the reflex (Collewijn and Grootendorst 1979, Barnes 1979, Steinmann and Collewijn 1980, Shelhamer et al. 1994, Gauthier et al. 1995). Retinal slip may become more variable or less predictable to the visual system with PALs due to their variable power profile, which may affect adaptation of the VOR and potentially may affect adaptation to the PALs.

Chapter 6 Experimental Methods 1: Head movement studies

Two experiments were conducted to investigate the temporal dynamics of the head movements that people make during common visual tasks. Firstly, data were collected to establish parameters for the range of angular head movements and head movement velocity occurring in two commonly undertaken tasks. These data were required to set values for head movement angle and velocity in experiments investigating motion detection thresholds in the presence of head movements and PAL wear (Chapter 9). Head movement velocities have previously been established during walking and running (Grossman et al. 1988). However, as body motion was not part of the motion detection experiments, with head movement in these experiments to be generated by active rotation of the head (see Chapter 9), measures of head movement velocity in tasks involving a stationary body position were undertaken to establish parameters for head movement under these conditions.

Secondly, head movement angular extent and velocity were recorded in new PAL wearers prior to and after adaptation to the PAL. PALs have been shown to alter head movement behaviour (Jones et al. 1982, Gauthier et al. 1989, Pedrono, Obrecht and Stark 1987, Han et al. 2003ab). Head movements occur earlier in gaze shifts, head movement velocity increases, and there is a greater contribution of head movement to gaze shifts when wearing PALs. The greater contribution of head movement is due to the peripheral visual field restriction caused by the peripheral power profile of the PAL. In terms of the cause of swim, or induced motion, with PALs, increased head movements and head movement velocity may be contributing factors. In addition, an increase in head movement velocity may be accompanied by increased variability in head movement velocity when PALs are worn. This was examined in this experiment.

6.1 Recording of head movements

Head movements were recorded using a Polhemus InsideTrack head movement monitoring system (Polhemus, USA, 1996), allowing real time six degrees of freedom measurement of head position (X, Y and Z Cartesian coordinates) and orientation (azimuth, elevation and roll). Interface software for the head movement recorder and computer was written and supplied by SOLA International Holdings Research Centre, Adelaide, Australia. The recording system consisted of a transmitter cube mounted on the rear of a copy stand (Figure 6.1), and a sensor cube mounted on a spectacle frame worn by the subject. The sensor cube was set 2 cm anterior, 3 cm temporal and 2 cm higher than the corneal apex position.

Figure 6.1 Set-up of Polhemus Inside-Track system for the copy task. The transmitter cube is the grey box at the top rear of the copy holder to the left of the monitor; sensor cube is mounted on the spectacle frame and is visible just in front of the right temple.

The zero value for head position relative to the position of the transmitter cube was set for the Inside-Track system prior to each measurement, by the subject fixating a target centred on the top of the monitor. Head movement and position was then recorded at a sampling rate of 10Hz. Output of the head movement recorder provided values for position of the head relative to the transmitter in X (anterior-posterior distance from the transmitter), Y (lateral distance from the transmitter) and Z (elevation relative to the transmitter) Cartesian coordinates. This is shown in Table 6.1, which is an extract from a trial for one subject during the copy task (described in Section 6.2.2). Data shown in this table represent a leftward head movement. Cartesian coordinate values are shown in the columns X Pos, Y Pos and Z Pos. Movements of the head relative to the set zero position were output in degrees of angle for azimuth (lateral head movement), elevation (vertical head movement) and roll (head tilt from the vertical). Negative values for angular data represent leftward head turn in azimuth, left head tilt in roll, and upward elevation of the head when the sensor cube was in front of the transmitter cube as in these experiments. Angular data calculated by the Polhemus system are relative to the distance of the plane of the sensor cube to the transmitter plane (X Pos) for each subject. In the case of the copy task (Section 6.2.2), the front face of the Polhemus transmitter was immediately behind the plane of the target text passage, which was aligned with the screen of the computer monitor. In the case of the search task (Section 6.2.3), the front face of the Polhemus transmitter was in the same plane as the search targets.

X Pos	Y Pos	Z Pos	Azimuth	Elevation	Roll
46.0971	-41.1540	-3.9543	-0.2050	0.9009	1.2243
46.1043	-41.1317	-3.8319	-0.3257	0.7170	1.3054
46.0483	-41.0713	-3.9160	-0.5207	1.0475	1.4049
45.8807	-40.7356	-3.8055	-1.9938	1.6856	1.5939
45.6268	-40.2252	-3.7170	-4.3528	2.4815	1.5513
45.5389	-39.7905	-3.6351	-5.8192	2.9192	1.4632
45.1844	-39.5114	-3.5311	-8.6421	3.5619	1.3332
45.1982	-38.6991	-3.5639	-10.8460	4.1430	1.5778
45.1498	-37.7778	-3.5822	-14.2142	5.2044	1.8783
45.3190	-36.8160	-3.3876	-15.8068	6.3295	2.0757
45.3063	-36.1902	-2.6225	-16.3831	8.8026	1.6466
45.1801	-35.8350	-1.6740	-16.0586	11.8802	2.4271
45.0607	-35.5626	0.5226	-14.1154	18.9262	3.3615
45.1020	-35.3408	1.9557	-12.7775	22.2789	3.4994
45.3114	-34.2518	1.6033	-15.9813	20.7008	1.6081
45.7063	-32.8360	0.0840	-21.5218	15.7885	1.1328
45.9885	-32.1319	-0.5174	-24.1039	14.4366	1.6417
46.2158	-31.3355	-1.0013	-26.1783	13.5399	1.8851

Table 6.1 Sample output of the head movement recorder, recorded during a copy trial, subject 13

The InsideTrack system and software allowed recorded data to be saved as a comma-separated values file. Saved data files were then processed through a Windows (Microsoft, USA, 1998) based programme written in Delphi language (Delphi v5, Borland, USA, 2000). This used a reversal of direction algorithm (Figure 6.2) to detect individual head movements. Head position for each sampling point was subtracted from that of the preceding sampling point on a repeatable basis for azimuth, elevation or roll. This continued until the software recorded a change in sign for the result of the subtraction, recording this as a change in direction of head movement. Figure 6.2 shows a subset of a head movement recording made during the copy task. The green arrow indicates the beginning of a head movement to the left (sampling point 8). The red arrow at sampling point 19 indicates the end of the leftward head movement. The reversal of direction at each of these points is demonstrated. This head movement had a duration of 11 sampling intervals (1.1 sec).

Velocity of the head movement was calculated as the total angular extent of the head movement divided by the duration of the head movement. This was termed **average velocity** in the analysis. Additionally, maximal velocity of the head movement was calculated from the largest separation of sampling points in one sampling interval. The blue arrow in Figure 6.2 indicates this, where the widest separation of points is shown for a rightward head movement. This was termed **peak velocity** in the analysis.

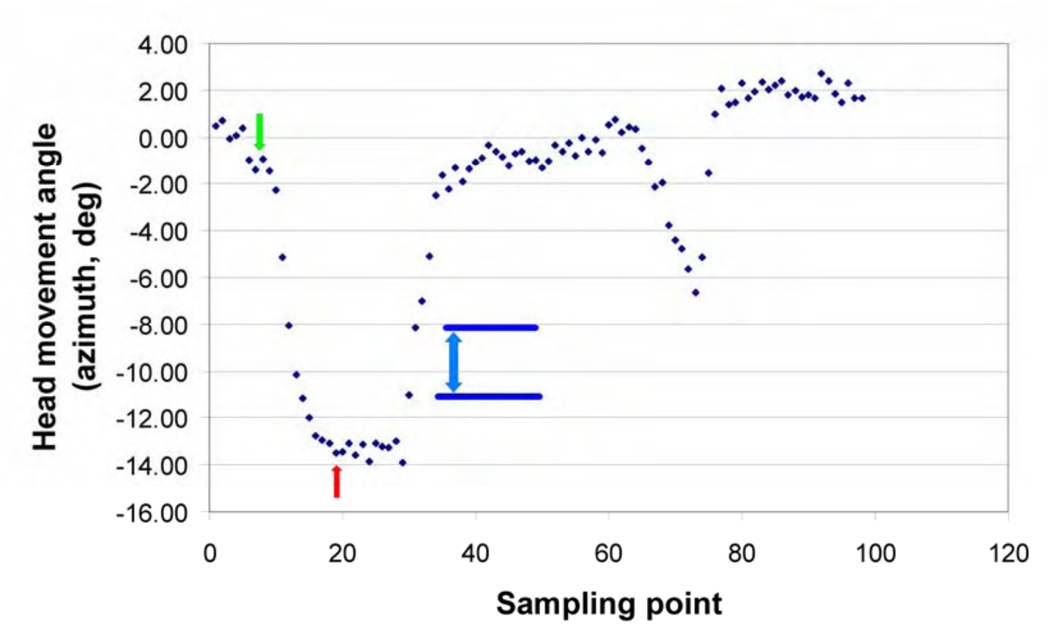

Figure 6.2 Sample head movement recording. (Green arrow = start of left HM, red arrow = end of left HM, blue arrow = largest separation of head position in one sampling interval (see text)). Sampling rate is 10 Hz.

For each subject, data for duration, absolute value of angular extent of head movement, and absolute values of average angular velocity and maximal angular velocity in degrees/sec (deg/s) were recorded. Head movements were also labelled with their direction (right or left). These data were also grouped for head movements in the following ranges of head movement:

- ≤ 2.999°
- 3 to 5.999°
- 6 to 8.999°
- 9 to 11.999°
- 12 to 14.999°
- 15 to 17.999°
- 18 to 20.999°
- 21 to 23.999°
- ≥ 24.999°

6.2 Establishing temporal parameters of head movements in common visual tasks

6.2.1 Subject selection criteria

Subjects were recruited from the staff and student population of the School of Optometry at the Queensland University of Technology, and from other tertiary institutions. This meant that they had at least a senior secondary schooling level of education and were older than 18 years of age. Subjects also met the criteria below.

1. Unaided or corrected visual acuity of 6/6 or better in each eye on a logarithmic scaled Snellen letter chart.
2. Normal binocular visual functions: Distance and near phorias within accepted clinical norms of between 2 prism dioptres (Δ) of esophoria and 8Δ exophoria at near (Saladin and Sheedy 1978). Stereopsis of 60 sec arc or better.
3. No evidence of ocular pathology assessed using monocular indirect and direct ophthalmoscopy, and slitlamp biomicroscopy of the anterior segment.
4. Normal visual fields as assessed by Humphrey central visual field screening.
5. Computing experience without formal typing training, in order to exclude trained touch typists.

6.2.2 Desk-top computing with a reading and copying task.

Subjects were required to accurately copy text from a printed page to a wordprocessor (Microsoft Word, Microsoft, USA, 1997). Text passages were 10 lines in length, typed in 12 point Times Roman font, at single line spacing, left justified, in portrait format on A4 paper, and was vertically centred on the page. Target text was extracted from magazine articles (New Scientist, Reed Publications, Australia) so that content was largely unfamiliar to subjects, and reproduced as stated. Text reproduced with the wordprocessor was 12 point Times Roman font at single line spacing, left justified. Each subject copied 1 paragraph of text. Average time to copy/type a test paragraph was approximately 3 minutes. Subjects were given refractive correction appropriate to their working distance in the form of single vision lenses where this was necessary.

6.2.2.1 Positioning of monitor and text.

To standardise the task, the target text and computer monitor were positioned adjacent to each other on a desk, separated by 25 mm with the text passage to the left of the computer monitor. The text and monitor were aligned so that the centre of the text passage and the centre of the monitor screen were on the same horizontal plane. Text was placed on a copy stand (Fellowes Computerware, USA, Model 21125) (See Figure 6.3).

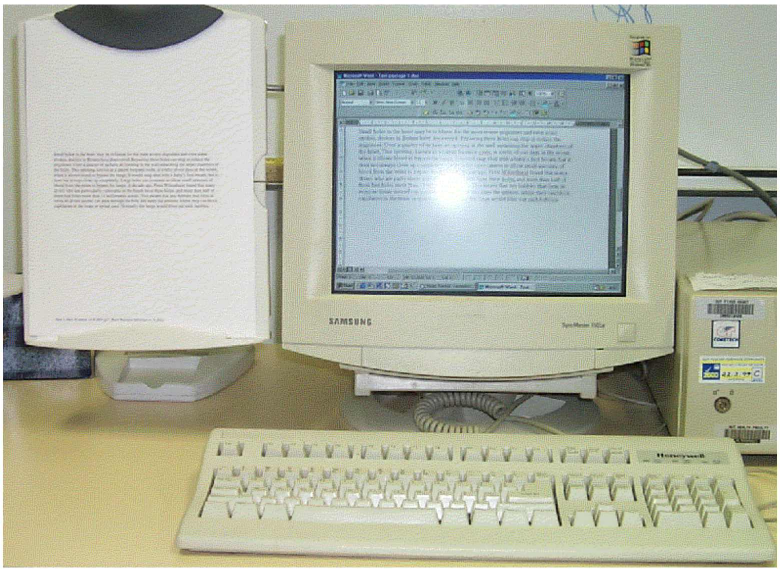

Figure 6.3 Source text and monitor positioning

Subjects were seated so that their working distance from the computer monitor was approximately 60-65 cm (see Figure 6.1). Working distance was recorded for each subject. With a 60 cm working distance, subjects were 26 cm from the desk edge, and the lower edge of the computer keyboard was 5 cm from the desk edge, with the vertical plane of the monitor 9.5 cm from the top of the keyboard. The keyboard was placed so that the centre of the alphabetical keys was aligned with the vertical midline of the monitor. Subjects were positioned so that they were centred on the monitor's vertical midline and so that the top of the monitor was approximately 5 degrees (°) below the subject's horizontal straight ahead gaze position.

With this positioning, the angle from subject to the right hand edge of the target page was 20.1°, to the centre of the target page 28.5°, and the left hand edge of the target page 35.6°, as measured from the vertical midline of the subject. Table 6.2 shows angular dimensions for the total gaze shift necessary for gaze to different aspects of the copy task, for a 65 cm working distance.

	Distance	Angle
Monitor screen H	13.95	13.1
Monitor screen V	10.3	9.7
Page RH	22	20.1
Page LH	43	35.6
Text LH	40.5	34.0
Text RH longest line	24.8	22.5
Text RH shortest line	25.9	23.3
Q-P key space	9.25	11.9
All keys H	14.25	17.9
All keys V	5	6.5

Table 6.5 Angular dimensions for copy task components (distance = cm, angle = deg, H = horizontal, V = vertical, RH = righthand, LH = lefthand)

6.2.3 Search task

Subjects were required to find and identify objects placed at varying positions on shelving to replicate head movement behaviour in situations such as those found in supermarkets or other shelving locations for an intermediate range visual task. Head movement measurements were obtained with the Polhemus InsideTrack system as described in Section 6.1, with the transmitter cube placed on the bookshelf at eye level for each individual subject, along the vertical centre line of the bookshelf.

6.2.3.1 Experimental set-up

An office type bookshelf 120 cm wide x 183 cm high was used as the shelving unit. A total of 64 target boxes were placed randomly on the shelves; these included 16 “search” objects (see Figure 6.4, also below Section 6.2.3.2). Search objects were placed at the subject’s eye level either side of the midline, and above and below eye level within a range of approximately 40 cm (approximately 30° at a distance of 70 cm from the bookshelf) above and below eye level so that minimal body position change was necessary. The total width of the grouped box targets was 70-71 cm. Angular gaze shift required for the end of each row was 28° from centre, for a 70 cm fixation distance. Vertical separation of the targets was 19 cm, resulting in an angular separation of 16° vertically at the same fixation distance.

Figure 6.4 Illustration of search task targets on shelving unit. The transmitter cube can be seen centrally on the second shelf from the top.

Subjects were asked to stand at a comfortable arm's length distance from the shelving unit in line with the vertical midline of the bookshelf. This distance was recorded for each subject. The zero position of the InsideTrack system was recorded with the subject standing upright at their preferred arm's length distance, viewing the centre of the transmitter cube.

6.2.3.2 Search objects

Objects used for this search task were small cardboard boxes measuring 70 mm x 36 mm x 36 mm, covered with coloured paper. On the face of each covered box were 3 letters or numerals, upper and/or lower case Helvetica 18 point font in black. In this font, upper case letters were 4.4 mm high; lower case letters were 3.3 mm high. At a fixation distance of 70 cm, these subtended 22.8 min arc and 17.4 min arc respectively. These angular subtenses equate to logMAR visual acuity of 0.65 and logMAR 0.54, which approximate Snellen acuity of 6/26 and 6/21, at a fixation distance of 70 cm.

Subjects were required to identify and record boxes with target text indicated by a list of text and required box colour. Distractors were either confusable text (eg Q for O, k for h) or required text on a different colour box. Subjects were required to indicate the location of the search objects by touching each object in sequence, using a provided list of the search objects. Subjects also checked objects off on the search list once they had been located.

Results of the experiment investigating head movement in the two visual tasks are reported in Chapter 7. Linear regression was undertaken to establish the relationships between peak and average velocity of head movement and head movement amplitude in these tasks.

6.3 To investigate the angular extent and velocity of head movement with PALs.

In considering the question of swim or induced motion created with PALs, variations in head movement velocity to which the vestibulo-ocular system is not adapted may be one factor in the subjective sensation of swim. In addition to evaluating head movement with PALs, this experiment also investigated whether PAL wear affects head movement velocity or induces more variability in head movement velocity than does single vision lens wear.

6.3.1 Subject selection criteria

1. Age range 48-55 years. Younger presbyopic patients were excluded as their residual accommodation may have influenced which regions of the progressive lens power gradient they used. Residual accommodation is minimal after the age of 50 (Millodot and Millodot 1989), so this factor was minimised in the experiments.
2. Visual acuity of 6/6 or better in each eye on a logarithmic scaled Snellen letter chart.
3. Normal binocular visual functions. Distance and near phorias within accepted clinical norms of between 2 prism dioptres (Δ) of esophoria and 8Δ exophoria at near (Saladin and Sheedy 1978). Stereopsis better than 60 sec arc.
4. No evidence of ocular pathology assessed using monocular indirect and direct ophthalmoscopy, and slitlamp biomicroscopy of the anterior segment.
5. Normal visual fields as assessed by Humphrey central visual field screening.
6. Refractive errors within the range of 2 dioptres (D) of myopia to 3 D of hyperopia, with up to 1D of astigmatism.

6.3.2 Experimental procedure

The shelving/search task described in Section 6.2.3 was repeated for subjects wearing PALs. Data was collected for head movement angular extent, average angular velocity and maximal angular velocity for subjects when wearing a single vision correction and while wearing a PAL. Subjects were recruited from the Optometry Clinic to meet the criteria in Section 6.3.1, where they were currently using either no refractive correction or a single vision correction and were being refitted with a PAL. Measurement of head movement behaviour took place with the single vision correction (or without correction), on collection and 1 month after collection of the PAL to assess the effect of adaptation. Data collection occurred in the manner described in Section 6.1 and 6.2.3. A different check list of target text and box colours was used for each measurement visit, with the list order randomised amongst subjects.

Data was collected for ten subjects for the angular extent of head movement, average angular velocity and maximal angular velocity. Variability of angular velocities was evaluated by using the standard deviation of these measures as a separate variable.

Results of this experiment are reported in Chapter 8. Data were analysed with repeated measures analysis of variance (ANOVA) to compare angular extent of head movement, average angular velocity, maximum angular velocity and the standard deviations for these measures in the non-PAL to the PAL situation, with post-hoc testing when indicated, using a Bonferroni adjustment for multiple comparisons. Linear regression was undertaken to establish the relationship between peak and average velocity of head movement to the amplitude of head movement.

Chapter 7 Head movements in common visual tasks

7.1 Introduction

This experiment aimed to establish parameters for the temporal characteristics of angular head movement and velocity of head movement occurring in two commonly undertaken visual tasks. These were a word-processing and copying task, and a search task designed to be equivalent to searching supermarket shelves. Parameters for head movement angles and velocities derived from this experiment were to be used to set the angular extent and velocity of head movement undertaken in subsequent experiments investigating minimum displacement thresholds with PAL wear. These subsequent experiments are described in Chapter 9 and the results reported in Chapter 10.

7.2 Methods in brief

Data for the angular extent of head movement, average velocity of head movement and the peak (maximal) velocity of head movement were obtained from subjects in two experimental conditions. Average velocity of head movement was calculated as the angular extent of head movement (in deg) divided by duration of head movement (in seconds). Peak velocity of head movement represented the maximal velocity within one sampling interval occurring within the head movement (in deg/0.1 sec, converted to deg/s) (see also Section 6.1 and Figure 6.2). Data were collected while subjects copied a ten-line paragraph of adult level text onto a computer-based word processor, and while subjects searched for letter or number targets presented on a shelving unit. Head movements were recorded using a Polhemus Inside Track head movement recording system, sampling head position at 10Hz. Custom written software analysed the head movement recordings off-line to calculate angular and velocity data.

A full description of the experimental design and data collection can be found in Chapter 6.

All subjects gave informed consent, and experimental and data collection methods were approved by the Queensland University of Technology's University Human Ethics Research Committee. Subject selection criteria are outlined in Section 6.2.1

Head movements were recorded for 15 subjects who performed the copy task, and for 10 subjects who performed the shelving search task. Five subjects participated in both experimental tasks. The angular extent, average and peak velocity, and duration for head movements in azimuth were extracted from the head movement recordings. Only azimuth data was used in analysis, as calibration experiments for the head movement recorder showed errors in estimating head movements in elevation (see Appendix A for results of these calibration trials). Head movements in azimuth less than 1° in angular extent and/or less than 0.3 s in duration were deleted from the resultant data set of head movements for each task. This was done to eliminate small head position changes due to the effects of breathing, and to eliminate any possible noise.

This resulted in 3516 head movements from the copy task, and 1164 head movements from the search task. Output from the Polhemus head tracker showed leftward directed head movements with negative values for angles and velocities; for the purpose of analysis, absolute values were used. The direction of the head movements was retained as a separate variable, and used as a factor in subsequent analyses. Head movements were also grouped in 3° ranges of movement. The effect of the direction of head movement on head movement angle and velocity was considered in a separate analysis (Section 7.7.1).

7.3 Head movements during the copy task

7.3.1 Angular ranges of head movement in the copy task

The distribution of head movements across all subjects recorded during the copy task is shown in Figure 7.1. This shows a markedly positively skewed distribution for the angular extent of head movements for the grouped data for all subjects. Median head movement angle across all subjects was 4.21°, with the interquartile range being 6.71°. The 90th percentile for head movement angle was 14.6°.

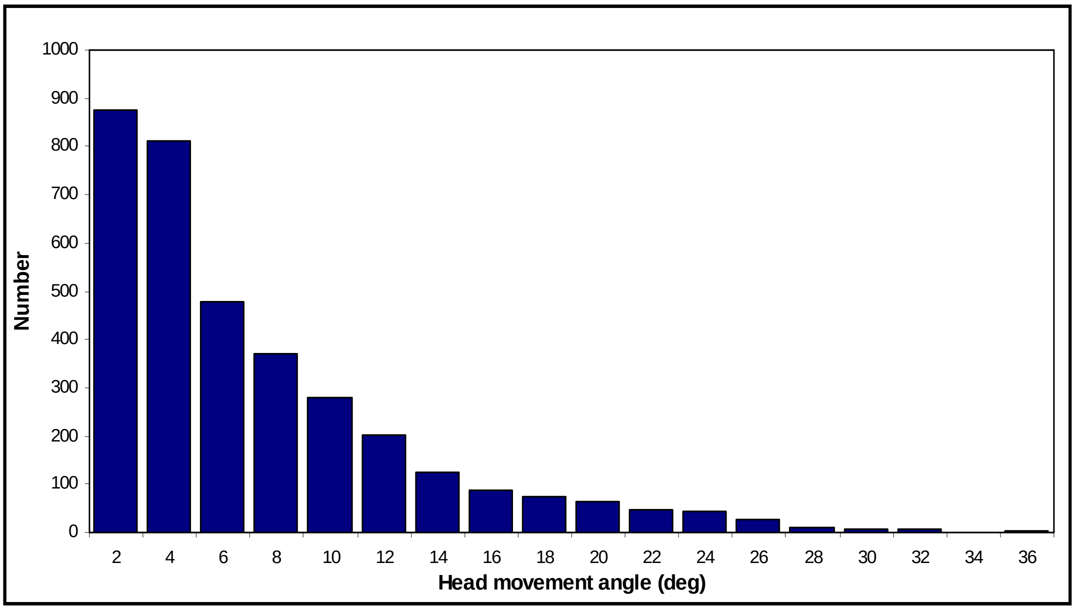

Figure 7.1 Frequency distribution of the angular extent of head movements during the copy task (ignoring direction of head movement). A positively skewed distribution is present, majority of head movements are under 12 -14°.

There was wide variation in the angular ranges of head movement performed during the copy task between subjects, particularly for the upper tail of the distribution (head movements greater in angular extent than subjects' 75th percentile for head movement angle). Descriptive statistics for individual subjects are shown in Table 7.2. These can be compared to the horizontal angular dimensions for the copy task shown in Table 7.1 (duplicate of Table 6.5). This shows that total horizontal gaze angle for the text passage was 22.5° to 34° from the centre line of the computer monitor to which subjects were aligned. In this context, the term gaze indicates the shift in fixation from central to a peripheral target (or the reverse): in terms of extent this shift in fixation is a result of both head turn and eye turn. Maximal angular gaze shift therefore was 34° for either a leftward gaze shift toward the beginning of the text paragraph, or for the return gaze shift to the keyboard/monitor centre line; gaze shifts to the right hand side of the monitor screen or keyboard would exceed 34°.

	Distance	Angle
Monitor screen H	13.95	13.1
Monitor screen V	10.3	9.7
Page RH	22	20.1
Page LH	43	35.6
Text LH	40.5	34.0
Text RH longest line	24.8	22.5
Text RH shortest line	25.9	23.3
Q-P key space	9.25	11.9
All keys H	14.25	17.9
All keys V	5	6.5

Table 7.1 Angular distances of the copy task, (* measured from centre); distance in cm, angle in degrees (as per Table 6.5). Angular distances for a 60 cm working distance. (H = horizontal, V = vertical, RH = righthand, LH = lefthand)

Other horizontal gaze shift amplitudes necessary for the copy task were 13º for the horizontal width of the computer monitor, and 18º for the width of the keyboard. As subjects were centred on the midline of the monitor and keyboard, gaze shifts required for these tasks are 6.5º and 9º respectively either side of centre. As can be seen from Table 7.2, the angular head movement component of the gaze shift was much less than the theoretical maximal gaze shift in most subjects. Maximum head movement angle was less than 20° in 8 of the 15 subjects, and 17º (half the maximum gaze shift distance) or less in 4 subjects.

Subject	Median	I-Q range	25 pctile	75 pctile	90 pctile	95 pctile	Maximum
1	3.72	6.91	1.62	8.54	10.79	11.50	17.11
2	2.95	5.52	1.40	6.93	10.53	11.53	19.18
3	6.60	13.88	3.33	17.21	22.87	24.97	34.54
4	4.63	6.98	1.97	8.95	13.30	16.08	24.28
5	2.90	4.88	1.69	6.57	8.30	9.30	15.90
6	10.18	9.74	2.70	12.44	13.63	15.69	19.60
7	8.38	6.79	3.30	10.09	13.72	15.51	18.79
8	11.73	16.34	2.57	18.91	24.63	30.64	32.33
9	2.60	14.95	1.71	16.66	22.73	25.50	31.20
10	2.29	1.91	1.74	3.65	5.00	6.86	12.78
11	2.50	2.16	1.77	3.92	5.28	6.23	18.98
12	2.79	2.70	1.65	4.35	7.08	8.28	13.59
13	3.12	4.07	1.81	5.88	9.96	13.07	23.79
15	4.47	4.66	2.44	7.10	9.75	11.04	20.54
16	8.75	9.59	2.96	12.59	15.70	17.41	23.71

Table 7.2 Descriptive statistics for the angular extent (in degrees) of head movements for individual subjects in the copy task. (I-Q range = interquartile range, pctile = percentile; viz. 25 pctile is the 25^{th} percentile)

In three subjects (subjects 3, 8, 9) maximal head movement angle reached in excess of 30º, indicating that some gaze shifts were accomplished by head movement only. Alternately, subjects 1, 5, 10 and 12 showed maximal head movement angles to an extent less than 50% of the maximum required gaze shift.

Table 7.2 and Figure 7.1 also indicate that there were a considerable number of small angle head movements. This is further demonstrated in Figures 7.2 and 7.3. These show head position in azimuth plotted against head position in elevation for two subjects, representative of subjects who made gaze shifts predominantly by head movement, or subjects in whom head movement made a lesser contribution to gaze shift.

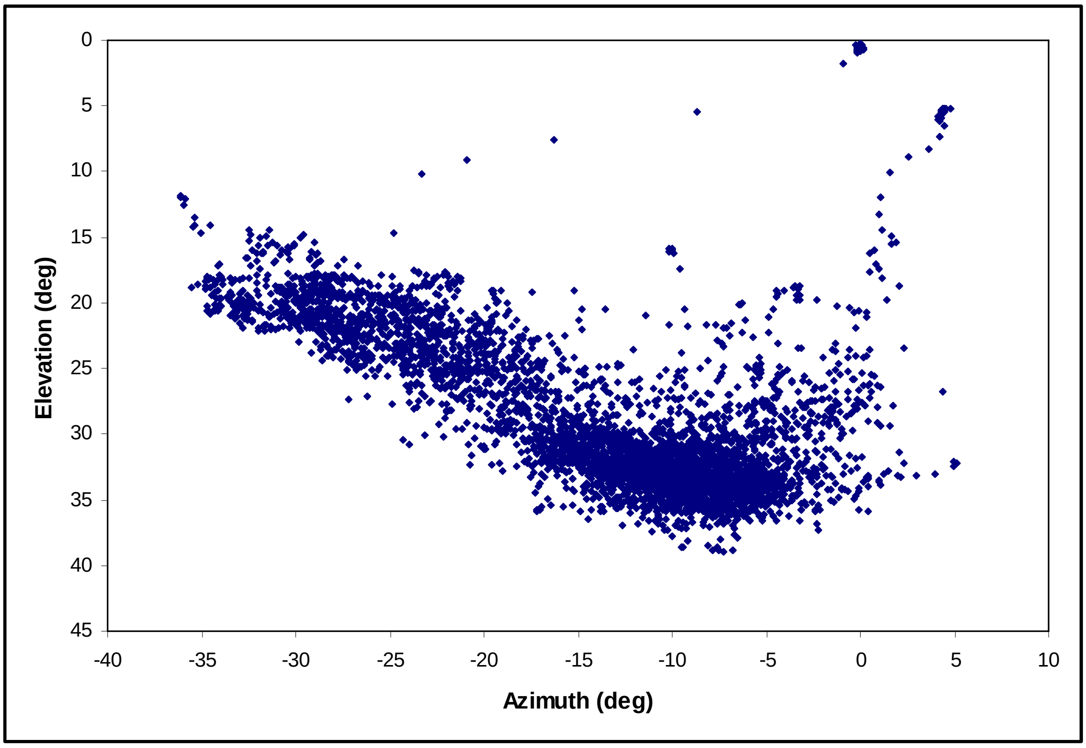

Figure 7.2 Head position in azimuth plotted against head position in elevation for subject 3. Negative values for azimuth represent left of centre; note reversed scale for *y-axis* as positive values for elevation indicate downward head movement. Head position at start of the recording represented by cluster of points at *x,y = 0,0*. Clusters of points represent gaze to keyboard and source text (see text below)

In Figure 7.2, there is a cluster of head position data points between *x = -20 and x = -35*. This indicates head position when attention was directed to the text (source copy) to the left of the monitor. Head position at the start of the recording is represented by the cluster of points at *x,y = 0,0*; this zero reference point for the head movement recorder was set by the subject fixating a target centred on the top of the computer monitor.Gaze shifts to the source copy were accomplished principally by head movement in this subject. A second cluster of points is located between *x = -5 to -15, at y 30 to 35.* These points, with the head depressed approximately 35º, indicate when subject's gaze was directed to the keyboard. This second cluster is of particular note, as this 10º range of gaze field shows that some gaze shifts within this range were accompanied by head movement in this subject.

Figure 7.3 similarly shows head position in azimuth plotted against head position in elevation for subject 5, who shows a different pattern of head positioning.

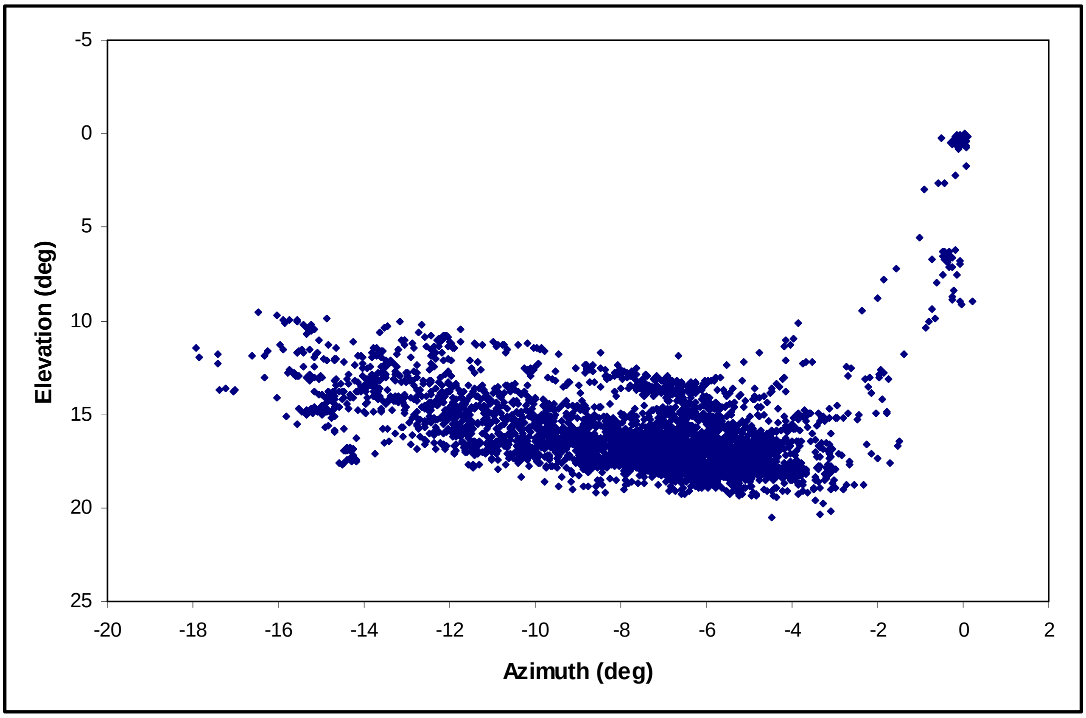

Figure 7.3 Head position in azimuth plotted against head position in elevation for subject 5. Negative values for azimuth represent left of centre; note reversed scale for *y-axis* as positive values for elevation indicate downward head movement. Head position at start of the recording represented by cluster of points at *x,y = 0,0*. Note difference in linear scale for both *x and y axes* compared to Figure 7.2.

For this subject, points representing head position cluster between *x = -12 and x = -16 for y = 10 to 15;* and secondly between *x = -2 to –10, y = 15 to 17.* As above, the first grouping represents head position when gaze is directed to the source copy, and the second grouping the keyboard. For this subject, the gaze shift to the source copy is associated with a lesser contribution of head movement than with subject 3.

7.3.2 Head movement velocity during the copy task

Velocity of head movement can be expressed as two variables; average velocity (angular extent of head movement/duration of head movement) and peak velocity (maximal velocity within one sampling interval within the head movement) (refer to Section 6.1 and Figure 6.2).

As was the case for the angular extent of head movement, the frequency distributions for average and peak velocity were markedly positively skewed. The distribution of average velocity is shown in Figure 7.4, while Figure 7.5 illustrates the distribution of peak velocities during the copy task. Median average velocity was 8.18 deg/s, with an interquartile range of 8.50 deg/s. Median peak velocity was 17.80 deg/s, with an interquartile range of 22.93 deg/s. The 90th percentiles for average and peak velocity were 20.74 deg/s and 51.69 deg/s, respectively.

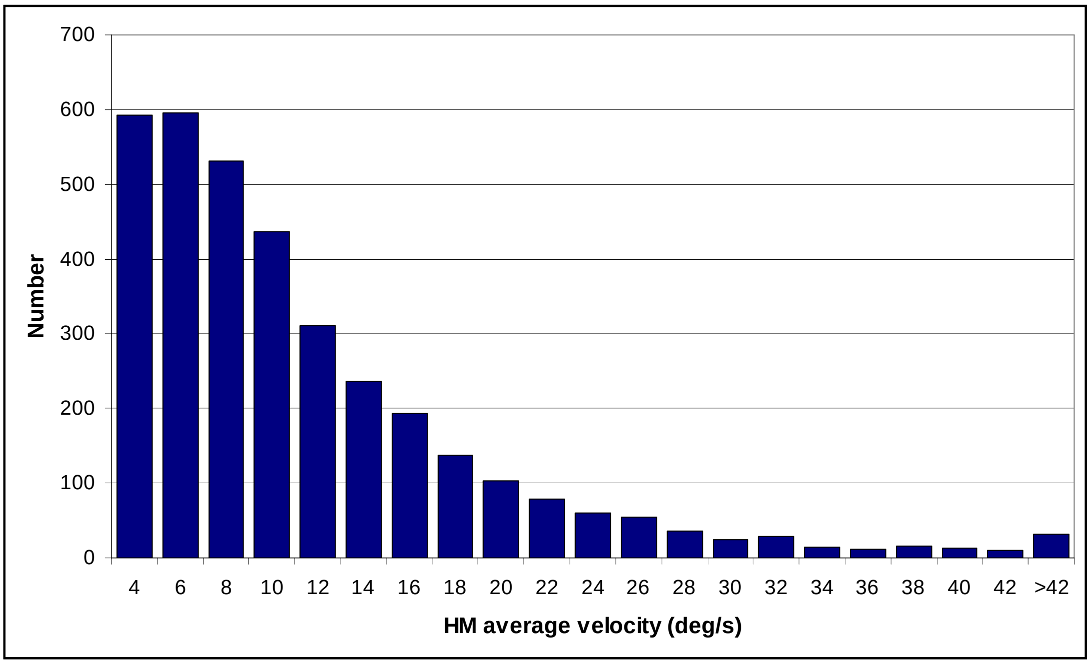

Figure 7.4 Frequency distribution of the average velocity of head movement (deg/s) during the copy task. The distribution shows a marked positive skew, with the majority of head movements showing average velocity below 16 deg/s.

Head movement velocity parameters for individual subjects are shown in Table 7.3 (average velocity) and Table 7.4 (peak velocity) (below).

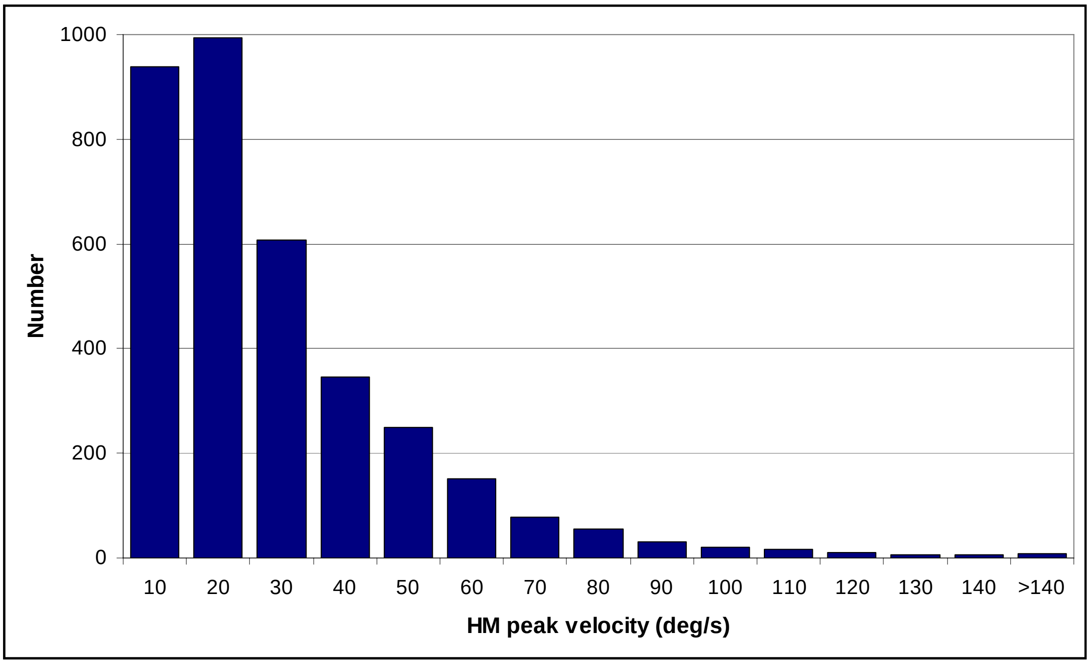

Figure 7.5 Frequency distribution of peak velocity of head movement (deg/s) during the copy task. As in Figures 7.1 and 7.4, distribution is positively skewed. The majority of head movements show peak velocity below 50 deg/s.

Subject	Median	I-Q range	25 pctile	75 pctile	90 pctile	95 pctile	Maximum
1	6.46	6.58	3.71	10.29	14.59	17.87	42.77
2	6.36	6.18	3.98	10.17	14.79	19.52	27.21
3	14.05	12.33	8.47	20.80	30.98	39.04	85.86
4	6.53	5.96	3.92	9.88	14.09	17.70	26.11
5	5.34	4.71	3.55	8.26	11.22	13.30	21.50
6	11.67	10.04	5.05	15.09	19.52	23.92	26.39
7	8.62	5.86	6.08	11.94	16.56	22.75	30.65
8	13.03	12.71	5.11	17.82	26.70	30.19	37.95
9	4.02	11.93	2.71	14.64	37.06	38.66	42.03
10	8.44	6.08	5.33	11.41	18.22	21.54	32.20
11	9.25	6.78	6.73	13.51	21.15	25.34	42.16
12	5.78	4.54	3.98	8.52	12.86	16.08	27.18
13	5.91	5.48	4.13	9.60	15.62	22.93	40.04
15	6.84	4.73	4.82	9.55	12.83	14.69	33.30
16	11.04	11.51	6.07	17.58	25.93	31.41	58.76

Table 7.3 Descriptive statistics for head movement average velocity (in deg/s) individual subjects during the copy task. (I-Q range = interquartile range, pctile = percentile; viz. 25 pctile is the 25th percentile)

Subject	Median	I-Q range	25 pctile	75 pctile	90 pctile	95 pctile	Maximum
1	13.70	23.21	6.78	29.99	40.10	49.29	74.51
2	11.58	17.77	6.92	24.69	37.05	46.27	79.99
3	28.18	33.21	15.57	48.79	78.65	103.78	248.91
4	13.91	19.16	7.01	26.17	38.39	46.70	67.79
5	11.85	12.90	7.50	20.40	27.69	31.49	58.80
6	33.66	40.30	9.25	49.55	58.94	64.24	119.51
7	25.45	24.98	12.63	37.61	48.87	66.54	84.09
8	30.02	33.29	13.39	46.67	64.95	85.96	101.83
9	9.13	38.80	5.77	44.57	71.28	95.29	100.55
10	17.40	14.00	11.60	25.60	33.64	44.96	65.60
11	20.34	18.74	13.98	32.72	46.41	54.62	103.86
12	12.16	11.27	7.37	18.64	27.43	32.89	55.32
13	12.35	13.74	7.86	21.59	39.86	50.94	74.98
15	15.29	12.37	9.24	21.61	26.99	34.15	55.64
16	30.58	38.46	12.14	50.60	66.10	78.28	133.44

Figure 7.4 Descriptive statistics for peak head movement velocity (in deg/s) of individual subjects during the copy task. (I-Q range = interquartile range, pctile = percentile; viz. 25 pctile is the 25th percentile)

7.4 Head movements during the search task

7.4.1 Angular extent of head movement during the search task

Head movements made during the search task also showed a positively skewed distribution (Fig 7.6, overleaf). Median head movement angle across all subjects was 4.91°, with an interquartile range of 8.78°. Maximum head movement was 42.9°, and the 90th percentile was 18.7°. Descriptive statistics for head movement angles found for individual subjects are shown in Table 7.5. Maximum gaze shift required for search targets at the end of each target row was 28° (for a fixation distance of 70 cm) from the centre of the target display; gaze shift required for an end to end gaze shift along a target row was 56° (see also Section 6.2.3.1).

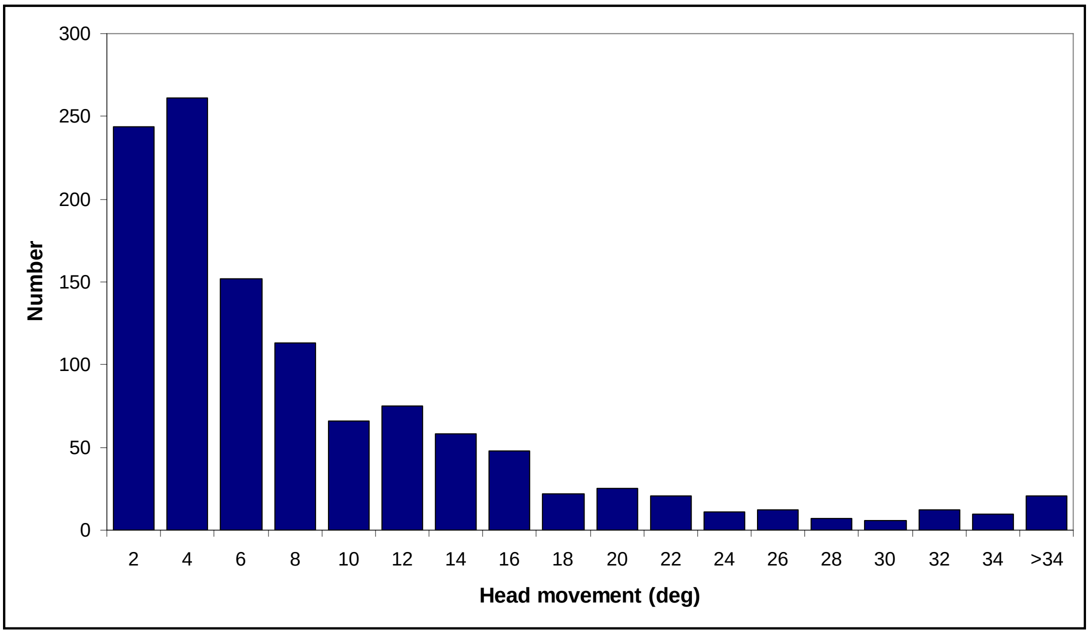

Figure 7.6 Frequency distribution of head movement angles (in degrees) during the search task. The majority of head movements are less than 16°; contrasted to Figure 7.1.

Subject	Median	I-Q range	25 pctile	75 pctile	90 pctile	95 pctile	Maximum
1	3.05	3.75	1.80	5.55	7.28	8.05	14.64
21	5.25	16.75	2.47	19.22	31.30	33.60	39.87
12	6.09	8.46	3.32	11.78	14.60	15.60	19.46
13	4.73	5.11	2.26	7.37	11.76	14.38	19.22
15	5.95	9.08	2.22	11.30	15.09	16.49	30.17
16	16.38	25.83	5.35	31.18	35.50	36.88	42.90
17	7.58	13.41	3.36	17.30	22.56	25.40	28.06
18	2.94	4.55	1.82	6.37	14.08	19.33	21.91
19	4.29	7.20	2.02	9.22	13.27	15.23	20.66
20	4.53	6.44	2.30	8.73	12.68	15.80	25.09

Table 7.5 Descriptive statistics for the angular extent (in degrees) of head movements of individual subjects in the search task. (I-Q range = interquartile range, pctile = percentile; viz. 25 pctile is the 25th percentile)

The angular extent of head movements made by individual subjects showed less variation between subjects compared to those made by subjects in the copy task for the upper tail of the distribution (see also Table 7.2). This would result from subjects adopting similar strategies for head movement during the search task. This is demonstrated in Figures 7.7 and 7.8, which show head position during the search task for two subjects.

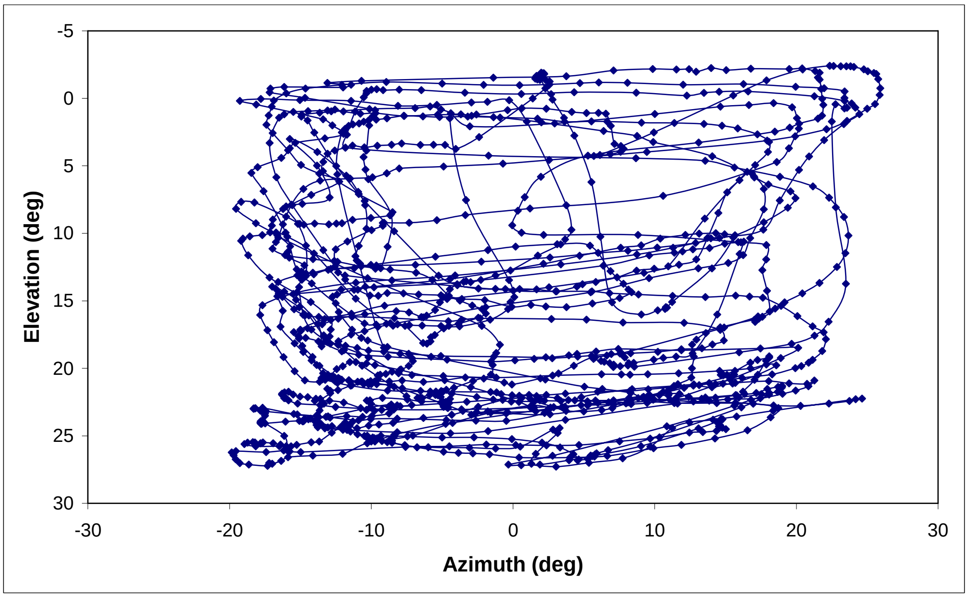

Figure 7.7 Head position during search task for subject 16 who has a maximum head movement angle of approximately 42°. Negative values for azimuth indicate head position to the left of centre, note reversed scale for *y-axis* as positive values for elevation indicate downward head movement.

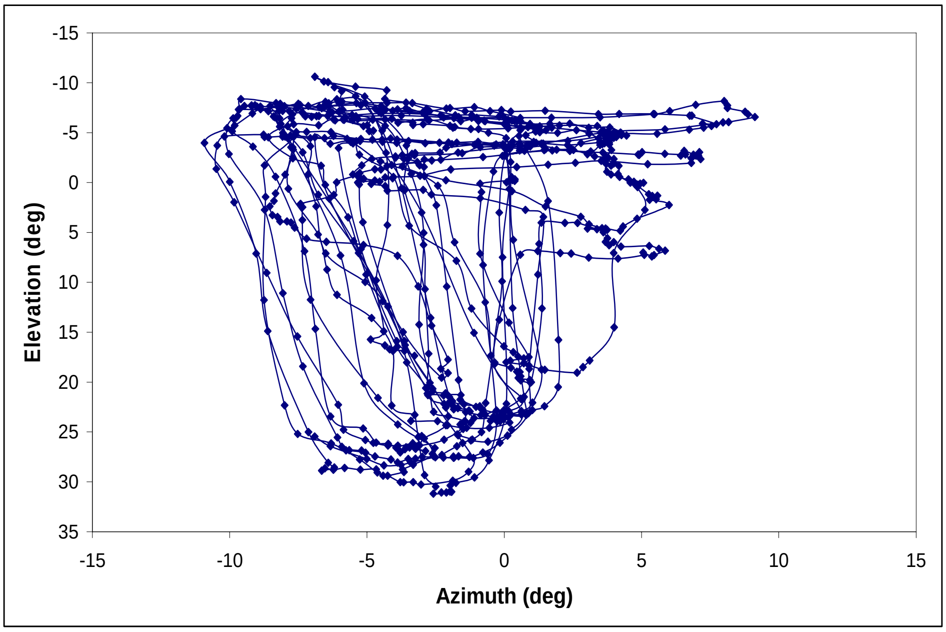

Figure 7.8 Head position during the search task for subject 13, who has a maximum head movement angle of approximately 19°. Note difference in scale for *x-axis* compared with Figure 7.7. Negative values for azimuth indicate head position to the left of centre; note reversed scale for *y-axis as* positive values for elevation indicate downward head movement.

Both subjects, who are representative of all subjects during the search task, show a linear pattern of head position which represents head movement along the linear arrangement of the targets (see Figure 6.5). The differing vertical range of head position is due to the different heights of the two subjects, subject 16 being slightly taller than subject 13. Subject 13 (Figure 7.8) also illustrates the vertical difference between the two components of the task, where the cluster of points at the top of the figure represents head position when gaze is directed to the target list which was hand held during the experiment. These two subjects also illustrate the difference in head movement strategy between a subject who accomplished gaze shifts during the search task primarily by head movement (subject 16, Figure 7.7) as opposed to a subject who showed a significantly reduced contribution of head movement to gaze shifts in this task (subject 13, Figure 7.8). Also apparent from Table 7.5, and Figures 7.7 and 7.8, is that, as in the copy task, gaze shifts to the various targets making up the search task, which were within a gaze shift range of $\pm 28°$ either side of centre (primary gaze), were accompanied by head movement.

7.4.2 Head movement velocity during the search task

As with the copy task, head movement velocity was described by two variables, average velocity (angular extent of head movement/duration of head movement) and peak velocity, the maximum angular separation of two sampling points during the head movement.

Similar to the situation with head movements during the copy task, head movement velocity during the search task showed a positively skewed distribution for both average and peak velocity. Figure 7.9 shows the distribution of average velocity, and Figure 7.10 the distribution of peak velocity (figures overleaf).

Median average velocity was 6.16 deg/s, with an interquartile range of 5.48 deg/s. Median peak velocity was 13.07 deg/s, with an interquartile range of 13.34 deg/s. The 90^{th} percentile for the velocity measures was 14.19 deg/s for average velocity, and 33.54 deg/s for peak velocity.

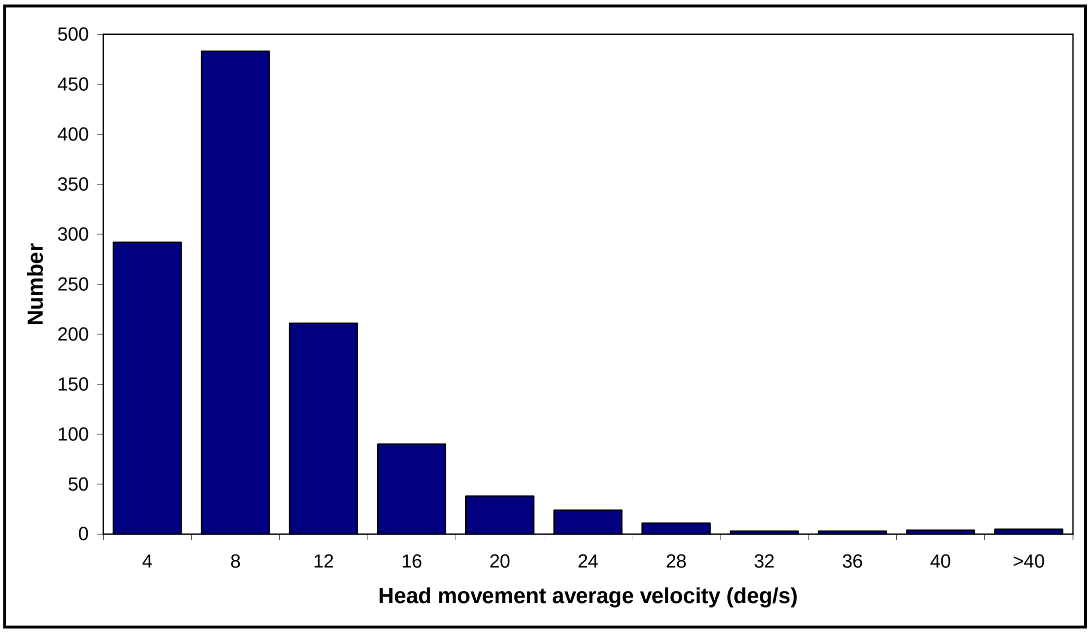

Figure 7.9 Frequency distribution of average velocity of head movements during the search task. Compare to Figure 7.4 – ‘peak’ of distribution in both tasks at 8 deg/s.

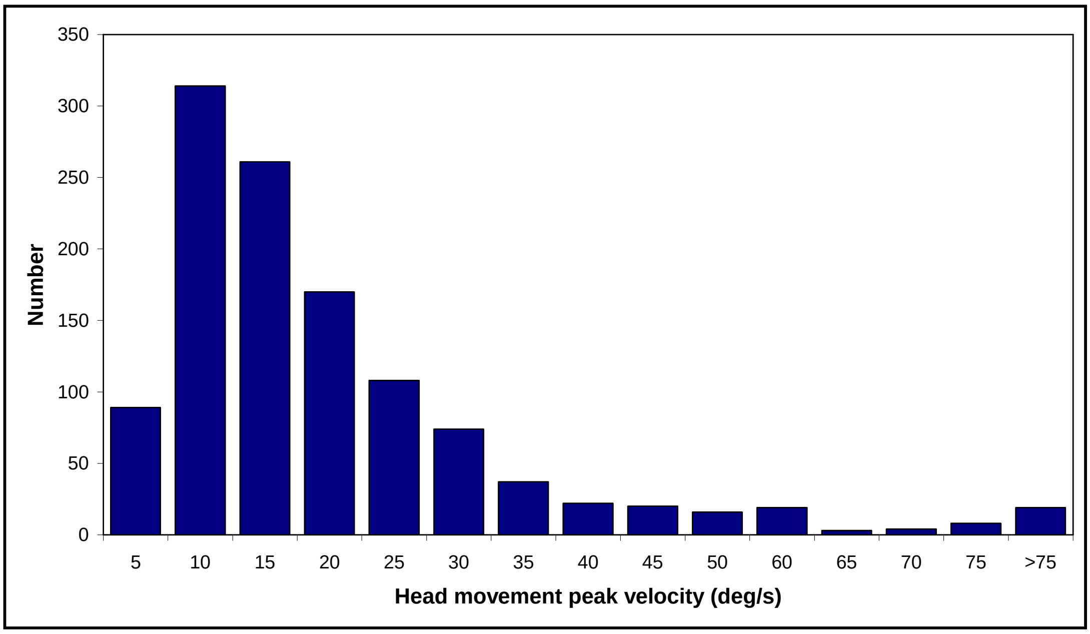

Figure 7.10 Frequency distribution of peak velocity of head movements during the search task. In comparison to Figure 7.5, the ‘peak’ of this distribution is at 10 deg/s compared to 20 deg/s in the copy task. Also note the difference in *x-axis* scaling between Figures 7.10 and 7.5.

Descriptive statistics for individual subjects are shown as Table 7.6 for the average velocity of head movement, and Table 7.7 for peak velocity.

Subject	Median	I-Q range	25 pctile	75 pctile	90 pctile	95 pctile	Maximum
1	4.00	2.38	2.93	5.55	7.28	8.05	12.00
21	9.58	12.52	4.97	17.49	24.90	37.18	73.55
12	7.82	4.64	5.53	10.17	13.53	14.52	21.70
13	6.56	3.71	4.46	8.17	10.74	13.64	24.09
15	5.58	3.24	4.01	7.26	9.80	11.36	14.88
16	12.99	11.91	8.51	20.41	25.58	29.30	54.06
17	7.23	4.41	5.27	9.68	12.50	15.28	29.43
18	5.25	3.74	3.63	7.37	10.77	13.43	23.22
19	5.17	4.46	3.57	8.21	11.48	13.79	19.84
20	5.35	4.52	3.40	7.92	12.15	14.50	17.92

Table 7.6 Descriptive statistics for individual subjects for average head movement velocity (in deg/s) for the search task. (I-Q range = interquartile range, pctile = percentile; viz. 25 pctile is the 25th percentile).

Subject	Median	I-Q range	25 pctile	75 pctile	90 pctile	95 pctile	Maximum
1	8.30	8.70	5.60	14.30	19.70	25.85	41.10
21	20.70	30.04	9.67	39.71	59.41	81.40	131.48
12	19.12	13.84	10.95	24.79	32.51	40.49	51.10
13	12.63	9.28	8.76	18.04	23.99	27.22	30.34
15	12.73	8.48	7.70	16.18	19.50	26.16	37.92
16	30.72	38.44	17.14	55.57	78.98	85.62	104.00
17	16.80	12.82	11.29	24.11	32.60	40.38	72.70
18	10.23	9.37	7.35	16.72	24.93	29.74	49.82
19	11.09	10.46	7.37	17.83	25.93	29.73	57.78
20	11.26	10.77	7.42	18.19	26.51	34.49	54.62

Table 7.7 Descriptive statistics for individual subjects for peak head movement velocity (in deg/s) for the search task. (I-Q range = interquartile range, pctile = percentile; viz. 25 pctile is the 25th percentile).

Figures 7.9 and 7.10 however show a distribution of average and peak head movement velocity that is over a lower range of velocity than the distribution of velocities in the copy task as shown in Figures 7.4 and 7.5. Median average and peak head movement velocity are lower in the search task than in the copy task. Median average head movement velocity during the search task was 6.16 deg/s compared to 8.18 deg/s in the copy task. For peak velocity, the median for peak velocity during the search task was 13.07 deg/s compared to 17.8 deg/s in the copy task. The slower head movement velocity for the search task is also apparent when Tables 7.6 and 7.7 are compared to the equivalent tables for the copy task (Tables 7.3 and 7.4, Section 7.3.2). This is examined in Section 7.5 for the relationship between head movement velocity and head movement angular extent.

7.5 Relationship between the angular extent and velocity of head movement

The main sequence (Bahill et al. 1975, see also Section 4.4) for head movement was established for head movements found in both tasks in this study. While skewness is reported to not make a substantive difference in analysis in large sample sizes (Tabachnik and Fidell 2001), log transformation of angular and velocity data was performed to normalise the distribution in order to meet the assumptions of normality underlying linear regression. Normality of the log-transformed data was established using the Kolmogorov-Smirnov statistic, bearing in mind that with large samples this statistic is often significant (Pallant 2002), which would indicate a non-normal distribution. For this reason, the Normal Q-Q plots produced by SPSS analysis software were also inspected. These plot the observed value of a variable against the expected value for the normal distribution based on the sample mean and standard deviation (Pallant 2002). A reasonably straight line on these plots indicates a normal distribution. An illustrative Normal Q-Q plot resulting from this analysis is shown for log peak velocity during the copy task as Figure 7.11 below, with the frequency distribution histogram of the log transform for peak velocity (log deg/s) during the copy task shown as Figure 7.12. For each of the variables head movement angle, average velocity and peak velocity, in both visual tasks, the log transformations more closely resembled normal distributions than did the raw data.

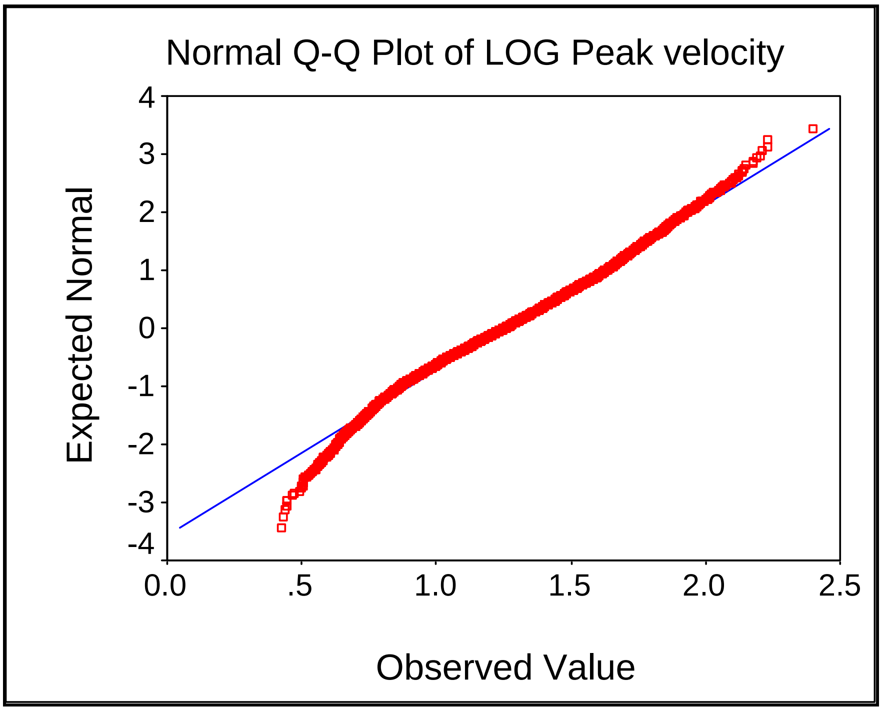

Figure 7.11 Normal Q-Q plot for log peak velocity (log deg/s) during the copy task. Distribution is approximately normal as points in majority lie along the straight line which represents the expected result if distribution was normal.

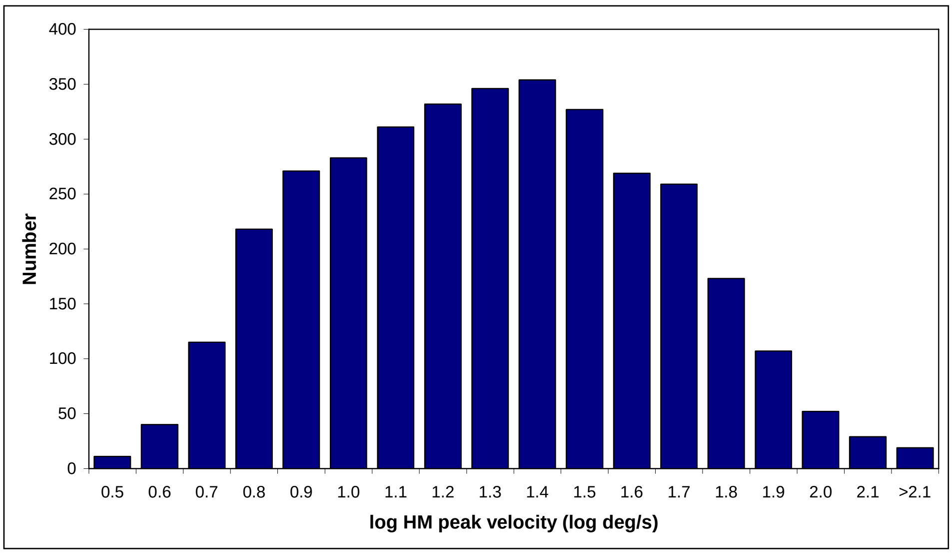

Figure 7.12 Frequency distribution of log peak velocity (log deg/s) in the copy task, showing a more normal shape to the distribution. Compare to Figure 7.5 which shows a marked positive skew to the distribution of peak velocity in the copy task.

Linear regression was then performed on the log-transformed data to establish the relationship between log head movement angle and log average and log peak velocity of head movement for both tasks. Main sequence type relationships were found for both log average velocity and log peak velocity with the log angle of head movement, for both tasks. The main sequence plots of log peak velocity and log angle are shown for the copy task (Figure 7.12) and the search task (Figure 7.13).

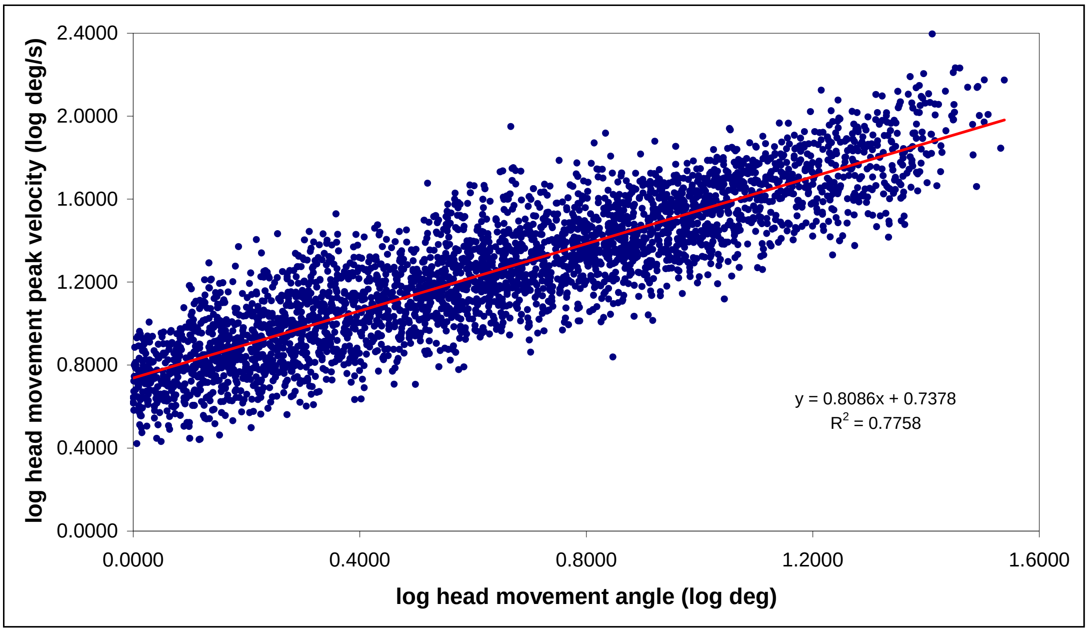

Figure 7.12 Main sequence plot of log peak velocity (log deg/s) on log angle (log deg) for head movements during the copy task. The regression equation for log peak velocity on log angle is also shown. Peak velocity and amplitude are linearly related.

Figures 7.12 and 7.13 demonstrate a linear relationship between log peak velocity and log angle for head movements in both tasks. The slope of the main sequence is steeper in the copy task than in the search task.

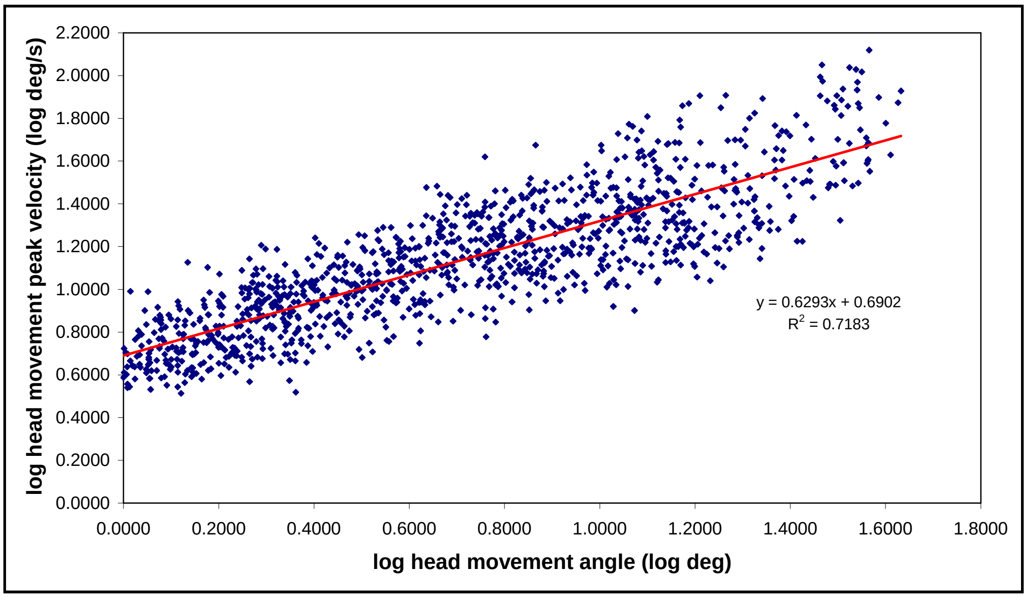

Figure 7.13 Main sequence plot of log peak velocity (log deg/s) on log angle (log deg) for head movements during the search task. The regression equation for log peak velocity on log angle is also shown; as in Figure 7.12, peak velocity and amplitude are linearly related.

Regression equations were calculated for log average and log peak velocities on log head movement angle for both tasks using the linear regression function of SPSS. The resultant equations are shown in Table 7.9. Correlations between the three variables were determined by Pearson's ‘r’, 2 –tailed. The regression equations show that both greater log average and log peak velocities result for a given head movement angle change in the copy task compared to the search task.

	Regression equation	Pearson's 'r'	'r^2'	Significance (2 tail)
Copy task				
log average velocity	log AV = 0.631 log ANG + 0.514	0.791	0.626	p<0.0001
log peak velocity	log PV = 0.809 log ANG + 0.738	0.881	0.776	p<0.0001
Search task				
log average velocity	log AV = 0.50 log ANG + 0.45	0.77	0.593	p<0.0001
log peak velocity	log PV = 0.629 log ANG + 0.69	0.848	0.719	p<0.0001

Table 7.9 Regression equations and correlation coefficients for head movement log average velocity and log peak velocity (log deg/s) with log angle (log deg), for both tasks. Steeper slope of the regression line exists for velocity in the copy task than the search task.
(AV = average velocity, PV = peak velocity, ANG = head movement angle)

7.6 Other temporal aspects of head movements in the two tasks

7.6.1 Directional effect on head movement velocity

During the initial analysis of head movement angle and velocity, observation of the head movement recorder output suggested an asymmetric velocity profile for head movements during the copy task, dependent upon the direction of the head movement. This is illustrated in Figure 7.14 (same head movement recording extract as shown in Figure 6.2), where the leftward head movements starting at sampling point 8 and sampling point 62 (shown by the downward curves on the graph from these points, red arrows) are followed by rightward head movements (upward curve, green arrows) of approximately the same extent in each case, but involving fewer sampling points, and a steeper slope to the curve representing the head movement. This indicates the rightward directed head movements are of greater velocity than the leftward movements, during the copy task. In the copy task from which this example is drawn, the subjects' task required them to copy from source text situated to the left of the computer monitor. To do this accurately, subjects would be required to accurately relocate gaze to the previously read portion of source text. Returning gaze to the computer keyboard (or monitor) would not necessarily require an accurate re-fixation landing point for gaze. Hence, subjects could have adopted a gaze strategy where gaze shifts to specific landing sites on the source text (leftward gaze/leftward head movement) were slower than the return gaze shifts which took gaze back to a less precisely selected keyboard or monitor location.

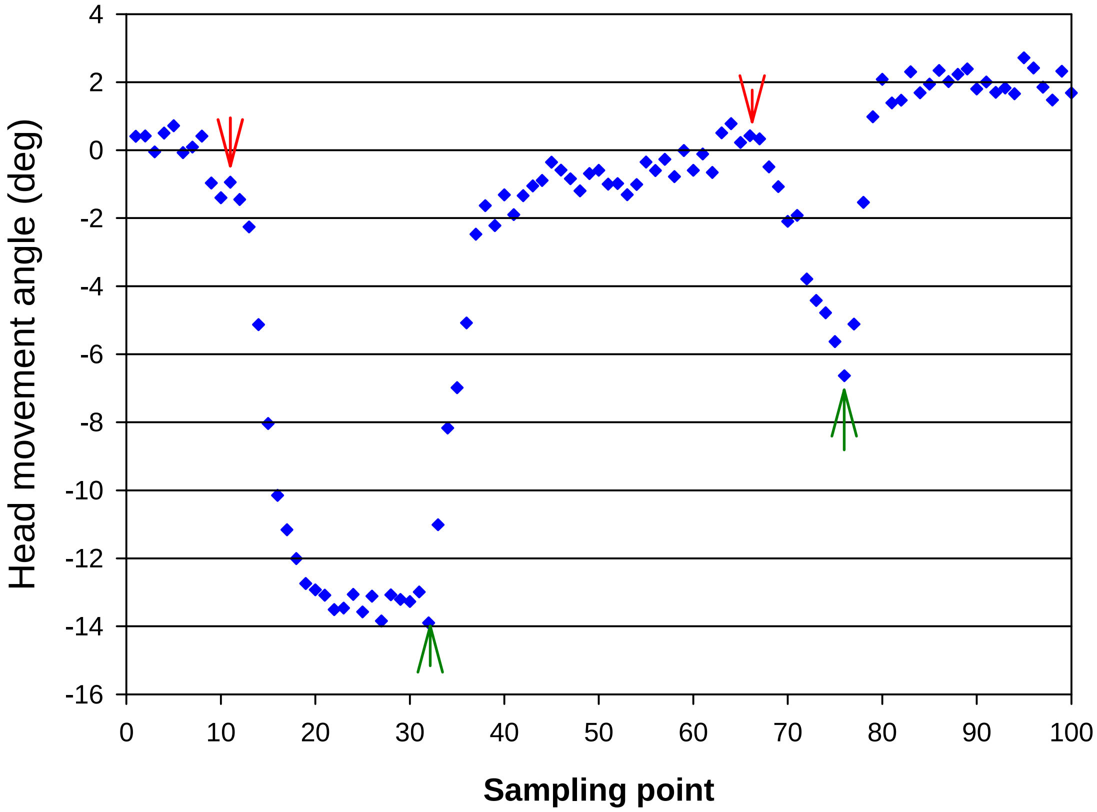

Figure 7.14 Head movement recorder output during the copy task. Negative values for angle represent left directed movements. Leftward head movements (from sampling points 8 and 62, red arrows) followed by rightward movements (green arrows) of greater velocity (steeper slope to curve)

To investigate this, for both tasks, head movements were labelled by direction (left or right), and were also grouped into 3° range groups according to the absolute value of their angular size (Table 7.10, see also Section 6.1). A multivariate analysis of variance (MANOVA, SPSS Inc) , with log average velocity and log peak velocity as dependent variables, and direction (2 levels) and head movement range (9 levels) as the independent factors[1] was performed separately for head movements from the copy and search tasks.

[1] The assistance of Dr Harry Bartlett, Dept of Mathematics and Statistics, Queensland University of Technology, in providing advice for this statistical analysis is gratefully acknowledged.

Head movement range group	Angular extent
1	≤ 2.999º
2	3 to 5.999º
3	6 to 8.999º
4	9 to 11.999º
5	12 to 14.999º
6	15 to 17.999º
7	18 to 20.999º
8	21 to 23.999º
9	≥ 24º

Table 7.10 Head movement angular extent range groups used in analysis of directional effects on head movement velocity in both visual tasks.

7.6.1.1 Effect of head movement direction, copy task

The multivariate analysis of variance showed a statistically significant effect of head movement direction on the combined dependent variables of log velocity of head movement (Wilks' lambda = 0.986, $F_{2, 3497} = 24.03$, $p < 0.0005$). The effect of the head movement range on the log velocity of head movement was statistically significant (Wilks' lambda = 0.271, $F_{16, 6994} = 402.0$, $p < 0.0005$). This effect of head movement range would be expected, as, as already shown (Section 7.5), there is a linear relationship between both head movement log average and peak velocities and the log angular extent of head movement, with velocity increasing as head movement angle (represented in this analysis by range groups) increases.

The combined interaction of head movement direction and head movement range also had a statistically significant effect on log head movement velocity (Wilks' lambda = 0.984, $F_{16, 6994} = 3.62$, $p < 0.0005$). This is considered further below.

Considering the dependent variables (log average velocity and log peak velocity) separately, head movement direction, head movement range and the combined interaction of direction and range showed statistically significant effects on log average and log peak head movement velocity respectively.

Rightward directed head movements during the copy task were overall faster across all subjects and head movements than leftward directed head movements. The mean log average velocity of rightward head movements was 1.20 log deg/s(SE of mean 0.01, 95% CI for mean 1.18 – 1.220), leftward directed head movements had a mean log average velocity of 1.114 log deg/s (SE of mean 0.007, 95% CI for mean 1.10 – 1.13); this difference was statistically significant ($F_{8, 3498} = 43.11$, $p < 0.0005$). Similarly, mean log peak velocity of 1.60 log deg/s (SE of mean 0.009, 95% CI for mean 1.58 – 1.62) for rightward head movement was statistically significantly ($F_{8, 3498} = 42.95$, $p < 0.0005$) faster than the leftward head movement mean log peak velocity of 1.516 log deg/s (SE for mean 0.007, 95% CI for mean 1.5 – 1.53). These values for log velocities represent differences between right- and left- directed head movements of 2.86 deg/s (average head movement velocity) and 6.69 deg/s (peak head movement velocity) for the head movement components of gaze shift in the copy task, with rightward movements being faster than leftward ones.

The directional effect of the head movement differs for different head movement angles (represented by range groups). The interaction of direction with head movement range is statistically significant for both log average velocity ($F_{8, 3498} = 5.546$, $p < 0.0005$) and log peak velocity ($F_{8, 3498} = 5.373$, $p < 0.0005$). This is shown in Figure 7.15 and 7.16. These show log average velocity (Figure 7.15) and log peak velocity (Figure 7.16) for rightward and leftward head movements plotted against head movement range. The difference in log head movement velocity for the directions of head movement is minimal for smaller range head movements, but increases as head movement range increases. Leftward directed head movements (towards the source copy) during the copy task become slower than rightward directed head movements as head movement angle increases.

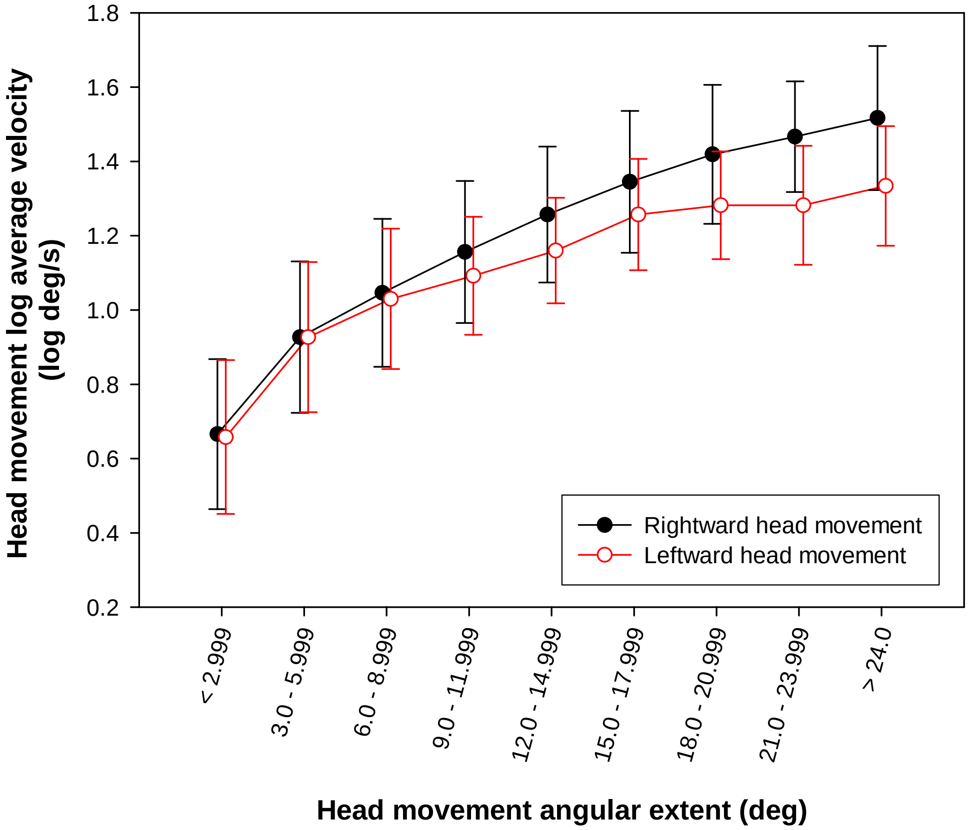

Figure 7.15 Log average velocity of head movement for both right- and left- directed head movements during the copy task plotted against head movement range. Points are displaced for clarity. Error bars represent one standard deviation. Velocity differential between right and left directed movements increases past head movement range of 9-11.999°.

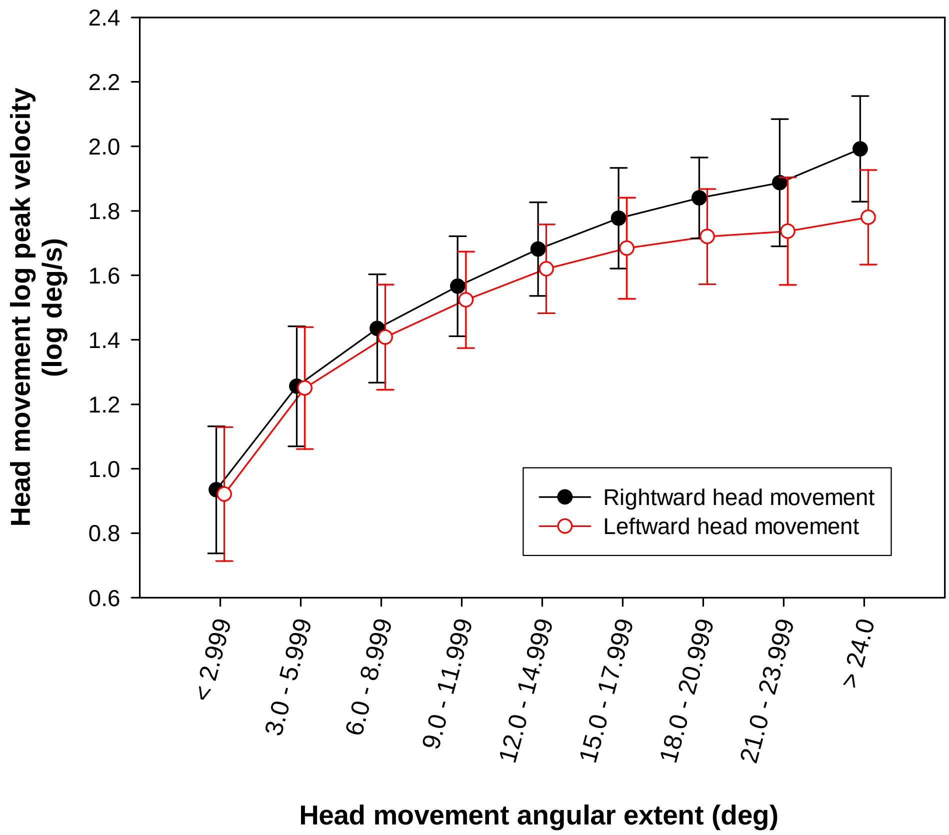

Figure 7.16 Log peak velocity of head movement for both right- and left- directed head movements during the copy task plotted against head movement range. Points are displaced for clarity. Error bars represent one standard deviation. Velocity differential between right and left directed movements increases past head movement range of 6 – 8.999°.

Tables 7.11 (log average velocity) and 7.12 (log peak velocity) show the values of the difference in rightward and leftward head movement velocity for both average and peak head movement velocity during the copy task.

Head movement range group	Right (log deg/s)	Left (log deg/s)	Right (deg/s)	Left (deg/s)	R - L diff (deg/s)
1	0.666	0.658	4.63	4.55	0.09
2	0.927	0.927	8.45	8.45	0.00
3	1.046	1.030	11.13	10.72	0.40
4	1.156	1.092	14.33	12.37	1.97
5	1.257	1.161	18.08	14.48	3.61
6	1.345	1.257	22.16	18.09	4.07
7	1.419	1.282	26.25	19.13	7.12
8	1.467	1.283	29.28	19.17	10.12
9	1.517	1.334	32.91	21.60	11.31

Table 7.11 Mean log average velocity (log deg/s) for right and left directed head movements for head movement range groups during the copy task. Shown also are the equivalent mean velocities in deg/s, and the difference (deg/s) (right – left) of these velocities.

Head movement range group	Right (log deg/s)	Left (log deg/s)	Right (deg/s)	Left (deg/s)	R - L diff (deg/s)
1	0.935	0.921	8.60	8.35	0.26
2	1.256	1.249	18.02	17.75	0.27
3	1.435	1.408	27.24	25.58	1.65
4	1.566	1.524	36.84	33.46	3.38
5	1.681	1.621	48.02	41.76	6.26
6	1.777	1.684	59.80	48.28	11.52
7	1.840	1.720	69.23	52.52	16.71
8	1.887	1.737	77.14	54.53	22.60
9	1.992	1.780	98.23	60.28	37.95

Table 7.12 Mean log peak velocity (log deg/s) for right and left directed head movements for head movement range groups during the copy task. Shown also are the equivalent mean velocities in deg/s, and the difference (deg/s) (right – left) of these velocities.

The right to left velocity differences for log average and log peak velocity were not significantly different for a head movement range less than 9º (groups 1-3) (at p = 0.05, 2 -tailed, independent t-tests, Bonferroni adjustment for multiple comparisons). The right to left differences for both log average and log peak velocity were significantly different for each head movement range group for head movement ranges of 9º or greater (independent t-tests, $p< 0.05$, 2 tailed, Bonferroni adjustment for multiple comparisons). For each range group, rightward head movements were faster than leftward head movements. The right to left difference for the mean peak velocity increased from 3.38 deg/s for head movements between 9 and 12º, to 37.95 deg/s for head movements greater than 24º (Table 7.12), with leftward head movements being slower as head movement range increased. Head movements of these angular sizes would be most likely associated with gaze shifts to the source copy (situated 22° to 34° left centre, see Table 7.1). This supports the hypothesis above that subjects adopted a selective strategy dependent upon the task required, within the copy task. As outlined, leftward gaze shifts would be required to land on an accurate refixation point for each subsequent gaze shift to the source text, owing to the need for accurate processing of text information, whereas the gaze shift returning fixation to the keyboard or monitor could be less accurate in its landing point.

7.6.1.2 Effect of head movement direction, search task

No statistically significant effect of the direction of head movement was found on the multivariate analysis of variance for the combined dependent variables of log average and peak velocity (Wilks' lambda = 0.998, $F_{2, 1145} = 1.410$, $p = 0.245$). Thus head movement velocity was not significantly affected by head movement direction during the search task. No significant effect for head movement direction was found for log average and log peak velocity during the search task, when the two variables were considered separately.

As with the copy task, a statistically significant effect on head movement velocity was found for head movement range (Wilks' lambda = 0.31, $F_{16, 2290} = 113.78$, $p < 0.0005$). This effect was expected, as head movement log average and peak velocity showed a linear relationship with log head movement angle in the search task (Section 7.5). Head movement range also showed a statistically significant effect on log average velocity ($F_{8, 1146} = 181.13$, $p < 0.0005$) and log peak velocity ($F_{8, 1146} = 314.41$, $p < 0.0005$), as would be predicted from the regression equations in Section 7.5.

For the combined log velocity dependent variables, there was a significant effect of the interaction between head movement range and direction (Wilks' lambda = 0.974, $F_{16, 2290} = 1.904$, $p = 0.016$). When considering this interaction effect for the dependent variables separately, direction and head movement range showed a significant interaction for log average velocity ($F_{8, 1146} = 2.065$, $p = 0.036$) and also log peak velocity ($F_{8, 1146} = 2.162$, $p = 0.028$).

Figure 7.17 shows log average velocity during the search task plotted against head movement range for each direction of head movement (right and left). Figure 7.18 is the interaction plot on a similar basis for log peak velocity.

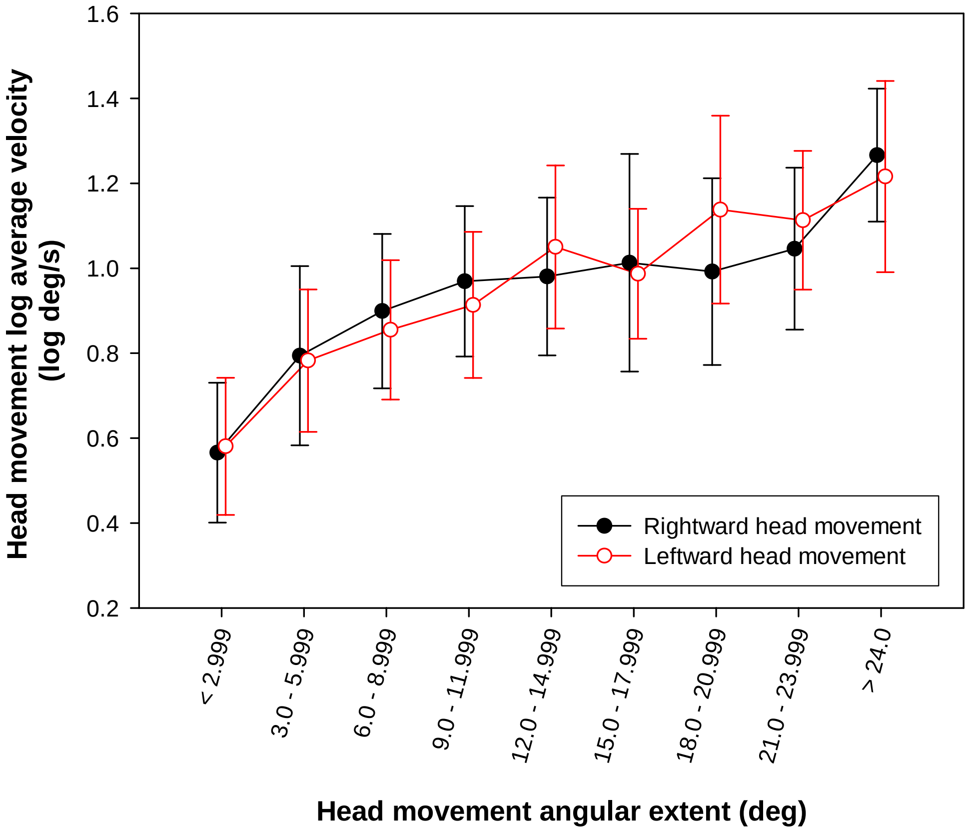

Figure 7.17 Interaction plot of log average velocity (log deg/s) for head movements during the search task by direction against head movement range group. Error bars are one standard deviation. Points are displaced for clarity. Compared to Figure 7.15, less difference exists for average velocity in rightward and leftward head movement.

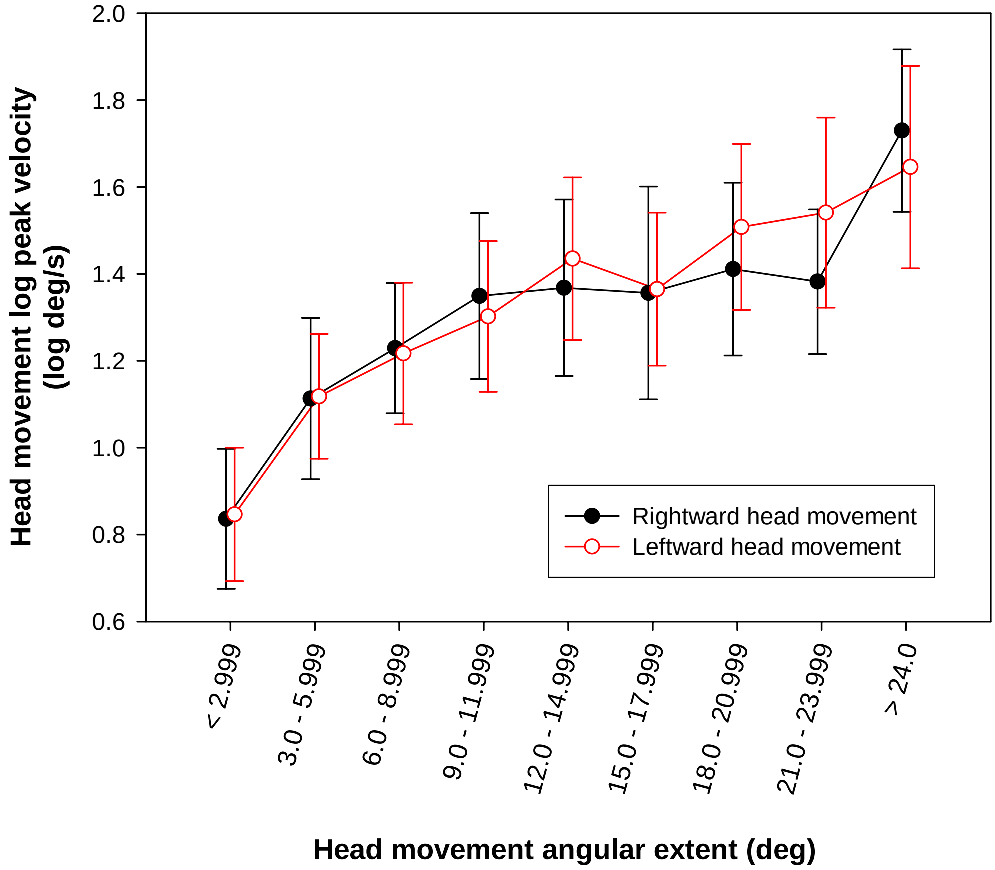

Figure 7.18 Interaction plot of log peak velocity (log deg/s) for head movements during the search task by direction against head movement range. Error bars are one standard deviation. Points are displaced for clarity. Again, as with Figure 7.17, compared to Figure 7.16, less difference exists in the search task between rightward and leftward directed head movement.

The right to left differences in the means of log average and log peak velocity during the search task are shown in Tables 7.13 and 7.14; also shown are the equivalent values of the means in deg/s.

Head movement range group	Right (log deg/s)	Left (log deg/s)	Right (deg/s)	Left (deg/s)	R - L diff (deg/s)
1	0.566	0.581	3.68	3.81	-0.13
2	0.794	0.783	6.22	6.06	0.16
3	0.899	0.855	7.93	7.16	0.77
4	0.969	0.914	9.31	8.20	1.11
5	0.981	1.050	9.56	11.22	-1.65
6	1.013	0.987	10.30	9.71	0.60
7	0.992	1.138	9.82	13.75	-3.93
8	1.046	1.113	11.11	12.98	-1.87
9	1.262	1.217	18.29	16.46	1.83

Table 7.13 Mean log average velocity (log deg/s) for right and left directed head movements for head movement range groups during the search task. Shown also are the equivalent mean velocities in deg/s, and the difference (deg/s) (right – left) of these velocities.

Head movement range group	Right (log deg/s)	Left (log deg/s)	Right (deg/s)	Left (deg/s)	R - L diff (deg/s)
1	0.836	0.846	6.86	7.02	-0.16
2	1.113	1.118	12.96	13.13	-0.16
3	1.229	1.217	16.96	16.49	0.47
4	1.350	1.302	22.37	20.06	2.32
5	1.368	1.435	23.36	27.24	-3.88
6	1.356	1.365	22.71	23.16	-0.45
7	1.411	1.508	25.79	32.19	-6.40
8	1.382	1.541	24.13	34.76	-10.63
9	1.730	1.646	53.71	44.30	9.41

Table 7.14 Mean log peak velocity (log deg/s) for right and left directed head movements for head movement range groups during the search task. The equivalent mean velocities in deg/s, and the difference in means (deg/s) (right – left) of these velocities are also shown.

The difference in log velocities for right and left directed head movements, suggested by the analysis of variance, was further explored by independent t-tests, which were performed for the unpaired right and left directed log velocity data as the dependent variables within each head movement range grouping. No statistically significant difference was found between log average or log peak velocity for right and left directed head movement within any head movement range group (for $p \leq 0.05$, 2-tailed, Bonferroni adjustment for multiple comparisons). The direction of head movement within the search task therefore did not affect the log average or peak velocity of head movement within the search task.

Figures 7.17 and 7.18 also show a plateau in the curve for log average velocity for head movements between 9º and 24º; and between 6º and 24º for log peak velocity. This is also evident in Tables 7.13 and 7.14, where the log velocity values are similar between the different head movement ranges between 6º and 24º. When each direction of head movement is considered separately, a series of independent t-tests comparing log velocities between head movement range bins shows no significant difference for log average velocity for range group pairs between 9º and 24º, and similarly no significant difference between log peak velocity for range group pairs between 6º and 24º ($p > 0.05$, 2 tailed, Bonferroni adjustment), in each instance. These head movement range groups are equivalent to a head movement angular extent (in log deg equivalents) of between 6° and 23.99°. This indicates that subjects adopted a common head movement velocity profile over this range of head movement, with a constant head movement velocity component to gaze shift in scanning rows of targets.

7.6.2 Relationship between velocity measures

The eye movement literature shows that the two expressions of velocity, average (mean) and peak, as used in this experiment in relation to head movement, are linearly related when saccadic eye movements are considered (Inchingolo et al. 1987, Becker 1989, Pelisson and Prablanc 1988, Lebedev et al. 1996, Harwood et al. 1999) (see also Section 4.4.1). If similar linear relationships exist between the velocity parameters for head movements in this experiment, any effect of PAL wear on the velocity profile of head movement in new PAL wearers (Section 6.3, also Chapter 8) may be manifest in the relationship between peak and average velocity of head movement. To establish these relationships for head movement in the tasks used in the current experiment, slope of the regression line for peak on average velocity was calculated for each subject group and for subjects individually, and compared for the different directions of head movement for each task.

The ratio of peak to average velocity has been published for saccadic eye movements, and shown to be constant over a range of amplitudes (Pelisson and Prablanc 1988, Harwood et al. 1999). As this is constant for saccadic eye movements over a range of saccade amplitudes, this would represent optimal control of the timing of eye movement. The ratio of peak to average velocity for head movements has not been reported previously, and is established in this experiment for head movements occurring in two common visual tasks. Should peak to average velocity of head movement show a constant ratio, as exists for saccadic eye movement, any effect of PAL wear on the velocity profile of head movement may show as change to this ratio. This is investigated in the second experiment, where head movements in first time PAL wearers are investigated.

7.6.2.1 Peak to average velocity regressions

As described in Section 7.5, the log transformed values for peak and average velocity were used in this analysis. Figure 7.19 shows the main sequence for log peak on log average velocity for the copy task, and Figure 7.20 similarly for the search task.

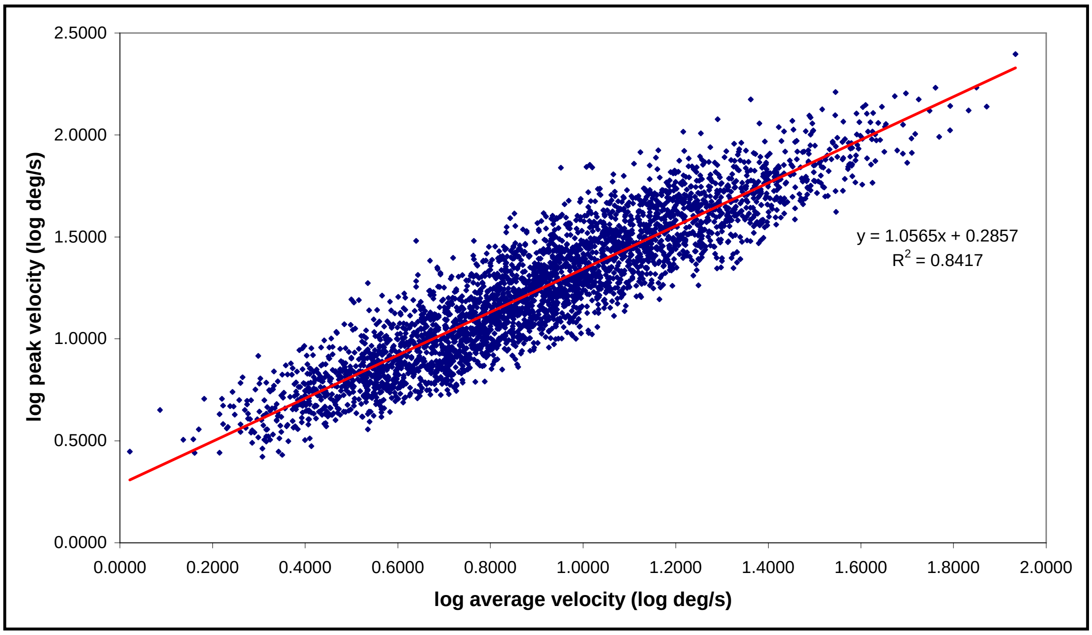

Figure 7.19 Regression plot of log peak velocity (log deg/s) on log average velocity (log deg/s) for head movements of all subjects during the copy task. A linear relationship is shown for peak and average velocity.

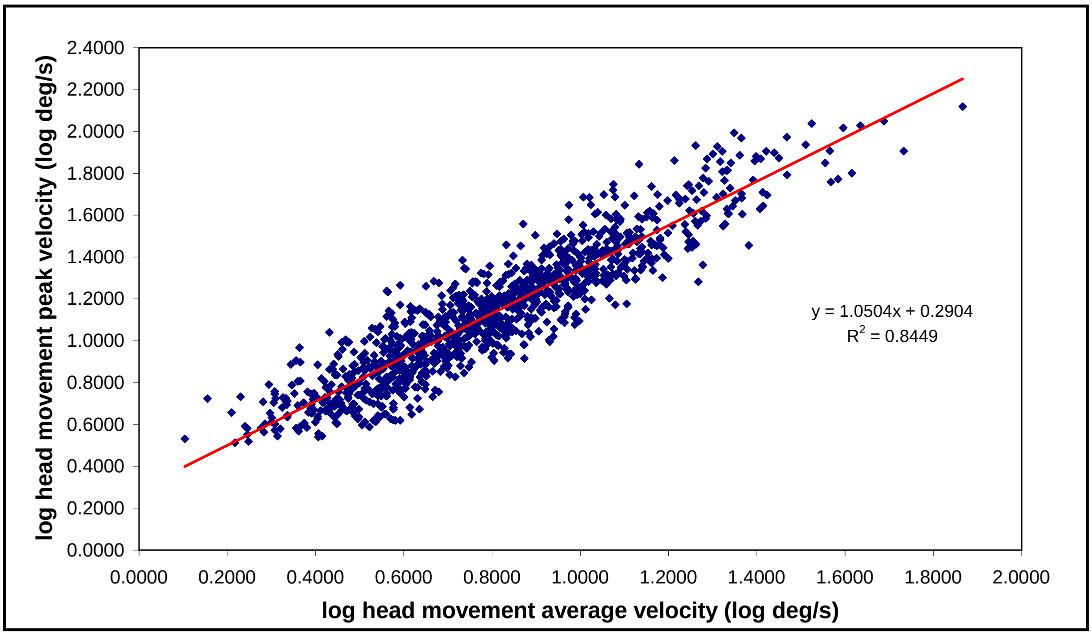

Figure 7.20 Regression plot of log peak velocity (log deg/s) on log average velocity (log deg/s) for head movements during the search task, all subjects. As in Figure 7.19, a linear relationship is shown; also note similarity in slope of regression in both figures.

Strong linear relationships exist between log peak and log average velocity of head movement in both visual tasks. For the copy task, log peak velocity = 1.0565 log average velocity + 0.286, $r^2 = 0.842$, Pearson's r = 0.9174, $p < 0.0005$ (2 tailed). In the search task, log peak velocity = 1.05 log average velocity + 0.282, $r^2 = 0.862$, Pearson's r = 0.919, $p < 0.0005$ (2 tailed). Of note is the similarity between the regression line slopes for both tasks (copy: 1.0565, search 1.05), whereas the velocity profiles (Section 7.3.2 and 7.4.2) are different in the two tasks, with the search task showing a slower velocity profile than the copy task.

When head movements are classified by their direction, log peak velocity and log average velocity are also linearly related (Table 7.15); the table shows data for all subjects. Slopes of the regression line for each direction of head movement show little difference between directions and tasks.

	Regression equation	Pearson's 'r'	'r^2'	Significance (2 tail)
Copy task				
Right head movt	log PV = 1.045 log AV + 0.294	0.923	0.852	p < 0.0005
Left head movt	log PV = 1.071 log AV + 0.274	0.911	0.83	p < 0.0005
Search task				
Right head movt	log PV = 1.058 log AV + 0.282	0.929	0.862	p < 0.0005
Left head movt	log PV = 1.043 log AV + 0.299	0.909	0.826	p < 0.0005

Table 7.15 Regression equations for log peak velocity on log average velocity of head movement during both tasks. (PV = peak velocity, AV = average velocity)

The slope of the regression line of log peak on log average velocity was calculated for each subject for both directions of head movement within both tasks. Slope of the regression line for each subject was then used as the dependent variable in a within subjects/between groups repeated measures analysis of variance, with direction of head movement (2 levels) as the within subjects factor, and task (2 levels) as the between groups factor.

The mean difference (right – left) in regression line slope for log peak on log average velocity for the copy task was -0.045 ± 0.099 (95% CI for difference: -0.0998 to 0.0097). Mean difference in regression line slope for the search task was –0.0096 ± 0.008 (95% CI for difference: -0.026 to 0.007). In both tasks, leftward directed head movement showed a minimally steeper slope, on average, to the regression line of log peak on log average velocity than rightward directed head movement.

This minimal difference in slope for the different directions of head movement was not statistically significantly different ($F_{1, 23} = 1.267$, $p = 0.272$). The interaction of direction of head movement with task also had no effect on regression line slope ($F_{1, 23} = 0.569$, $p = 0.458$). The visual task undertaken again had no effect on regression line slope ($F_{1, 23} = 0.131$, $p = 0.721$).

7.6.2.2 Ratio of peak to average velocity

The ratio of peak velocity to average velocity (peak/average) for head movements in both tasks was calculated, and termed 'velocity ratio' for subsequent analysis.
The velocity ratio for both tasks showed a noticeably positively skewed frequency distribution of values. Table 7.16 shows descriptive statistics for velocity ratio for both tasks. In the copy task, median velocity ratio was 2.14, with an interquartile range of 0.95. For the search task, median velocity ratio was 2.12, with an interquartile range of 0.80.

	Median	I-Q range	25 pctile	75 pctile	90 pctile	95 pctile	Minimum	Maximum
Copy	2.14	0.95	1.73	2.68	3.39	3.82	1.01	7.71
Search	2.12	0.80	1.76	2.56	3.10	3.44	1.03	4.10

Table 7.16 Descriptive statistics for velocity ratio, both tasks. (I-Q range = interquartile range, pctile = percentile (viz. 25 pctile = 25^{th} percentile))

As the frequency distribution of velocity ratio was positively skewed for both tasks, data was log transformed to normalise the distribution, as discussed in relation to peak and average velocity in Section 7.5. Normality tests on the log transformed distribution for velocity ratio were conducted as described in Section 7.5.

A univariate analysis of variance was performed to investigate the effect of direction of head movement (2 levels) and amplitude of head movement (represented by range groups, 9 levels) on log velocity ratio as the dependent variable separately for both tasks.

In the copy task, head movement direction had no effect on log velocity ratio ($F_{1, 3498} = 0.489$, $p = 0.484$). Head movement range had a statistically significant effect ($F_{8, 3498} = 128.22$, $p < 0.005$), which was expected as the velocity values from which the ratio is derived show an effect for head movement range, with velocity increasing as head movement amplitude increases. The combined interaction of direction and range has no significant effect on log velocity ratio ($F_{8, 3498} = 1.341$, $p = 0.218$). This is illustrated in Figure 7.21, which shows similar log velocity ratio across the different head movement range groups.

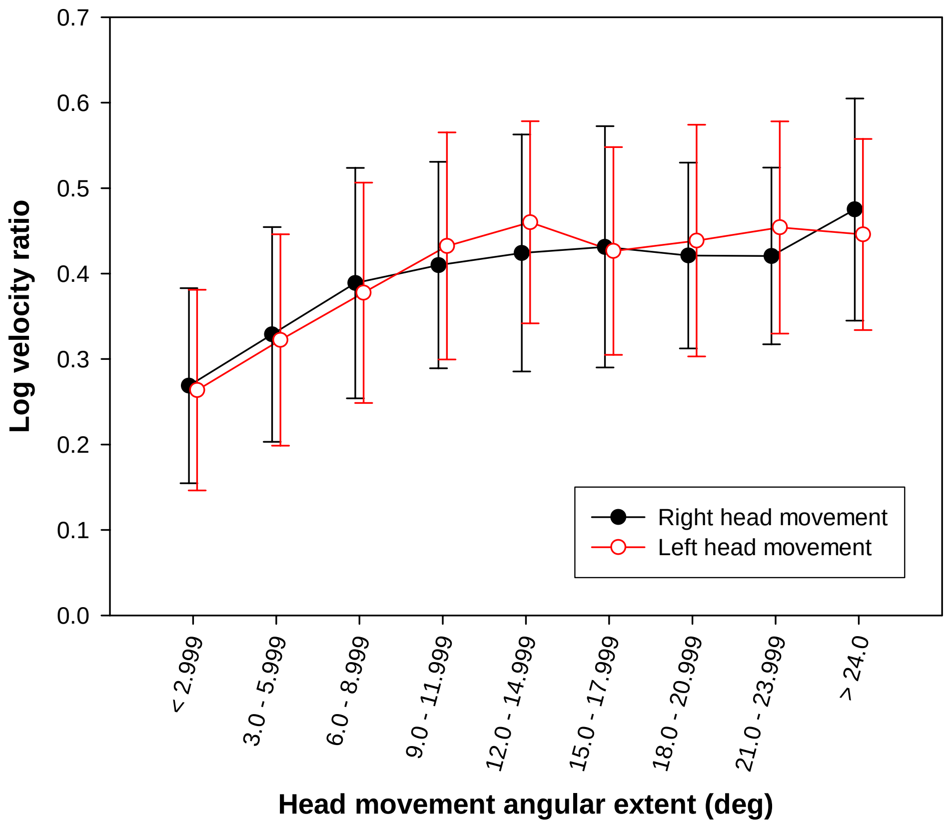

Figure 7.21 Log velocity ratio for right and left directed head movements plotted against head movement range (represented by range groups, see Table 7.10) for the copy task. Points displaced for clarity. Velocity ratio is similar for both directions of head movement over the range of amplitudes.

Log velocity ratio also increased linearly for head movement amplitudes less than 2.999° to 8.999°, and then was relatively constant for head movements > 9°.

For the search task, head movement direction also had no significant effect on log velocity ratio ($F_{1, 1146} = 0.326$, $p = 0.568$). The combined interaction of direction and head movement range also had no significant effect on log velocity ration ($F_{8, 1146} = 0.876$, $p = 0.536$). Head movement range had a statistically significant effect on log velocity ratio ($F_{8, 1146} = 35.07$, $p < 0.0005$), as indicated above, this was expected.

The lack of effect of direction of head movement is apparent in Figure 7.22, where log velocity ratio is plotted by direction against head movement amplitude.

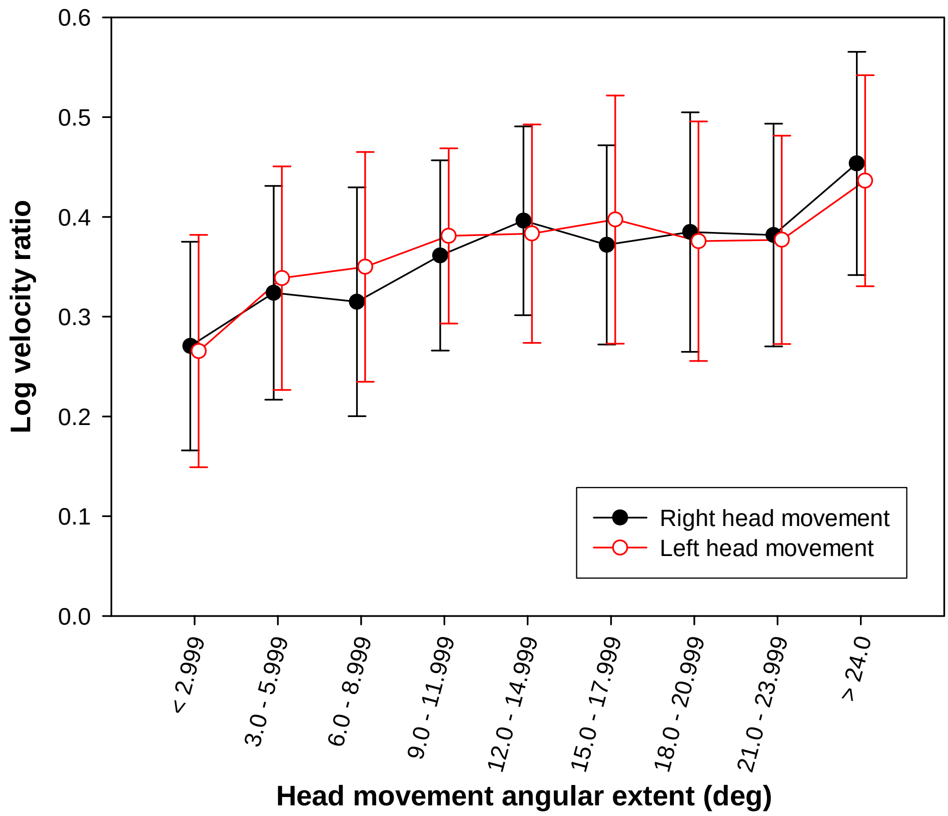

Figure 7.22 Log velocity ratio for right and left directed head movements plotted against head movement range (represented by range groups, see Table 7.10) for the search task. Points displaced for clarity. As in the copy task (Figure 7.21), velocity ratio is similar for both directions of head movement.

As was seen with the copy task, log velocity ratio increased linearly initially for small head movements, then was more constant for head movements > 9°.

Log velocity ratio data for both directions was then combined for each task separately, and plotted against head movement amplitude represented by range groups. The result is shown in Figure 7.23.

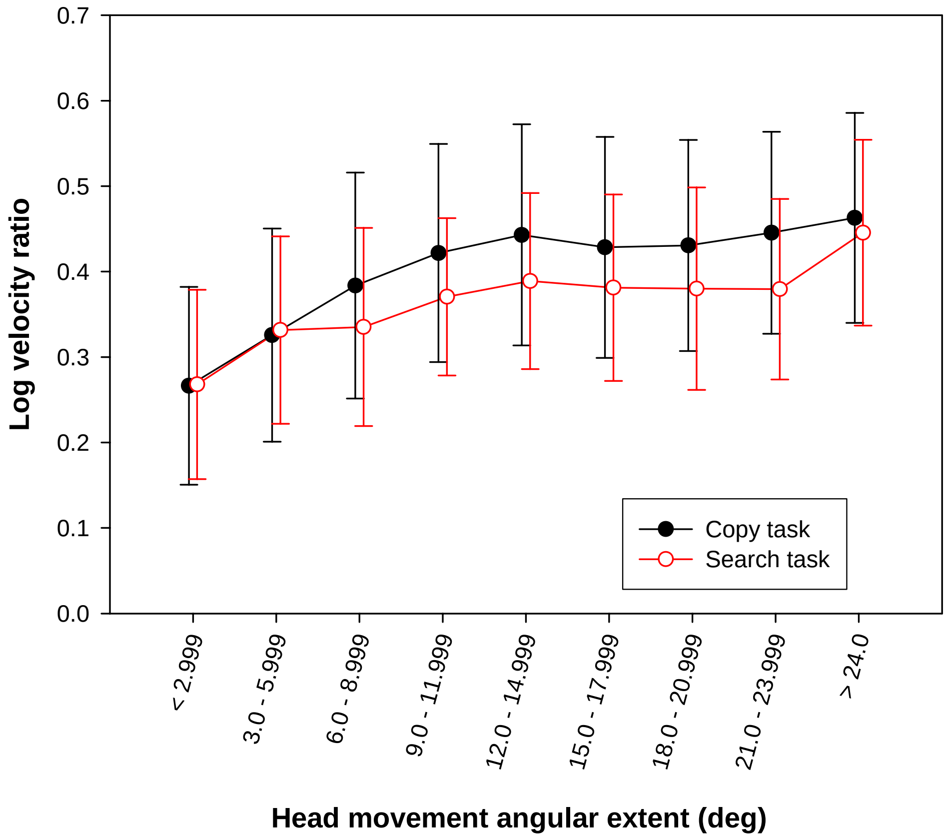

Figure 7.23 Log velocity ratio for both tasks for head movement range groups. Points displaced for clarity. Data for all subjects.

For small angle head movements (< 6°, range group 2), log velocity ratio was identical for both tasks. This was then constant for both tasks, ranging from 0.42 to 0.44 for the copy task, and 0.37 to 0.39 for the search task for head movements from 9° to 24° (range groups 3 to 8). These equated to velocity ratios of 2.63 to 2.75 for the copy task, and 2.34 to 2.45 for the search task.

Data for log velocity ratio in both tasks was combined, and the effect of task on log velocity ratio was investigated with an analysis of variance with log velocity ratio as the dependent variable, and task (2 levels: copy and search) and head movement range (9 levels) as the independent factors.

The task undertaken had a significant effect on log velocity ratio ($F_{1, 4662} = 28.61$, $p < 0.0005$). Head movement amplitude represented by range groups had an expected effect on log velocity ratio ($F_{8, 4662} = 112.28$, $p < 0.0005$); this is expected as the velocity variables from which the ratio is derived increase linearly in relation to head movement amplitude. The combined effect of task and head movement range had a significant effect on log velocity ratio ($F_{8, 4662} = 3.931$, $p < 0.0005$). These effects are shown in Figure 7.23, where log velocity ratio in the copy task is greater for all ranges of head movement above 6º compared to the search task.

Subjects adopted differing head movement velocity strategies dependent upon task, with slower peak and average velocities in the search task. The slope of the main sequence regression line of log peak to log average velocity was unaffected by the task.

7.7 Discussion

7.7.1 Head movement angular extent during the visual tasks

For both visual tasks undertaken in this experiment, the frequency distributions of head movement angular extent showed a significant number of small angle head movements, in a markedly positively skewed distribution (Figures 7.1 and 7.6). Median head movement angle was 4.21º (interquartile range 6.71º) in the copy task, and 4.91º (interquartile range 8.78º) in the search task.

There was considerable inter-subject variability in the ranges of head movement undertaken in both tasks (Tables 7.2 and 7.5). This is more apparent for head movements greater than the 75th percentile in each subject. In the copy task, horizontal gaze angle for the source text passage was 22.5º to 34º to the left of the subject midline (which was centred on the computer monitor midline). These angles, and for the return of gaze from source text to the computer monitor/keyboard (which could exceed 34º) would represent the maximum gaze shift required. Differences in maximal head movement angles during the copy task were found between subjects. Maximum head movement angle was in excess of 30º for three subjects, indicating they made the gaze shifts required for the monitor/keyboard to source text (and return) predominantly by head movement. Other subjects showed maximum head movement angles that were less than 50% of the maximum gaze shifts. This variation in individual head movement behaviour, and by implication, eye movement behaviour, is consistent with gaze shifts being accomplished with either a greater contribution of head movements ('head movers') or with a lesser contribution of head movements ('eye movers' or 'non-movers') (Afandor and Aitsebamao 1982, Fuller 1992, Stahl 1999). This inter-subject variation was also found in the search task, but to a lesser extent (Table 7.5). For the search task, maximum gaze angle would be from the start of one row of targets to the end of the row (Figure 6.5), which subtended an angle of 56º at a fixation distance of 70 cm. At this distance, individual search targets were separated by 2.9º. Maximum head movement angle in this group of subjects was 14.64º to 42.9º, indicating that some subjects accomplished gaze shifts with a bigger contribution of head movement than others, as in the copy task. The lesser inter-subject variability in the search task indicates subjects adopted similar strategies for head movement during the search task.

Few investigations have performed tasks similar to the ones in this experiment. Lee (1999) investigated eye and head movements for three subjects in a reading task for Korean text which subtended a visual angle of 90º across the lines of text (at a fixation distance of 35 cm). Individual characters subtended approximately 38 min arc. Lee's (1999) experimental task more closely resembles the search task of this experiment, albeit at a shorter working distance. Head movement angular parameters were not reported in the study, although Lee reports mean gaze amplitudes of 2.57º (approximately 4 Korean characters), with head movements contributing approximately 16% of individual gaze movements. Han et al. (2003) have investigated eye and head movements in a simulated computer task. Head and eye movements were recorded while subjects read either a single page of text (to simulate a computer screen) presented on the subjects' midline at a distance of 60 cm, or a two-page layout where one text page was on the subject's midline and the second page centre placed 30º to the right of the midline (to simulate the workplace environment for office based equipment, with subjects required to read from page to page). They recorded the total amplitude of head movement across the lines of text. For the double page layout, mean total head movement amplitude while reading was 16º for subjects wearing single vision lenses.

In the present experiment, subjects were required to copy text from a source page onto a computer monitor, which differed from the subject requirement in Han et al. (2003). Their subjects were required to read across the paired rows of text in the two page layout; in this experiment, subjects made step (saccadic like) head movements from source to copy.

Gaze shift angles for the components of the visual task required in the copy task (e.g. viewing the target text, computer keyboard, computer monitor) and the search task were all within the angular ranges in which it has been reported gaze shifts result predominantly from eye movement. Head movements are considered to contribute minimally to gaze shifts of <20º (Tomlinson and Bahra 1986 ab, Gresty 1974, Guitton and Volle 1987, Phillips et al. 1995, Freedman and Sparks 1997, Stahl 1999). Afandor and Aitsebaomo (1982) and Aitsebaomo and Afanador (1982) indicate a 'dead zone' of approximately 13.5º at near in which head movement is unlikely to occur for LED targets subtending 25 min arc at the fovea; this "dead zone" was increased to 22º for letter recognition stimuli. Stahl (1999) found a range of eye-only movement (35.8º ± 31.9º) for step-like gaze shifts to LED targets spaced 1º apart over a 180º array at a fixation distance of 97 cm. These studies investigating head and eye movement contributions to gaze shifts have used targets for the gaze shift requiring fixation only, rather than including a visual processing component, unlike the visual tasks required in the copy task in this experiment. Head movement angles found in both tasks in this experiment would indicate that head movements contribute to gaze shift over a greater range of gaze shift amplitudes. This is in agreement with the finding of Lee (1999) of close coupling between eye and head movement for small (<3º) gaze shifts.

7.7.2 Head movement velocity

Two expressions of head movement velocity were determined in this experiment. Average velocity (deg/s) was derived from the amplitude of the head movement/duration of the head movement. Peak velocity (deg/s) was the maximal velocity of the head movement occurring in one sampling interval. Head movement velocity (peak or average) showed a positively skewed distribution (Figures 7.4, 7.5, 7.9 and 7.10). Average velocity of head movement was greater in the copy task compared to the search task, with a median value of 8.18 deg/s in the copy task compared to 6.16 deg/s in the search task. Peak velocity was also greater in the copy task compared to the search task; median peak velocity in the copy task being 17.8 deg/s compared to 13.07 deg/s in the search task. Variability of both peak and average velocity was also greater in the copy task compared to the search task, with wider interquartile ranges in the copy task (Tables 7.3, 7.4. 7.6 and 7.7). These findings suggest a task related effect on head movement velocity (see below).

Measures of peak velocity of head movements have been made under a number of differing experimental conditions. Stark et al. (1980) found peak velocity of head movement ranging from around 8 deg/s to 150 deg/s (from inspection of their graphed data). Zangmeister et al. (1981), using a similar experimental protocol to that of Stark et al. (1980), showed peak head movement velocities ranging from 10 deg/s to 150 deg/s. Uemura et al. (1980) found the maximal velocity of head movement to range from approximately 20 deg/s to 80 deg/s over a head movement angular range of 10° to 50° (from inspection of their graphed data). Gresty (1974) reported peak head movement velocities of 25 deg/s to 220 deg/s for gaze shifts to either continuous or flashed targets. Ron et al. (1993), for successively flashed targets of varying offsets, recorded peak head movement velocities of 100 – 200 deg/s for 50° target displacements. These studies all used helmet mounted mechanical systems linked to potentiometer driven electronic systems to record head position. Han et al. (2003b), in their study of eye and head movements in reading with different lens designs, found mean peak head movement velocities of 64 ± 8.77 deg/s to 75 ± 6.24 deg/s, using the Polhemus Insidetrak instrument. Measures of peak (maximal) velocity in these studies are comparable to the range of peak head movement velocities found in this investigation, over a similar range of fixation angles.

Apart from Han et al. (2003), the studies above have also used saccadic (step) like gaze shifts to fixation targets which were light sources. The visual task demand in this investigation however is quite different to that of the earlier studies, requiring active visual processing, such as that used by Han et al. (2003). Similarity in head movement peak velocity between studies with differing experimental protocols and task demands probably reflects nervous control factors, anatomical restriction of maximal muscle responses in the generation of head movement via the muscles of the neck, and the physical factors relating to head mass and the rotational dynamics of the head.

Epelboim et al. (1995a, 1995b, 1997) and Epelboim (1998) present a series of reports detailing gaze shift dynamics in sequential looking tasks, all based on the same data set. Head position in their experiment was recorded by detecting arrival time of acoustic signals, generated by a sound emitter mounted on a helmet worn by the subject, to 4 microphones set at the corners of a room. Subjects were required to either look at a series of targets presented in random sequence, or to look at and touch the randomly presented targets. Head movement speeds recorded in their experiment are analogous to the measure of average velocity of head movement in the current study. Whilst Epelboim et al. (1997) and Epelboim (1998) indicate that the task demand affected the gaze shift dynamics, speeds of head movement they recorded ranged from 3 deg/s to 25 deg/s for gaze shift amplitudes between 5° and 45° for their 4 subjects for both tasks in their experiment. These values are comparable to the average velocities of head movement found in the current investigation.

The reduced head movement average and peak velocities found during the search task compared to the copy task suggest selective strategies for the head movement component of gaze shift which are dependent upon the task requiring the gaze shift. This is consistent with Epelboim et al. (1997) and Epelboim (1998) who found in two sequential looking tasks, where one task required subjects simply to look towards targets and the other requires subjects to touch the sequential targets, that head movement peak velocity increased in the tapping task, with the difference in head movement velocity increasing as gaze shift amplitude increased. Head movement velocity in the tapping task was 2-3 times faster than head movement peak velocity in the looking task.

It can be argued that the effect of task on average and peak head movement velocity found relates to inherent differences between groups as not all subjects participated in both experimental tasks. Data for peak head movement velocity are presented in Table 7.16 for the five subjects who completed both tasks. Data on the blue background are for the search task; data on the white background are for the copy task.

Subject	Median	I-Q range	25 pctile	75 pctile	90 pctile	95 pctile	Maximum
1	13.70	23.21	6.78	29.99	40.10	49.29	74.51
1	8.30	8.70	5.60	14.30	19.70	25.85	41.10
12	12.16	11.27	7.57	18.64	27.43	32.89	55.32
12	19.12	13.84	10.95	24.79	32.51	40.49	51.10
13	12.35	13.74	7.86	21.59	39.86	50.94	74.98
13	12.63	9.28	8.76	18.04	23.99	27.22	30.34
15	15.29	12.37	9.24	21.61	26.99	34.15	55.64
15	12.73	8.48	7.70	16.18	19.50	26.16	37.92
16	30.58	38.46	12.14	50.60	66.10	78.28	133.44
16	30.72	38.44	17.14	55.57	78.98	85.62	104.00

Table 7.16 Descriptive statistics for peak head movement velocity (deg/s) for five subjects who completed both experimental tasks. Data on white background are for the copy task, on blue background for the search task. (I-Q range = interquartile range, pctile = percentile; viz. 25 pctile is the 25th percentile).

For 3 of these 5 subjects (subjects 1, 13 and 15) median, 25th, 75th, 90th and 95th percentile values for peak velocity are less in the search task than in the copy task, whereas the reverse occurs for the other 2 subjects. Maximum peak velocity of head movement is less in the search task than in the copy task for these 5 subjects. Paired sample t-tests for these subjects show the difference in median or percentile values of peak velocity between the two tasks to be non-significant (at p= 0.05), a not unexpected result given the small sample of subjects who completed both tasks. A larger sample in a repeated measures experimental protocol would be required to investigate the task demand effect on head movement velocity (see below).

7.7.3 'Main sequence' relationships for head movement velocity and angle

Head movement peak and average velocity was log-transformed for the linear regressions of the main sequence relationship due to the skewed distributions of peak and average velocity (Section 7.5).

Main sequence linear relationships were found for log average and log peak head movement velocity on log amplitude (log angle) of head movement in both the copy and search task (Figure 7.12 and 7.13, Table 7.9). For the copy task, log average velocity = 0.631 log angle + 0.514, and log peak velocity = 0.809 log angle + 0.738. Slopes of the main sequence regression lines for log velocity on log amplitude in the search task are flatter than those in the copy task. For the search task, log average velocity = 0.50 log angle + 0.45, and log peak velocity = 0.629 log angle + 0.69.

Previous studies (Zangmeister et al. 1981, Stark et al. 1980, Uemura et al. 1980, Han et al. 2003) have also shown linear relationships between peak velocity and angle of head movement. In these studies, as in the current study, peak velocity and angle were plotted on logarithmic scales. The lack of an asymptotic soft saturation value for head movement peak velocity, as occurs with saccadic eye movements, is also consistent with these studies.

The regression equations show that both greater log average and log peak velocities result for a given head movement angle change in the copy task compared to the search task. This indicates a possible task related effect on the control of the head movement component of gaze shift within the two different tasks, as is also indicated above with respect to the velocities found (Section 7.4.2, and 7.7.2). Slower head movements during the search task would be consistent with subjects adopting a slow head movement along the linear arrangement of the targets, whereas quicker, 'saccade-like' head movements were used during the copy task for the gaze shift changes from source copy to word-processed copy in this task. Again, it could be argued that this results from an inherent difference between the two groups of subjects, as only 5 subjects participated in both experimental tasks. Of the 5 subjects who performed both tasks, the slope of the regression line for log average velocity against log angle, and log peak velocity against log angle was steeper in the copy task as compared to the search task in 3 of the subjects, flatter in one subject, and similar in one subject. Whilst the slopes of the velocity regression lines between the two tasks for this subset of 5 subjects were not significantly different on a two-tailed paired t-test (owing to the small number of subjects), a trend towards a flatter slope for the regression line of log velocity on log angle of head movement in the search task is suggested, supportive of a task related effect. This would be consistent with subjects selecting a slower head (and gaze) movement strategy in the search task. As noted above, a repeated measures experimental protocol with a larger number of subjects would be needed to fully test this task related effect hypothesis.

7.7.4 The effect of head movement direction on head movement velocity

As indicated in Section 7.6.1, preliminary inspection of head recorder output suggested an asymmetric velocity profile for head movements during the copy task. Rightward directed head movements (from the source copy toward the computer/monitor) were faster for all subjects and head movement ranges than leftward directed head movements. Velocity difference between right and left directed head movements was 2.86 deg/s for average velocity and 6.69 deg/s for peak velocity. This directional effect differed across the range of head movements (Section 7.6.1.1, Figure 7.15 and Figure 7.16). The difference in log head movement velocity was minimal for smaller head movements (less than 9º). As head movement angle increases, leftward directed head movements become slower than rightward directed head movements (Table 7.11 and 7.12). Considering the peak velocity of head movement, the right – left difference between the means for the range groups increases from 3.38 deg/s for head movements 9º to 12º to 37.95 deg/s for head movements > 24º. This difference was significant for both log average velocity and log peak velocity. This is consistent with the hypothesis that subjects adopted a selective strategy within the copy task. Leftward gaze shifts toward the source text would be required to land on an accurate refixation point for each subsequent gaze shift to the source text for the cognitive demand of processing the text. Conversely, gaze shifts returning gaze to the computer monitor or keyboard could be less accurate in their landing site. It could be argued this is a subject related effect; this is unlikely as maximum head movement angle for 12 of the 15 subjects reached 18º or above.

All subjects undertook the copy task with the source text to the left, and the computer mouse to the right side of the keyboard for standardisation of the task. Subjects were also not selected for handedness.

In the search task, multivariate analysis of variance indicated a significant effect of the interaction between head movement range and direction). This interaction effect was also significant for log average velocity) and log peak velocity. The interaction plots are shown in Figures 7.17 and 7.18. Differences between rightward head movement and leftward head movements within each head movement range were further explored by independent t-tests subsequent to the analysis of variance. No significant differences (at p = 0.05, 2 tailed, Bonferroni adjustment for multiple comparisons) were found for right – left comparisons within head movement ranges of 9º - 24º for log average velocity, and within the 6º - 24º range. This is apparent in Figures 7.17 and 7.18, where the plot of velocity against head movement range shows a plateau in the curve across these ranges. This is indicative of a common head movement velocity profile over this range of head movement, in contrast to the velocities in the copy task which steadily increased over the head movement ranges (Figures 7.15 and 7.16).

7.7.4 Relationships between velocity measures

Peak velocity of saccadic eye movements is linearly related to the average velocity of saccadic eye movement (Inchnigolo et al. 1987, Lebedev et al. 1996). Inchigolo et al. (1987) indicated a correlation between average (mean in their paper) and peak velocity of saccadic eye movement of 0.98 or greater. Similar values have been reported by Becker (1989). Linear relationships were also found between the log transformed values of peak and average velocity in this experiment, illustrated by the main sequence plots in Figure 7.19 and 7.20. Whilst the velocity profiles of head movements in the two tasks differ, with head movements in the search task showing a slower velocity than the copy task, the regression line slopes of the log peak on log average velocity main sequence are similar for the two tasks (Table 7.15). Slopes of the log peak on log average velocity main sequence regression are also similar for rightward and leftward directed head movements (Table 7.15); difference in slope for the direction of head movement in both tasks was not significantly different on a within subjects/between groups repeat measures analysis of variance. Task also did not significantly affect slopes of log peak on log average velocity main sequence. As with saccadic eye movement, peak and average velocity of head movement are significantly linearly related.

The relationship between peak and average velocity of head movement was also considered in terms of the ratio of peak to average velocity (Section 7.6.22). This ratio was termed 'velocity ratio' in the analysis. Velocity ratio showed a positively skewed distribution for both the copy and search tasks. Median values for velocity ratio was similar in both tasks.

Velocity ratio (log transformed data) was not affected by head movement direction in either task. A linear increase in log velocity ratio was found for head movements to 6º, after which log velocity ratio was constant for head movements to 23º (Figure 7.23).

Log velocity ratio for head movements was significantly greater in the copy task compared to the search task (Figure 7.23). Ratios were similar in both tasks for head movements < 6º; however for head movements between 6º and 20º, log velocity ratio in the copy task ranged from 0.42 to 0.44 compared to 0.37 to 0.39 in the search task. The log values equate to ratios of 2.63 to 2.75, and 2.34 to 2.45 respectively. This effect of task lends further support to the hypothesis that head movement velocity profiles are dependent upon task, as previously discussed.

This constancy of velocity ratio for head movement is also found for saccadic eye movement. Pelisson and Prablanc (1988) showed ratios for maximum (peak) over mean (average) velocity of saccadic eye movements of 1.6 ± 0.1 over a range of eye movement from 0 – 20º. Harwood et al. (1999) found values of 1.54 to 1.8 for eye movements ranging from 2.5º to 20º.

Results of this experiment indicate visual task and its associated visual processing demands effect average velocity and peak velocity of head movement. Task also affects the main sequence relationships between average velocity and head movement amplitude, and peak velocity and head movement amplitude. Selective control of head movement velocity in differing processing demands is supported by the results of this experiment. Task and processing demands however do not have an effect on the relationships between average velocity and peak velocity of head movement.

Chapter 8 Head movement velocity in first time wearers of PALs

8.1 Introduction

PALs have been shown to alter head movement behaviour (Jones et al. 1982, Gauthier et al. 1989, Pedrono, Obrecht and Stark 1987, Ciuffreda et al. 2000, 2002). The onset of a head movement component of gaze shift is sooner, head movement velocity increases, and there is a greater contribution of head movement to gaze shift. The greater contribution of head movement is due to the peripheral visual field restriction caused by the peripheral power profile of the PAL. In terms of the cause of induced motion with PALs, increased head movements and head movement velocity may be contributing factors. In addition, an increase in head movement velocity may be accompanied by increased variability in head movement velocity when PALs are worn. This was tested in this experiment by investigating head movement velocity and variability of head movement velocity with PAL wear in subjects who were previously non-PAL wearers.

8.2 Methods in brief

Data for the angular extent of head movement, average velocity of head movement and the peak (maximal) velocity of head movement were obtained from 10 subjects while subjects searched for letter or numerical targets presented on a shelving unit. A full description of the subject selection criteria, experimental design and data collection procedures can be found in Chapter 6. Data were collected under three conditions. Baseline measures were taken while subjects wore their existing single vision or non-PAL spectacle correction. Measures were repeated on collection of the subject's first PAL correction. The baseline and first PAL wear data collection occurred on the same day. A repeat measure occurred after a one month period of PAL wear to assess the effect of adaptation to the PAL. All subjects had no previous experience of PAL wear. All except one subject previously wore single vision distance and/or near spectacles; one subject was currently wearing bifocal spectacles for near tasks prior to the experiment.

Head movements were recorded using a Polhemus Inside Track head movement recording system which sampled head position at 10 Hz. Recordings were analysed off-line by custom written software to calculate angular and velocity data for horizontal head movements.

All subjects gave informed consent, and experimental and data collection methods were approved by the Queensland University of Technology's University Human Ethics Research Committee.

As in the previous experiment (Chapter 7), only head movements in azimuth were used in analysis. Head movements in azimuth of less than 1° in angular extent and/or less than 0.3 s in duration were excluded from the data set of head movements at each measurement stage.

This resulted in 1400 head movements in the baseline measure, 1643 head movements on collection of the PAL correction, and 1514 head movements for the 1 month repeat measure. The Polhemus Inside Track head movement recording system output recorded left directed head movements with negative values; for the purposes of analysis, absolute values were used, and data were grouped for each subject.

For each subject in each of the three measurement conditions, median, interquartile range and the range between the 5^{th} and 95^{th} percentiles of the frequency distributions were calculated for head movement angle (amplitude), head movement average velocity and head movement peak velocity. The median, interquartile range and the 5^{th}-95^{th} percentile ranges of these head movement characteristics were used as dependent variables in a one way repeated measures analysis of variance, with measurement condition (3 levels: baseline, measurement 2 (collection of PAL) and measurement 3 (after 1 month of PAL wear)) as the independent factor. This allowed investigation of whether the distributions (represented by the interquartile and the inter-percentile range) of head movement angular extent or velocity were affected by PAL wear, with the hypothesis being that PAL wear increased the variability of the angular extent and velocity of head movement compared to non-PAL wear.

As frequency distributions for head movement angular and velocity values were markedly positively skewed, these data were log transformed to more closely resemble a normal distribution, as described in the previous chapter (Section 7.5). Linear regression of log peak velocity on log angle of head movement, and log peak velocity on log average velocity of head movement were performed for each measurement condition. The slopes of the main sequence of log peak velocity on log head movement angle, and log peak velocity on log average velocity (see Section 7.6.2) were also calculated for each subject in the three measurement conditions, and were used as dependent variables in separate one way repeated measures analyses of variance.

The ratio of head movement peak velocity to head movement average velocity ('velocity ratio', Section 7.6.2.2) was calculated; median, interquartile and the 5^{th} - 95^{th} inter-percentile ranges were calculated and used as the dependent variables in a repeated measures analysis of variance.

8.3 Head movement angular extent

8.3.1 Head movement angle

The group mean of subjects' median head movement angle was 5.56 ± 2.14 deg at baseline. This group mean increased in measurement condition 2 (on collection of the PAL) to 5.76 ± 2.26 deg. After one month of PAL wear, the group mean of subjects' median head movement angle had further increased to 7.09 ± 2.28 deg.. (Figure 8.1)

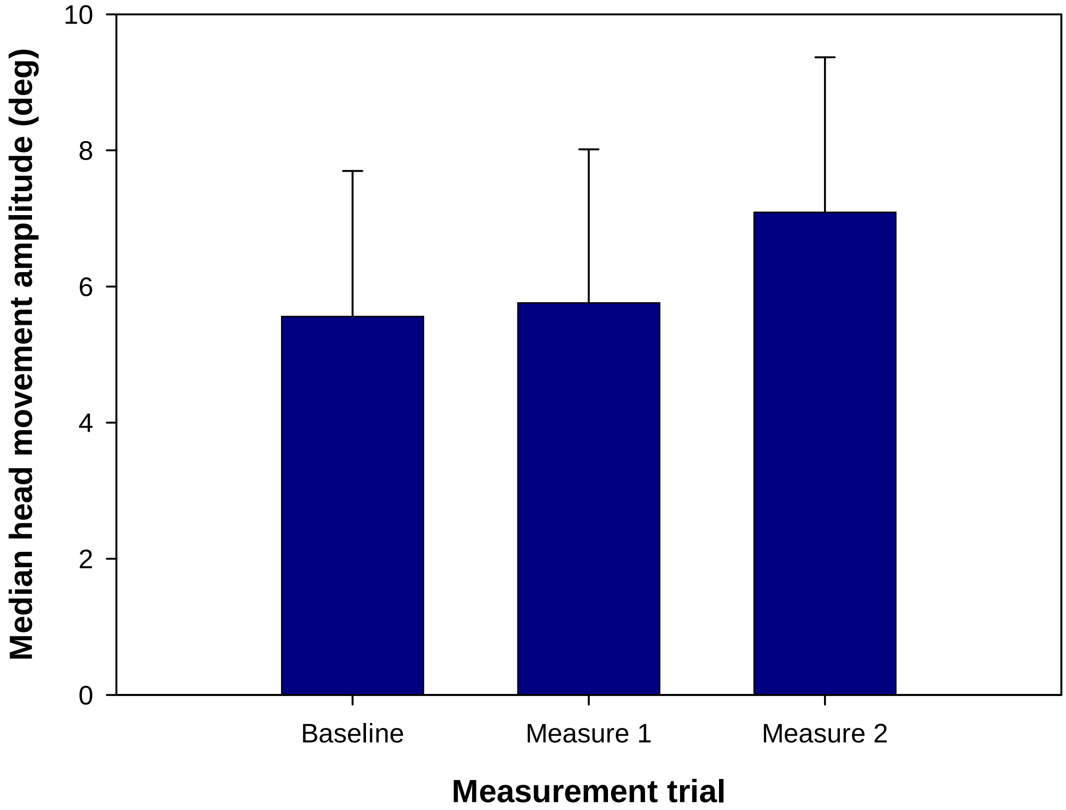

Figure 8.1 Group mean of subjects' median head movement angle (deg) in first time PAL wearers before PAL wear (baseline), on initial PAL wear (measure 1) and after 1 month PAL wear (measure 2) for head movement during a search task. Error bars are one standard deviation.

The increase in median head movement angle across measures was not significant ($F_{1,9} = 2.69$, $p = 0.099$). Commencement of PAL wear increased subjects' median head movement angle, and this was maintained after 1 month of PAL wear, although the increase in median head movement angle across measurement trials was not significant.

8.3.2 Interquartile range of head movement angle

The group mean of subjects' interquartile range of head movement angle increased with PAL wear compared to no PAL wear at baseline. Mean interquartile range was 7.94 ± 2.91 deg at baseline; this increased to 8.69 ± 3.13 deg on commencement of

PAL wear, and was relatively unchanged after 1 month of PAL wear (mean interquartile range 8.85 ± 2.08 deg) (Figure 8.2).

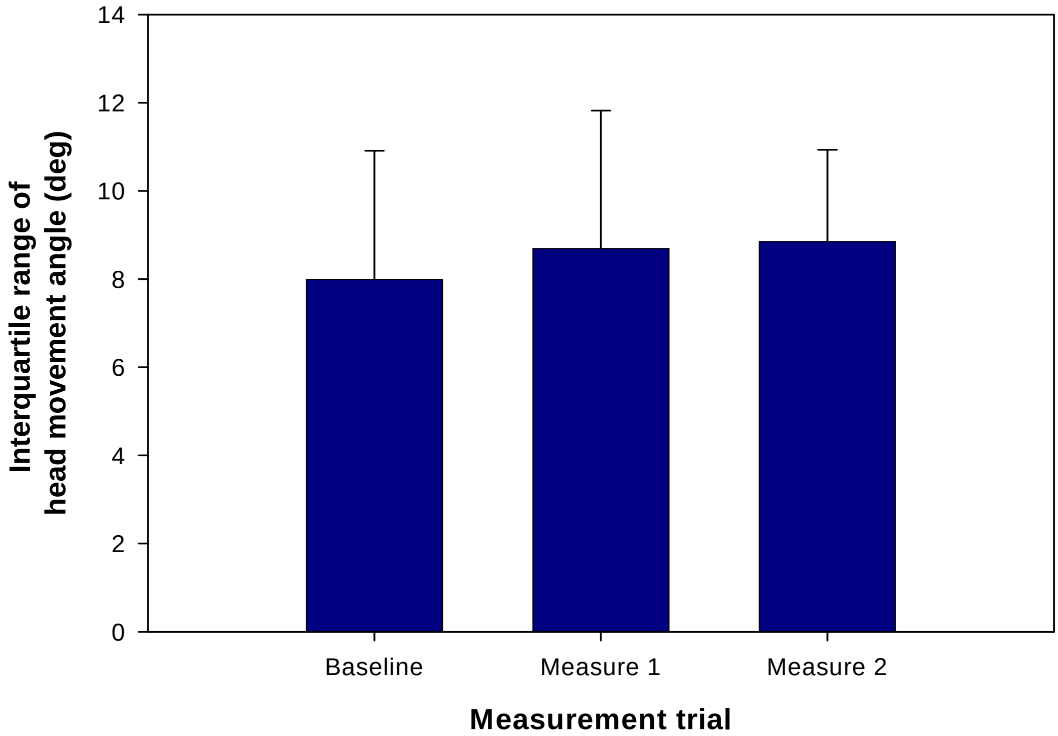

Figure 8.2 Group mean of subjects' interquartile range for head movement angular extent (deg) for first time PAL wearers, before PAL wear (baseline), on collection of PAL (measure 1) and after 1 month PAL wear (measure 2). Error bars are one standard deviation.

The increase in subjects' interquartile range for head movement log angle between the measurement trials was not significantly different ($F_{1,9} = 0.571$, $p = 0.469$). PAL wear increased the interquartile range of head movement angle in new PAL wearers, although this increase was not statistically significant.

8.3.3 5th – 95th inter-percentile range of head movement

The range between the 5th and 95th percentiles of head movement angle (termed inter-percentile range for this analysis) was calculated for individual subjects in each measurement condition, and considered as representative of the distribution of head movement angles for each measure.

The group mean of subjects' inter-percentile range at baseline was 17.57 ± 6.16 deg. This increased slightly to 18.04 ± 6.87 deg at collection of the PAL, and again increased slightly after 1 month of PAL wear (19.72 ± 3.95) (Figure 8.3).

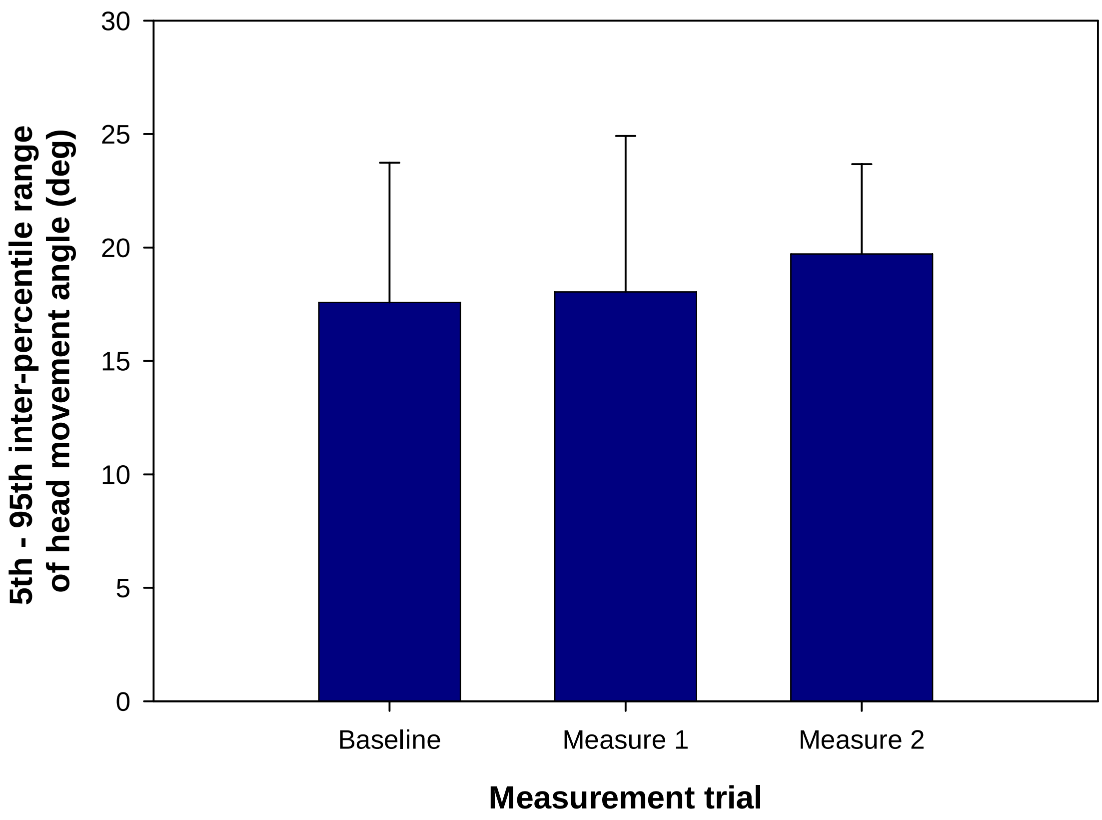

Figure 8.3 Group mean of subjects' inter-percentile (5th – 95th) range for head movement angle (deg) for first time PAL wearers, before PAL wear (baseline), on collection of PAL (measure 1) and after 1 month PAL wear (measure 2). Error bars are one standard deviation.

	Baseline	Measure 1	Measure 2
	6.91	14.65	20.76
	24.08	23.81	19.33
	18.15	11.94	12.72
	14.09	10.26	14.90
	14.64	20.07	20.23
	12.83	17.04	17.69
	15.06	33.55	26.55
	28.02	20.69	22.88
	19.79	13.87	19.98
	22.19	14.51	22.16
Group mean	17.58	18.04	19.72
Group sd	6.16	6.87	3.95

Table 8.1 Individual subject inter-percentile (5th – 95th) range for head movement angle (log deg) for first time PAL wearers, before PAL wear (baseline), on collection of PAL (measure 1) and after 1 month PAL wear (measure 2). Each row represents one subject. Last two rows of table are the group mean and standard deviation respectively.

Five of the ten subjects showed an increase in the inter-percentile range between baseline and the first PAL measure, indicating their overall extent of the head movements made with the PAL increased compared to the no-PAL baseline (Table 8.1). Five subjects showed a decrease in inter-percentile range. In 6 subjects, inter-percentile range remained greater than baseline after 1 month of PAL wear (measure 2).

The change in inter-percentile range of head movement angle was not significant across the three measurement conditions ($F_{1,9} = 0.545$, $p = 0.589$). PAL wear increased the 5^{th} – 95^{th} percentile range for head movement angle compared to baseline; differences though were statistically insignificant. Group comparisons were affected by wide inter- and intra subject variability in the differences between subject measures.

8.4 Head movement velocity in first time PAL wearers

8.4.1 Head movement average velocity

The group mean of subjects' median head movement average velocity (deg/s) at baseline was 6.31 ± 1.29 deg/s. This increased minimally in measurement conditions 2 and 3, where the group mean was 6.88 ± 1.43 deg/s on collection of the PAL, and 7.35 ± 1.91 deg/s after 1 month of PAL wear. (Figure 8.4).

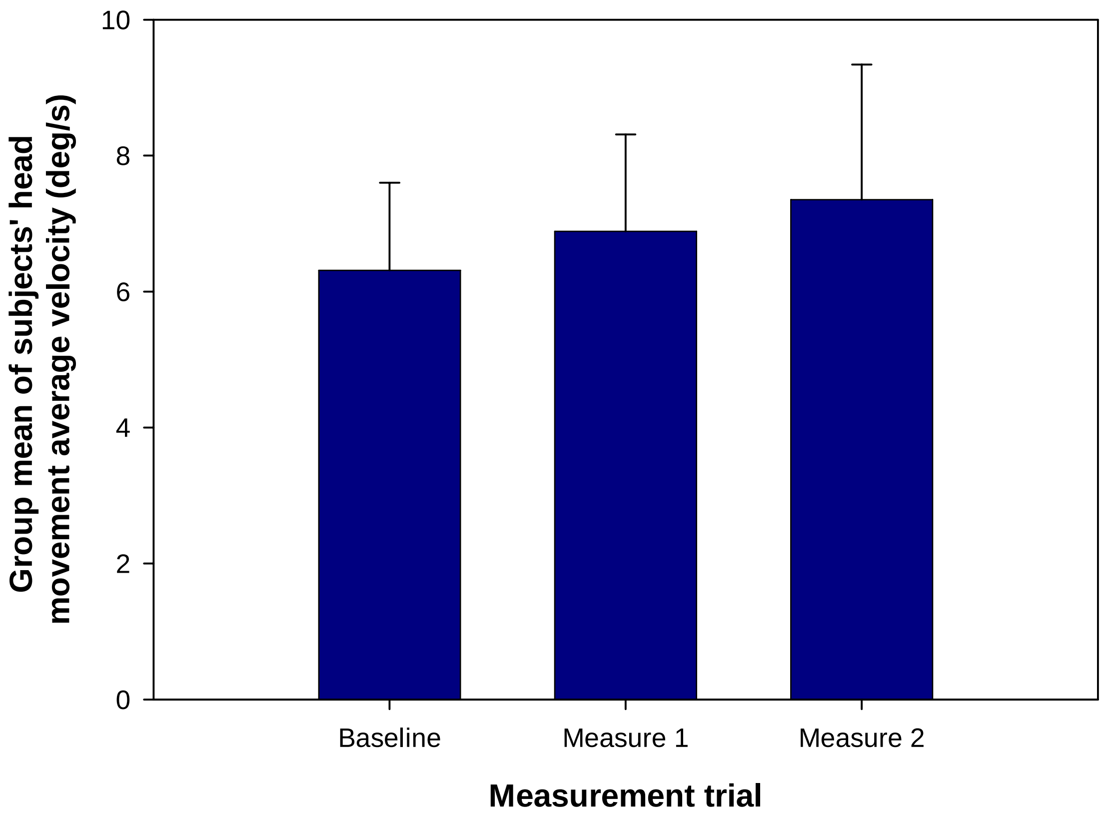

Figure 8.4 Group means of subject's median head movement average velocity (deg/s) for first time PAL wearers, before PAL wear (baseline), on collection of PAL (measure 1) and after 1 month PAL wear (measure 2). Error bars are one standard deviation.

The increase in the group mean of subject's median average head movement velocity across the measurement conditions was not significant ($F_{1,9}$ = 1.63, p = 0.234). PAL wear caused a non-significant increase in subjects' median average velocity compared to pre-PAL wear.

As head movement velocity is linearly related to head movement angular extent under the conditions of this experiment (Section 7.5; also Zangmeister et al. 1981, Stark et al. 1980, Uemuera et al. 1980, Han et al. 2003ab), the effect of head movement range on head movement log average velocity across the measurement conditions was investigated by an analysis of variance, with log average velocity as the dependent variable and measure (3 levels: baseline, measure 1 and 2) and head movement range (9 levels, see Table 7.10) as the independent factors. Log transformed average velocity variables were used for the analysis of variance due to the positively skewed distribution of average velocity (see also Section 7.5).

There was a significant difference in log average velocity across measures ($F_{2, 4530}$ = 3.371, p = 0.034). This difference was due to the increase in log average velocity across the measurement intervals (post-hoc multiple comparisons, Bonferroni adjustment for multiple comparisons). Log average velocity increased by 0.022 log deg/s (SE of mean difference 0.007, 95% CI for difference = 0.009 to 0.034 log deg/s, p = 0.001) between baseline and measure 1. Log average velocity increased by 0.20 log deg/s (SE of mean difference 0.006, 95% CI for difference = 0.007 to 0.032 log deg/s, p = 0.002). These differences, whilst statistically significant, are clinically insignificant, as effect size was very small (eta squared = 0.001, Cohen 1988). The minimal differences in log average velocity between measurement conditions are apparent in Figure 8.5, where log average velocity is plotted for each measure against head movement amplitude (represented by head movement range groups). As is shown in Figure 8.5, the curves for each measurement condition are essentially superimposed.

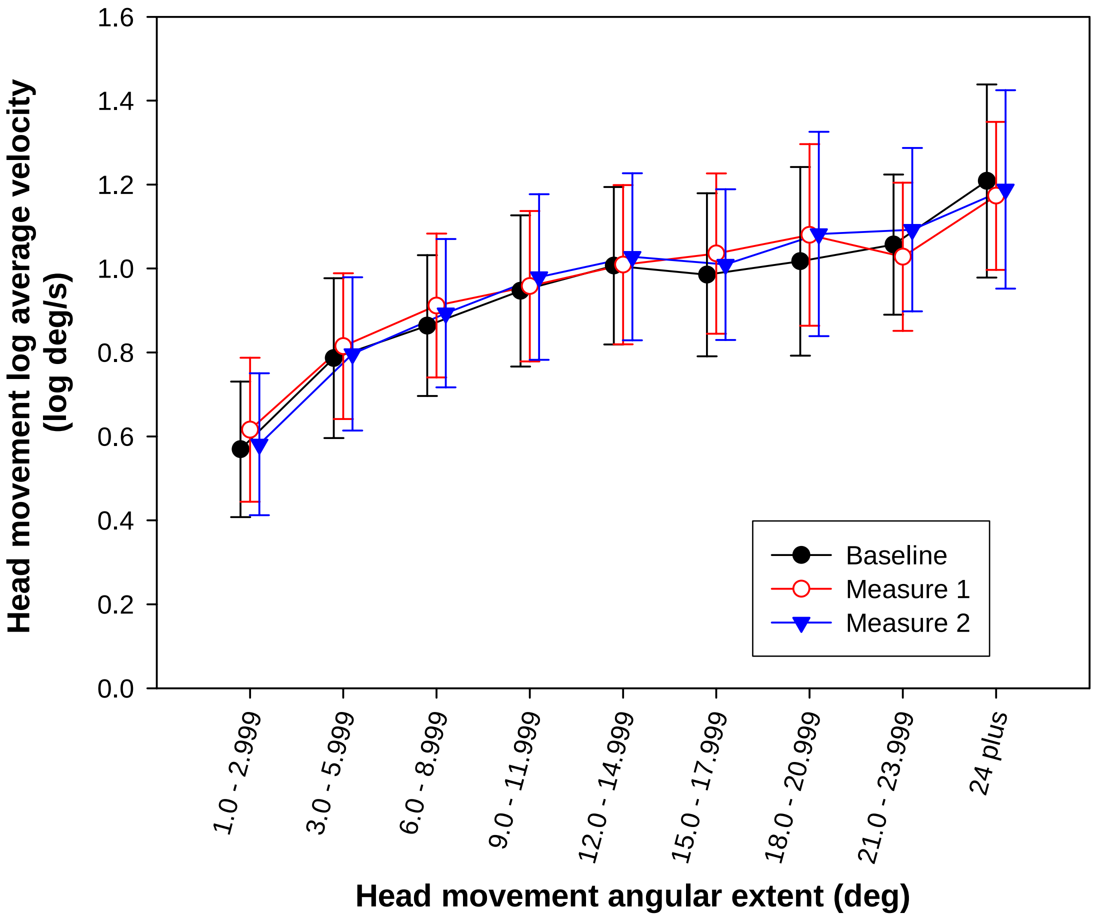

Figure 8.5 Log average velocity (log deg/s) of head movement during the search task under three conditions in first time PAL wearers. Points are displaced for clarity, error bars represent one standard deviation. Baseline was pre-PAL wear, Measure 1 was on collection of PAL, and Measure 2 was after 1 month of PAL wear.

As expected due to the linear relationship of log head movement velocity and log head movement angle, there was a significant effect of head movement range ($F_{8, 4530} = 543.6$, $p < 0.0005$). The combined effects of measure and head movement range had no significant effect on log average velocity ($F_{16, 4530} = 1.175$, $p = 0.28$); as is evident in Figure 8.5.

The commencement of PAL wear, or a 1 month period of adaptation, in this group of new PAL wearers did not affect the log average velocity of head movement.

8.4.1.1 Interquartile range of head movement average velocity

The interquartile range of head movement average velocity was calculated for each subject in each measurement condition. The group mean of subjects' interquartile range at baseline (pre-PAL wear) was 5.02 ± 1.93 deg/s. Commencement of PAL wear increased the group mean of subjects' interquartile range to 5.33 ± 1.66 deg/s. After 1 month of PAL wear, the group mean of subjects'' interquartile ranges of average velocity was 6.05 ± 1.96 deg/s (Figure 8.6, below). The increase in group means across the measurement conditions was not statistically significant ($F_{1, 9}$ = 1.517, p = 0.249).

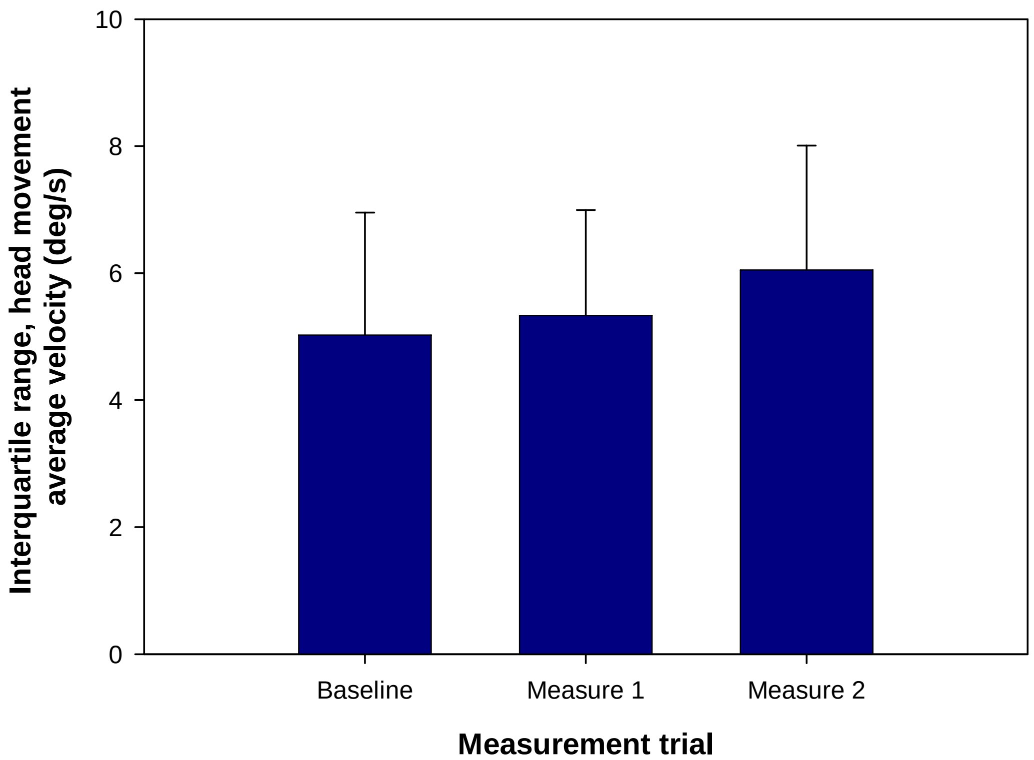

Figure 8.6 Group means of subjects' interquartile range of head movement average velocity (deg/s), first time PAL wearers in pre-PAL measures (baseline), on collection of the PAL (measure 2) and after 1 month of PAL wear (measure 3). Error bars are one standard deviation.

PAL wear therefore caused a non- significant increase in the interquartile range of head movement average velocity compared to pre-PAL wear.

8.4.1.2 5^{th} – 95^{th} inter-percentile range of average velocity

Group means of subjects' inter-percentile range of head movement average velocity were similar pre-PAL wear at baseline and on collection of the PAL (baseline: group mean = 13.91 ± 4.59 deg/s, on collection of PAL: group mean = 13.65 ± 4.09 deg/s). The group mean of the subjects' inter-percentile range after 1 month of PAL wear increased in comparison to the first two measures, with a group mean of 16.67 ± 4.21 deg/s. (Figure 8.7)

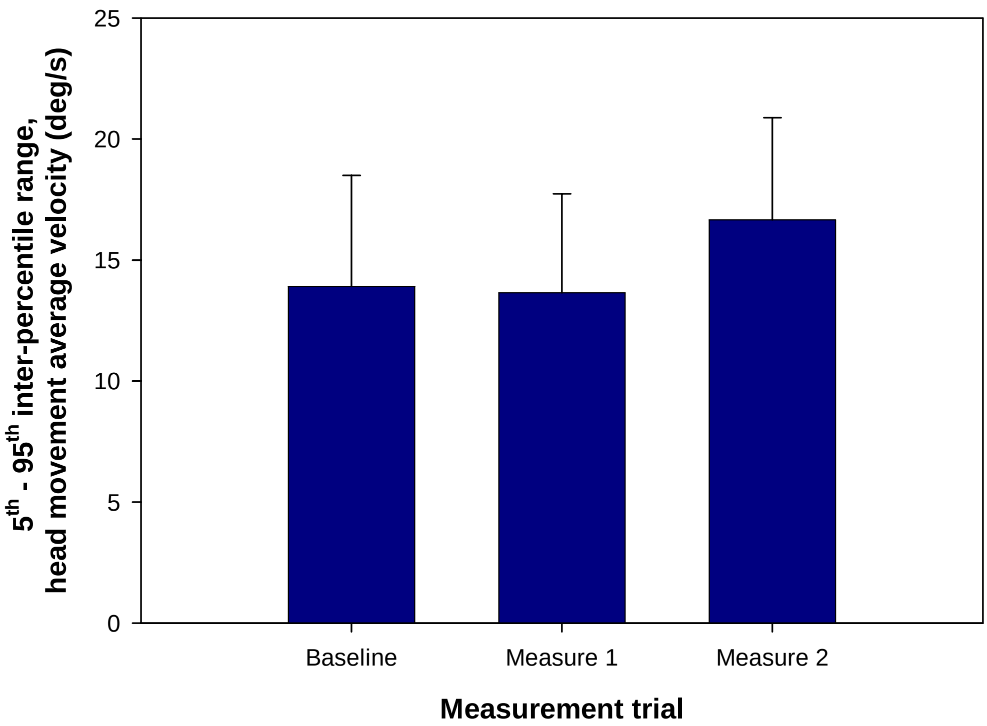

Figure 8.7 Group means of subjects' 5th – 95th inter-percentile range of head movement average velocity for first time PAL wearers under three measurement conditions (baseline = pre-PAL wear, measure 1 = on commencement of PAL wear, measure 2 = after 1 month of PAL wear). Error bars are 1 standard deviation.

The increase in the group mean of subjects' inter-percentile range for head movement average velocity was not significant ($F_{1, 9}$ = 3.09, p = 0.119). PAL wear did not affect the 5^{th} – 95^{th} inter-percentile range of head movement average velocity on commencement of PAL wear; after 1 month of PAL wear, the 5^{th} – 95^{th} inter-percentile range of head movement average velocity increased compared to previous measures. This increase however was not significant.

8.4.2 Head movement peak velocity

The group mean of subjects' median head movement peak velocity at baseline was 13.57 ± 3.41 deg/s. The group mean of subjects' median peak velocity increased minimally on collection of the PAL (14.85 ± 3.66 deg/s), and again increased minimally after 1 month of PAL wear (16.38 ± 4.94 deg/s) (Figure 8.6).

The increase in median head movement peak velocity across the measurement conditions was not significant ($F_{1, 9}$ = 1.791, p = 0.214).

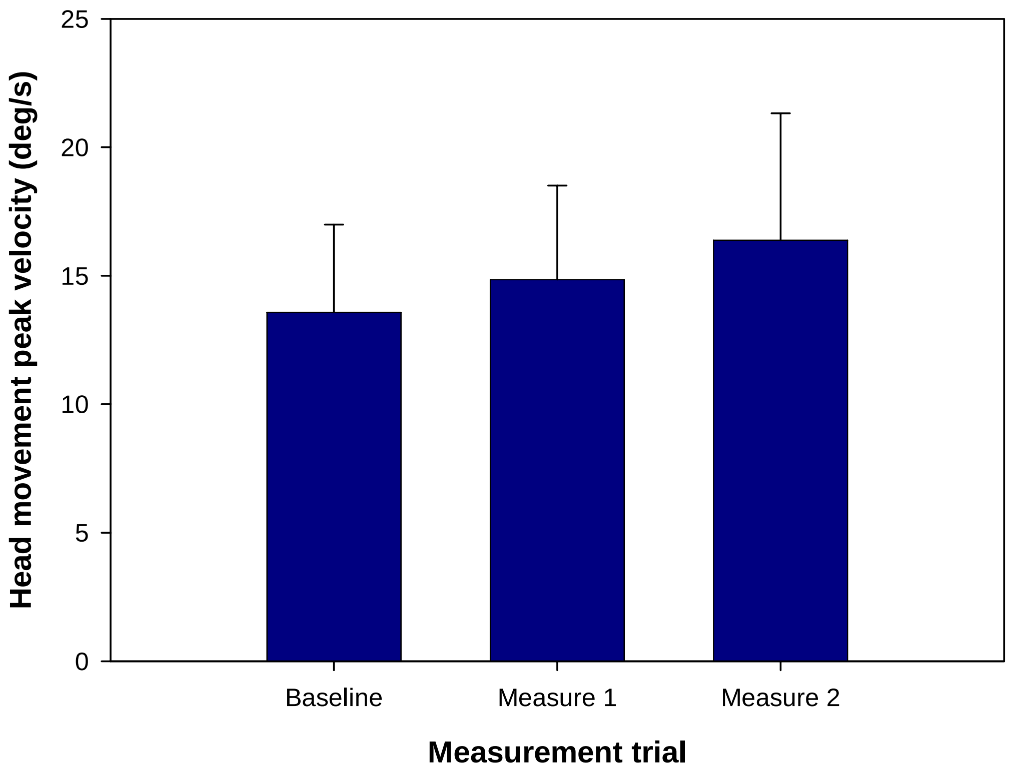

Figure 8.8 Group means of subjects' median head movement peak velocity (deg/s) for PAL first time wearers, before PAL wear (baseline), on collection of PAL (measure 1) and after 1 month PAL wear (measure 2). Error bars are one standard deviation.

As with average velocity, the effect of angular extent of head movement on peak velocity in the three measurement conditions was investigated. Data for peak velocity were log-transformed (see Section 7.5). The effect of head movement range on log peak velocity was investigated by an analysis of variance, with log peak velocity as the dependent variable and measure (3 levels: baseline, measure 1 and 2) and head movement range (9 levels, see Table 7.10) as the independent factors.

Measurement (baseline, measure 1 or measure 2) did not significantly affect log peak velocity ($F_{2, 4530} = 0.772$, $p = 0.462$). Head movement range, as would be expected due to its linear relationship with velocity, showed a significant effect ($F_{8, 4530} = 964.476$, $p < 0.0005$), with log peak velocity increasing as head movement range increased.

The combined effect of measure and head movement range had no significant effect on log peak velocity of head movement in the PAL wearers ($F_{16, 4530} = 1.308$, $p = 0.182$). This is apparent in Figure 8.9, where head movement log peak velocity for each measurement interval is plotted against head movement amplitude, represented by range groups.

As with log average velocity, points and curves representing the three measurement conditions overlap. Commencement of PAL wear in this group of subjects, and a 1 month adaptation period, did not significantly alter the log peak velocity of head movement from the baseline condition of pre-PAL wear when the effect of angular extent of head movement was considered.

For both log average and log peak velocity, head movement velocity increased almost linearly for head movements less than 12º, after which head movement log average and log peak velocities were more constant for head movement angular extents up to 21º to 23.99º (Figures 8.5 and 8.9). This would be consistent with the adoption of a consistent head movement strategy for the type of search task employed in this experiment. This is consistent with the result found in Experiment 1 (Section 7.6.1).

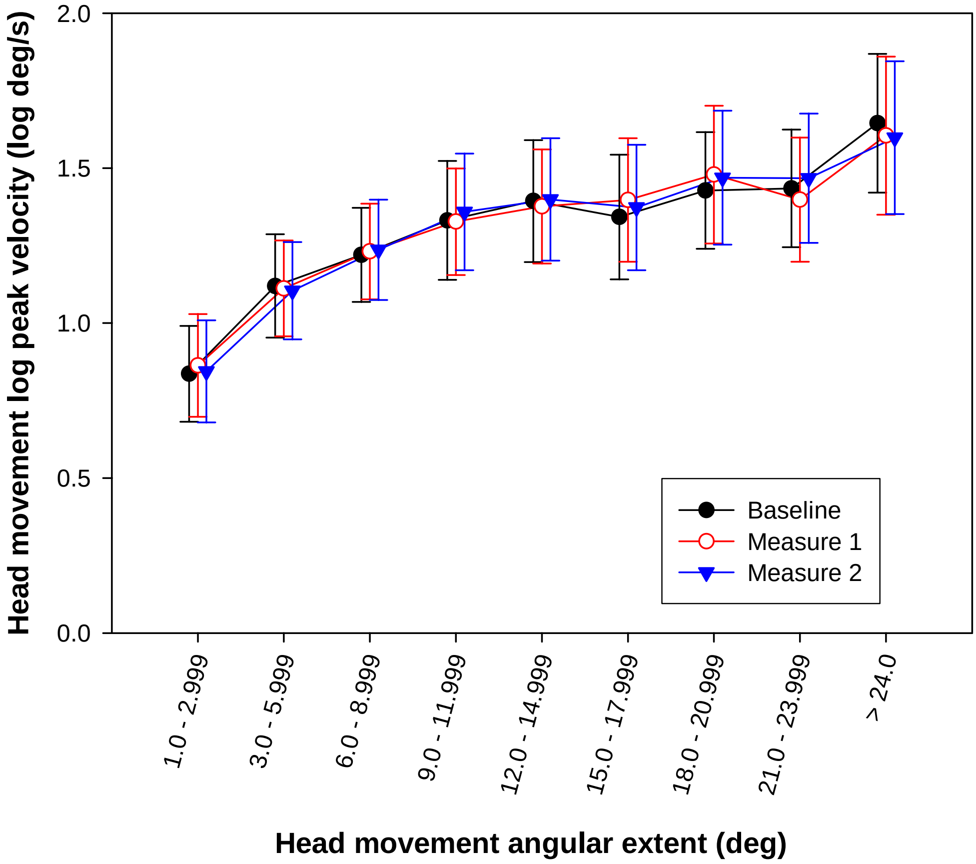

Figure 8.9 Log peak velocity (log deg/s) of head movement during the search task under three conditions in first time PAL wearers. Points are displaced for clarity, error bars represent one standard deviation. Baseline is pre-PAL wear, Measure 1 was on collection of PAL, and Measure 2 is after 1 month of PAL wear.

8.4.2.1 Interquartile range for peak velocity

Group means for subjects' interquartile range of head movement peak velocity were similar at baseline and on collection of PALs. Group mean at baseline was 12.22 ± 3.04 deg/s and at collection (measurement condition 2) was 12.35 ± 3.28 deg/s. Group mean of subjects' interquartile range increased after 1 month of PAL wear in comparison to the previous 2 measures, being 14.82 ± 5.32 deg/s (Figure 8.10). This difference across the measurement periods was not significant ($F_{1,9} = 1.791$, $p = 0.214$).

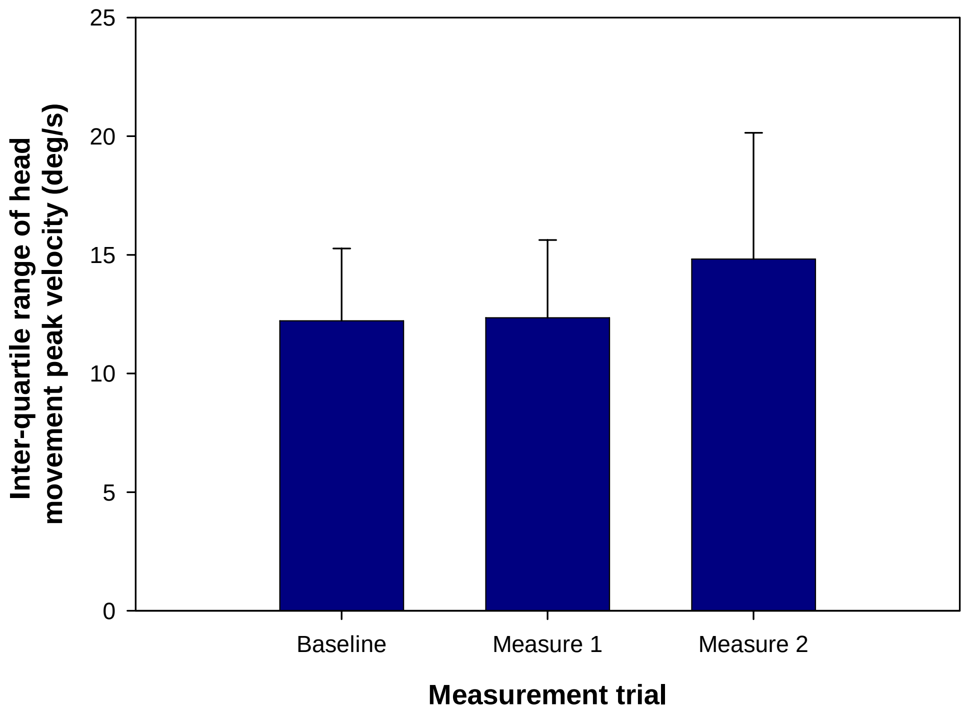

Figure 8.10 Group means of subjects' interquartile ranges for head movement peak velocity in PAL first time wearers at baseline (pre-PAL wear), on initial collection of a PAL (measure 2) and after 1 month of PAL wear (measure 3). Error bars are one standard deviation.

8.4.2.2 5th – 95th inter-percentile range of peak velocity.

Group means for individual subjects' inter-percentile range of head movement peak velocity were similar in the first two measurement conditions. At baseline, the group mean was 12.22 ± 0.96 deg/s, and on collection of the PAL the group mean for inter-percentile range was 12.35 ± 1.04 deg/s. The group mean after 1 month of PAL wear was 14.82 ± 1.68 deg/s (Figure 8.11). The increase in group mean across measurement conditions was not statistically significant ($F_{1, 9}$ = 1.203, p= 0.301).

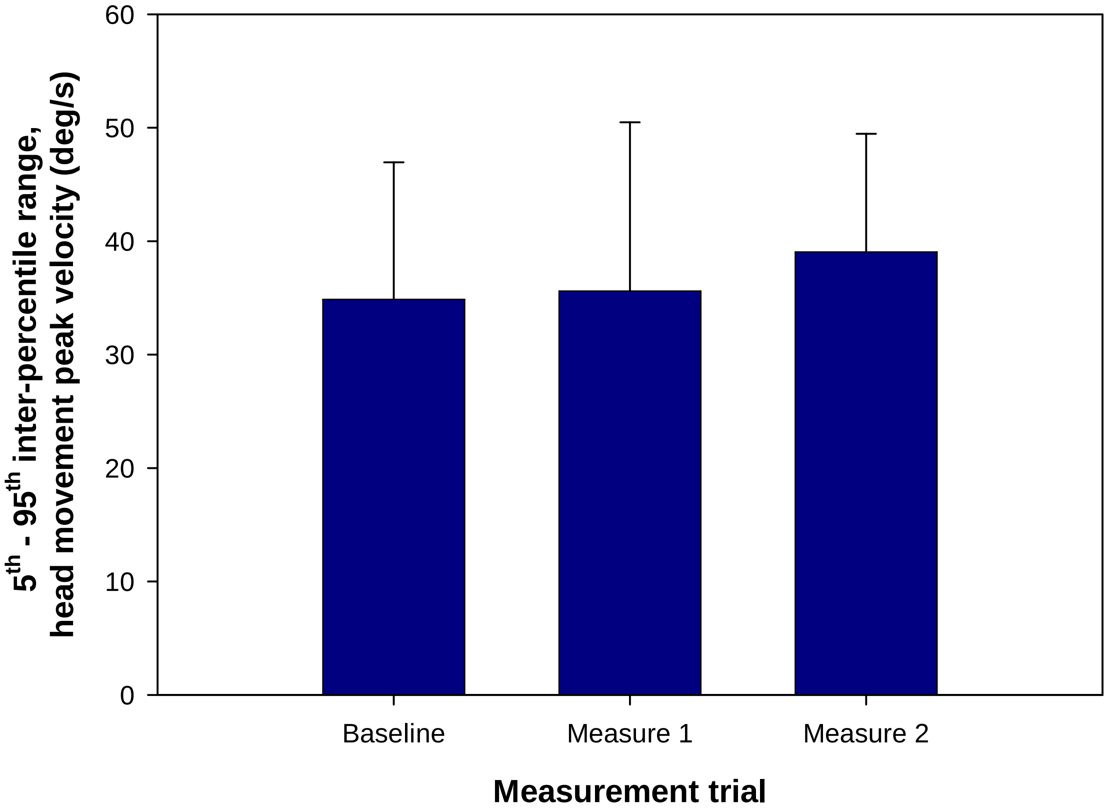

Figure 8.11 Group means of subjects' 5th – 95th inter-percentile range for head movement peak velocity in first time PAL wearers pre-PAL wear (baseline), on collection of a PAL (measure 1) and after 1 month of PAL wear (measure 2). Error bars are one standard deviation.

PAL wear increased the range of head movement peak velocities non-significantly over measurement conditions, with wide variability in the differences between measurement conditions.

8.4.3 Main sequence slopes

8.4.3.1 Velocity and head movement angle

The slope of the regression line for the main sequence relationships (Bahill et al. 1975) of log average and peak velocity with log head movement angle, and log peak with log average velocity were calculated for each subject for each measurement condition. Log transformed data values were used as the untransformed variables for head movement velocity and angular data show markedly positively skewed distributions (Section 7.5).

The group mean of subjects' main sequence slopes of log average velocity on log head movement angle varied across measurement conditions. At baseline, mean slope was 0.447 ± 0.08. On collection of the PAL (measurement condition 2), mean slope of the log average velocity-log angle main sequence increased to 0.456 ± 0.07; after 1 month of Pal wear (measurement condition 3), the slope was 0.483 ± 0.09 (Figure 8.12)

The change in the slope of the log average velocity-log angle main sequence was not significantly different across measurement conditions ($F_{1,9} = 2.047$, $p = 0.186$).

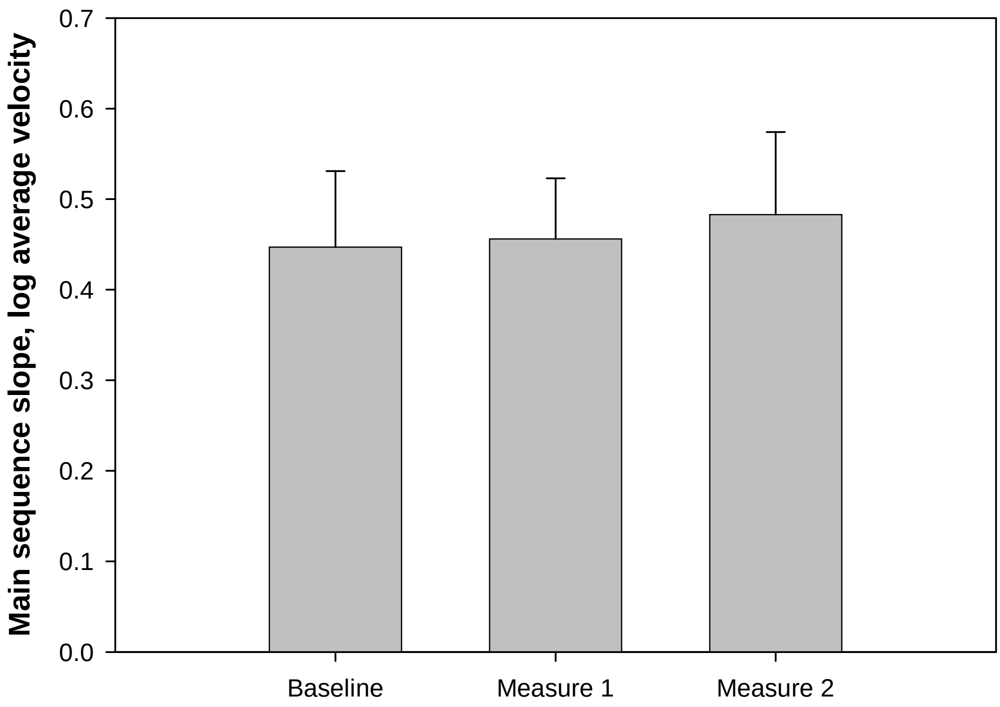

Figure 8.12 Slope of main sequence relationship of log average velocity (log deg/s) and log head movement angle (log deg) for PAL first time wearers, before PAL wear (baseline), on collection of PAL (measure 1) and after 1 month PAL wear (measure 2). Error bars are one standard deviation.

The group mean of subjects' main sequence slopes of log peak velocity and log head movement angle varied little across the measures, with differences in the means of the slopes being in the order of 0.002 – 0.005. In the baseline pre-PAL measurement condition, mean slope was 0.586 ± 0.09; in the initial PAL measurement condition mean slope was 0.589 ± 0.07, and after the 1 month adaptation period was 0.601 ± 0.09 (Figure 8.13).

Not surprisingly given the mean values for slope of the main sequence of log peak velocity on log head movement angle, there was no significant effect of the measurement condition ($F_{1,9} = 0.51$, $p = 0.493$).

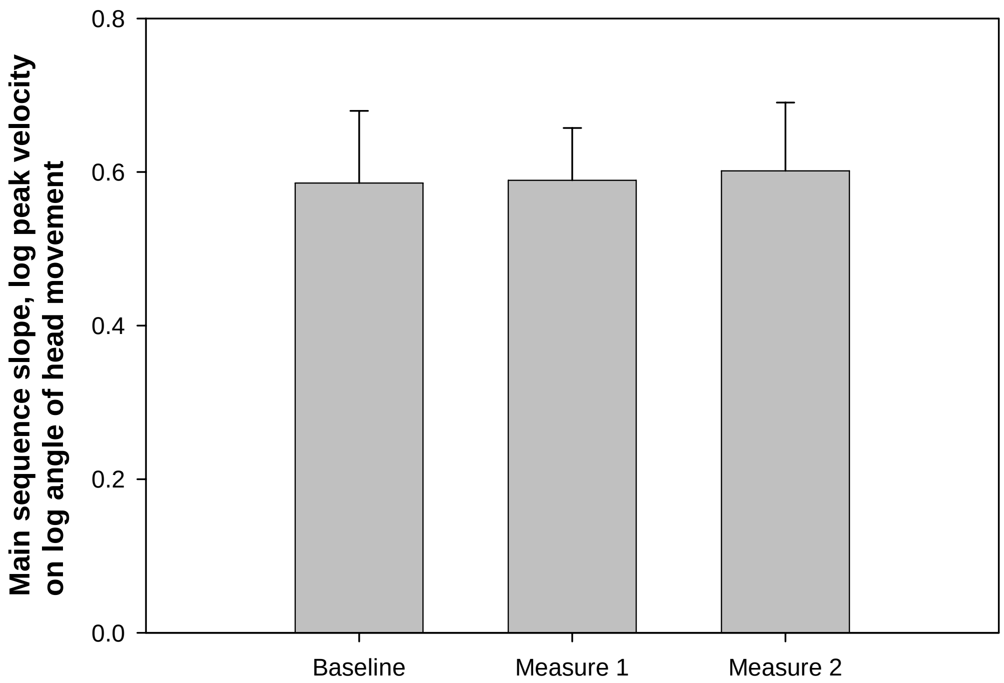

Figure 8.13 Slope of main sequence relationship of log peak velocity (log deg/s) and log head movement angle (log deg) for PAL new wearers, before PAL wear (baseline), on collection of PAL (measure 1) and after 1 month PAL wear (measure 2). Error bars are one standard deviation.

PAL wear therefore did not significantly affect the main sequence relationships between both the average and peak velocity and angular extent of head movement compared to baseline pre-PAL measures.

8.4.3.2 Peak velocity and average velocity main sequence

For the main sequence relationship of log peak velocity on log average velocity (see also Section 7.6.2), group mean of subjects' slopes was 1.02 ± 0.034 at baseline. Group mean of the slope of the main sequence regression line increased in the second measurement condition upon collection of the PAL (mean slope = 1.05 ± 0.084). Mean slope of the regression line returned toward the baseline value after 1 month of adaptation to PAL wear (measurement condition 3). After 1 month, mean slope was 1.03 ± 0.03 (Figure 8.14). Commencement of PAL wear increased the slope of the main sequence regression plot of log peak on log average velocity. This increase however was non-significant on a repeated measures analysis of variance ($F_{1, 9}$ = 0.277, p = 0.611).

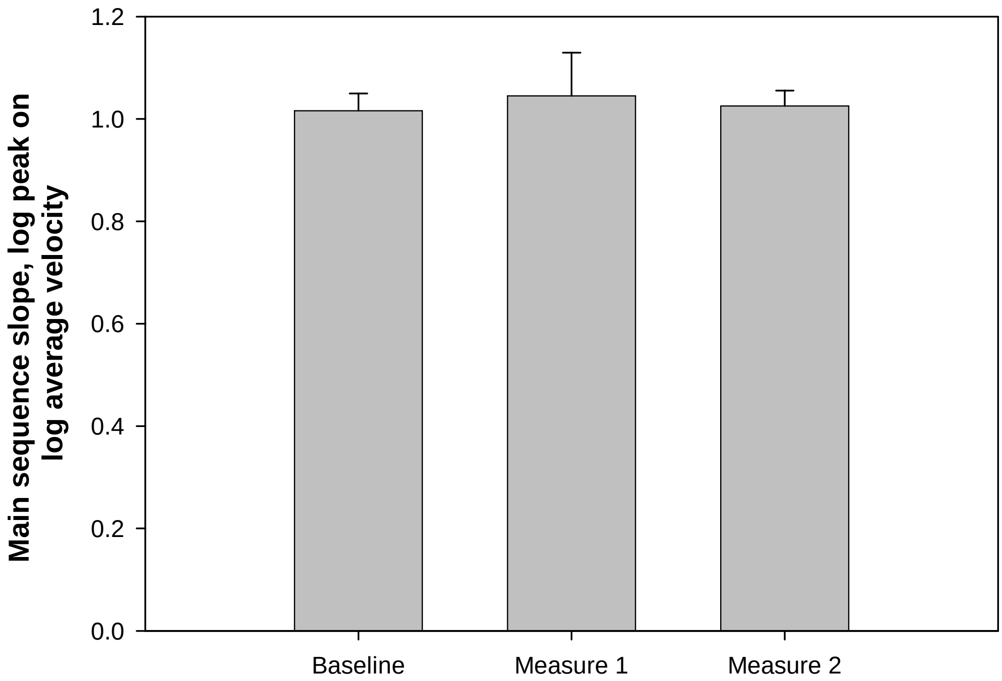

Figure 8.14 Slope of main sequence relationship of log peak velocity (log deg/s) and log average velocity (log deg/s) for first time PAL wearers, before PAL wear (baseline), on collection of PAL (measure 1) and after 1 month PAL wear (measure 2). Error bars are one standard deviation.

8.4.4 Velocity ratio

Velocity ratio was calculated as the ratio of peak to average head movement velocity (see Section 7.6.2, also Section 4.4.1). This ratio has been established for saccadic eye movements (Pelisson and Prablanc 1988, Harwood et al. 1999), and shown to be constant over a range of saccadic amplitudes. It has not previously been reported for head movement, and was shown in the first experiment in this thesis (Section 7.6.2.2) to be constant across a range of head movement amplitudes in both the copy and search task. The ratio reflects the interdependency between peak velocity and average velocity (i.e.amplitude/duration) and thus the optimal timing of the head movement. If PAL wear affects head movement velocity, this may be evident in a change in this ratio from a pre-PAL wear baseline, or an adaptive effect over time. This was investigated in this part of the current experiment.

Group mean of subjects' velocity ratio at baseline was 2.16 ± 0.06. Mean velocity ratio decreased to 2.02 ± 0.15 in the second measurement condition on collection of the PAL. Mean velocity ratio returned to baseline after 1 month of PAL wear (condition 3), when mean velocity ratio became 2.11 ± 0.09 (Figure 8.15). Measurement condition did not significantly affect velocity ratio ($F_{1,9}$ = 2.712, p = 0.134).

The interquartile range of subjects' velocity ratio in each measurement condition was not significantly different across measurement conditions ($F_{1,9}$ = 1.811, p = 0.211). Group means for subjects' interquartile ranges were 0.8 ± 0.11 at baseline, 0.76 ± 0.11 on collection of a PAL, and 1.02 ± 0.58 after 1 month of PAL wear.

The 5th – 95th inter-percentile range for velocity ratio was not significantly affected by the measurement conditions ($F_{1,9}$ = 0.006, p = 0.94). Baseline inter-percentile range was 2.17 ± 0.47; this decreased to 2.07 ± 0.29 on collection of PALs, and returned toward baseline after 1 month of wear (2.17 ± 0.55).

PAL wear thus did not significantly alter the frequency distribution of velocity ratio.

The decrease in velocity ratio in the second measurement condition occurred as average velocity increased in this condition (Section 8.4.1) while peak velocity was unchanged (Section 8.4.2). Return to baseline values in measurement condition 3 occurred due to an increase in both peak and average velocity of head movement. Adaptation in the control of head movement allowed the ratio of peak to average velocity to return to baseline by increasing peak velocity of head movement in the presence of increased average velocity.

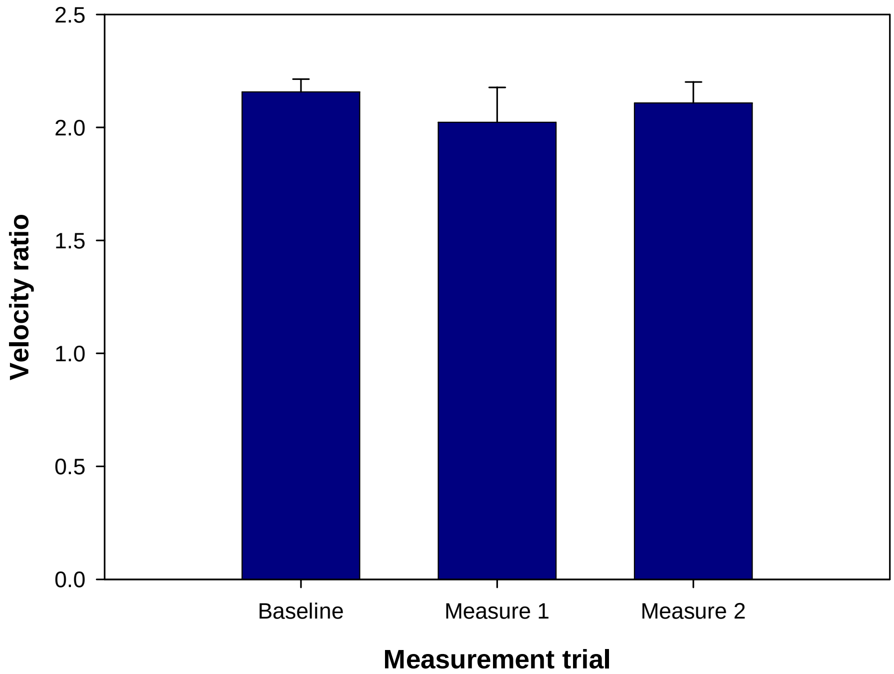

Figure 8.15 Velocity ratio (peak velocity/average velocity) for PAL first time wearers, before PAL wear (baseline), on collection of PAL (measure 1) and after 1 month PAL wear (measure 2). Error bars are one standard deviation.

Velocity ratio was then log-transformed for an analysis of variance, as frequency distribution of velocity ratio was found to be skewed. The effect of head movement extent (represented by head movement range groups) on velocity ratio was determined by analysis of variance, with log velocity ratio as the dependent variable and measurement condition (3 levels: baseline (pre-PAL), measure 1 on PAL collection and measure 2 after 1 month PAL wear) and head movement range (9 levels, Table 7.10) as the independent factors.

Measurement condition had a significant effect on log velocity ratio ($F_{2, 4530} = 5.04$, $p = 0.007$). Post-hoc comparisons (Bonferroni adjustment for multiple comparisons) are shown in Table 8.2. As above, log velocity ratio decreased on collection of the PAL (measure 2) and returned toward baseline after 1 month of PAL wear (measure 3).

	Mean Difference	Std. Error	sig.	95% CI lower	95% CI upper
Baseline - Measure 2	0.027	0.0004	0.0005	0.019	0.034
Baseline - Measure 3	0.008	0.0004	0.04	0.0004	0.016
Measure 2 - Measure 3	-0.018	0.0004	0.0005	-0.026	-0.01

Table 8.2 Post-hoc comparisons (Bonferroni) for log velocity ratio in new PAL wearers. Comparisons are significant at the p = 0.05 level.

Head movement amplitude, represented by range groups, had a significant effect on log velocity ratio ($F_{8, 4530} = 115.6$, $p < 0.0005$), which would be expected as the two variables from which the ratio is derived are linearly related to head movement amplitude, with velocity increasing as amplitude increases. This is shown in Figure 8.16, where log velocity ratio for each measurement condition is plotted against head movement range group. Log velocity ratios are lower across all ranges of head movement amplitude; log velocity ratio returns toward baseline after 1 month of PAL wear.

Log velocity ratio increases linearly for smaller head movements (groups 1 -3, head movement amplitude from 1 – 9º), and then is more constant across larger amplitudes, within the visual task required in this experiment. The combined effect of measurement condition and head movement range on log velocity ratio was not significant ($F_{16, 4530} = 0.904$, $p = 0.564$).

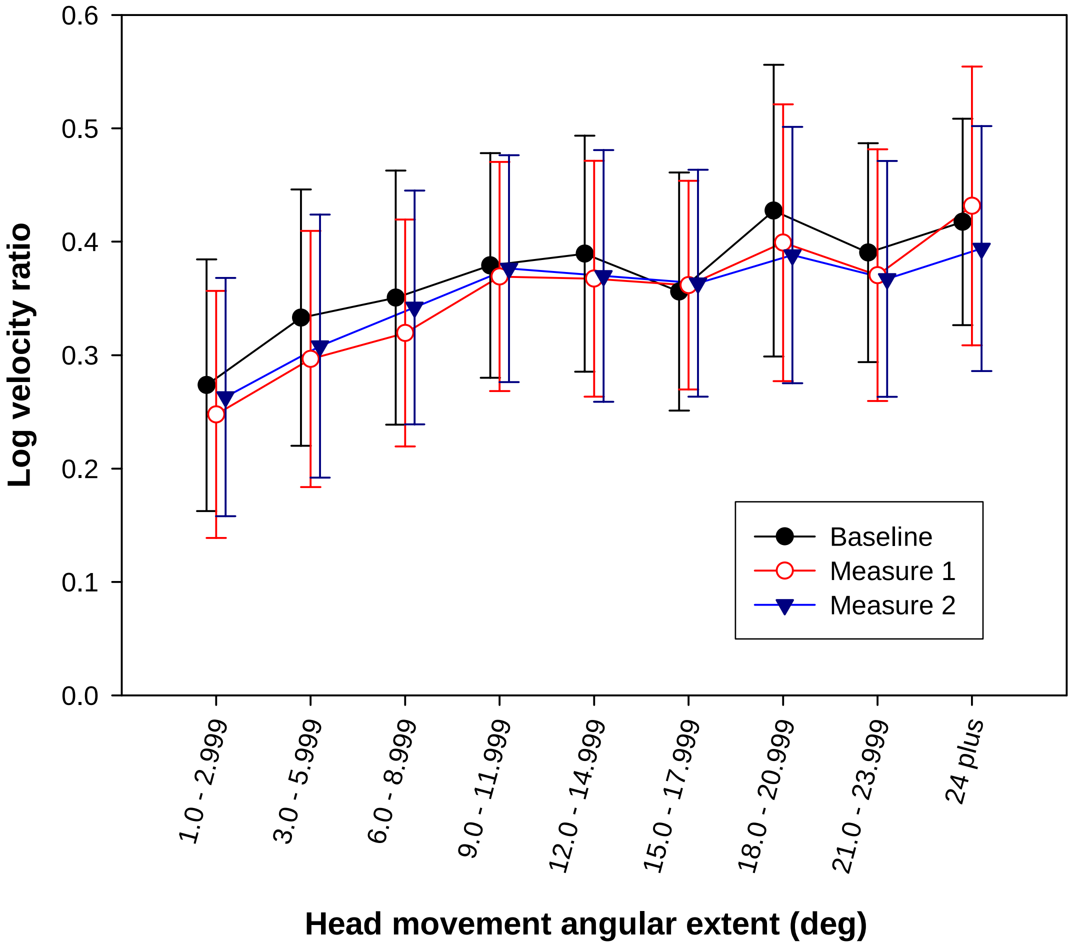

Figure 8.16 Log velocity ratio (log of the ratio of peak to average head movement velocity) of head movement during the search task under three conditions in first time PAL wearers. Points are displaced for clarity, error bars represent one standard deviation. Baseline is pre-PAL wear, Measure 1 was on collection of PAL, and Measure 2 is after 1 month of PAL wear.

PAL wear therefore showed an initial effect on the ratio of peak to average velocity, which was an adaptive effect, as this ratio returned to baseline after 1 month of PAL wear.

8.5 Discussion

8.5.1 Head movement angle (amplitude)

There was an increase in the means of the grouped data for subjects' median head movement angle, subjects' interquartile range of head movement and subjects' 5^{th} – 95^{th} inter-percentile range of head movement across the three measurement trials from baseline (pre-PAL wear), on collection of the PAL, and after 1 month of PAL wear (Section 8.3, Figures 8.1, 8.2 and 8.3). PAL wear increased the range and median amplitude of head movement in this group of subjects, although these differences were minimal for the three variables (median, interquartile range and 5^{th} – 95^{th} inter-percentile range) used to indicate the frequency distribution of head movement amplitudes. Figure 8.17 illustrates the minimal difference found between the measures. Linear scales represent the linear extent of the 5^{th} – 95^{th} inter-percentile range of head movement amplitude for the grouped data of individual subjects' head movements, and represent data for 1400 individual head movements in the pre-PAL measure (measurement condition 1), 1643 head movements recorded on collection of a PAL (measurement condition 2) and 1514 head movements after 1 month of PAL wear (measurement condition 3). Points shown on each scale are 5^{th} percentile, 25^{th} percentile, median, mean, 75^{th} percentile and 95^{th} percentile. Median values are marked by black arrows, means by red arrows. The increase in the inter-percentile range, and median value for head movement angle between the pre-PAL measure and after 1 month of PAL wear are evident, but not significantly different (as above).

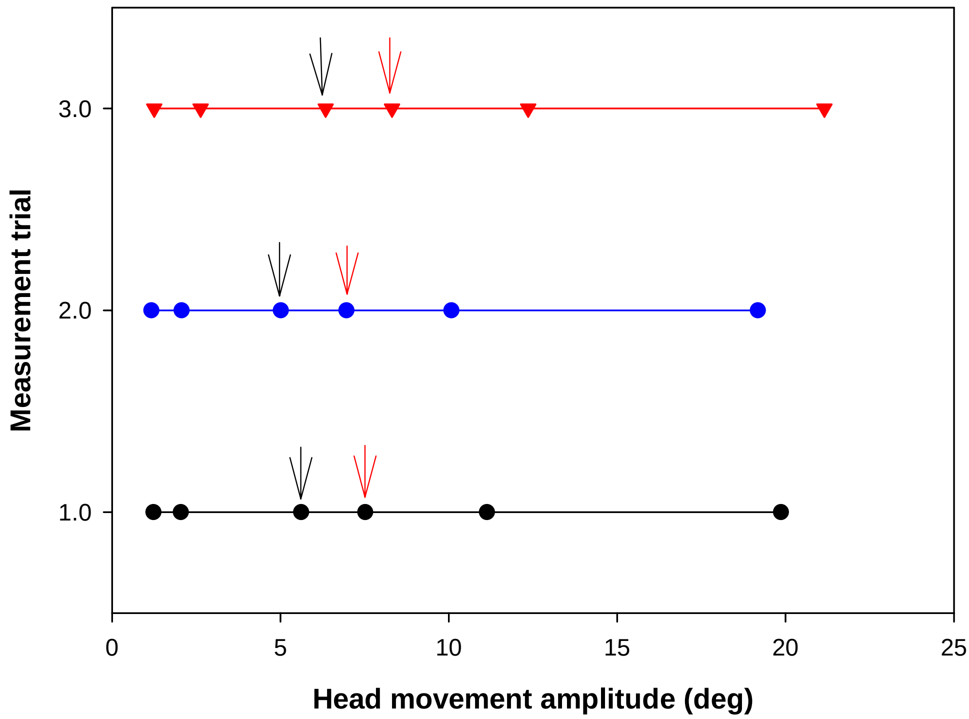

Figure 8.17 Head movement angular range across measurement conditions in first time PAL wearers. Points plotted for each distribution (left – right) are: 5th percentile, 25th percentile, median (black arrows), mean (red arrows), 75th percentile and 95th percentile. Measurement trial 1 = baseline (pre-PAL), 2 = on collection of PAL, 3 = after 1 month of PAL wear. Positive skew of the distributions is apparent.

Sample size (and hence statistical power) is one reason why differences failed to reach statistical significance. The 95% confidence intervals for the within subjects differences across the measurement conditions are quite wide for all three head movement angle variables investigated, in comparison to the mean difference. Thus there was wide intra-subject variability across the measurement conditions. Wide variability in eye and head movement behaviour was also found by Stahl (1999) who demonstrated the "eye only" component of gaze shifts to light emitting diode targets ranged from 35.8º ± 31.9º, representing wide variation in eye and head movement behaviour. Additionally, measures of head movement angular extent and velocity increased in only a subset of subjects and decreased in others; this would have the effect of decreasing the mean difference between grouped subject measures across the measurement trials, particularly with the size of the sample in this experiment.

The task required of subjects in this experiment may not have influenced head movement (and gaze shifts by implication), compared with task demands in other studies. Increases in head movement amplitude with PALs compared to single vision lenses have been found in studies where experimental conditions have been manipulated to force subjects to use the intermediate (progressive power) corridor of the lenses. The current experiment was designed to assess head movement strategy in first time PAL wearers, with head movement velocity and variability of head movement velocity compared pre- and post- PAL wear. Change in head movement velocity or its variability may be a factor in producing adaptive symptoms. If this is the case, assessment of head movement behaviour needed to be assessed in more natural conditions, as opposed to experimental conditions designed to induce head movement.

Selenow et al. (2001) investigated eye and head movements in reading low contrast print. Eye and head movements were recorded in 10 subjects whilst they read text printed at 40% contrast at 60 cm. Text was presented on a single page, or spaced as double paragraphs. Text size is not specified in the presentation abstract, however in other papers involving similar experimental protocols for text placement (Han et al. 2003 ab, Bauer et al. 2000) 9 pt font has been used. Font of this size gives a subtended visual angle of approximately 10 minutes of arc at 60 cm, equivalent to a logMAR acuity of 0.3 (6/12). This demand would force subjects to utilize the progressive corridor for resolution, and the horizontal extent of gaze would be affected by the rapid astigmatic change at the sides of the progressive corridor. Selenow et al. (2001) report in their conference abstract that vertical and horizontal amplitude and horizontal frequency of head movement was worse with PALs than with single vision lenses. In a later publication based on the same research (Han et al. 2003a), the same authors showed the total head movement amplitude in reading increased with 2 different corridor width PAL designs compared to single vision lenses in two reading conditions (standard page layout and double pages separated by 30º). Total head movement amplitude was defined as the horizontal head movement amplitude per line. Mean total head movement amplitude was between 3.5º and 4.5º greater for the two PAL designs studied compared to the single vision lenses in the single page condition. In the double page condition (angular separation 30º) mean total head movement amplitude for PALs was 8.8º to 11.5º higher than with single vision lenses. Standard deviations of the measures were not presented. Amplitude of head movement differed significantly between lens designs and text formats. Visual demands in this experimental protocol would have required subjects to use the progression zone of the lenses for the intermediate task, given the font size used.

Jones et al. (1982) also found increased head movements in reading with PALs and flat-top bifocals, for four text formats (5 point font to 14 point font at 45 cm), and found that the amount of head movement increased with smaller text fonts. Preston and Bullimore (1998) also found the degree of head movement with PALs is dependent upon print size, with smaller print (6 point as opposed to 10 point) inducing more head movement. This is consistent with the observations of Gauthier et al. (1987, 1989, 1991) and Semmlow et al. (1990, 1991) who showed increased head movement with artificially reduced peripheral fields in lenses. Their task required identification of peripherally presented targets subtending 1.7º vertically and 0.6º horizontally at ±27º eccentricity in the visual field. Peripheral visual field of lenses was masked by gel to form a vertical slit-aperture across the optical centre of the lenses, mimicking the effect of a PAL progressive corridor. In Gauthier et al. (1987, 1989, 1991) and Semmlow et al. (1990, 1991) experiments, subjects were only able to use the restricted area of the lens for vision, unlike the situation with PALs in this experiment, where peripheral areas of the lens would have been available to use for vision.

Afandor and Aitsebaomo (1982) investigated eye and head movement behaviour in in pre-presbyopic subjects and presbyopes wearing PAL lenses. They measured the range of eye movements which occurred before any head movements were initiated. Their aim was to detect the normal range of eye movement possible before head movement occurred, using a cut-off criteria for head movement greater than 2º. Fixation lights were used as targets, spaced at 2º intervals. They found the range of eye movement occurring prior to head movement occurring with both PAL wearers and pre-presbyopic subjects to be similar (13.4º in pre-presbyopic subjects and 13.5º in PAL wearers). Their experiment also indicated that head movement was not made to any greater extent in PAL wearers where the target stimulus would not necessitate use of the progressive corridor of the lenses to recognize the target, than it was in pre-presbyopic wearers.

In the current experiment, the visual demand of the search task employed may not have required subjects to use the progressive corridor of their PAL lenses to correctly identify the search targets. The experimental protocol required subjects to locate text (Helvetica 18 point high contrast black letters), presented at a 70 cm working distance according to a list that was hand held. The hand held list was also printed in Helvetica 18 point font. The aim was to simulate a typical daily task such as identifying supermarket shelf product labels. Apart from general information and description of usage of PALs, subjects were not given particular instruction as to whether or not to use the PAL progression for the task.

Angular subtense of the letters used as targets was 22.8 min of arc vertically for capital letters, and 17.4 min of arc vertically for lower case letters, at a fixation distance of 70 cm. These equate to logMAR visual acuity of 0.63 logMAR for capital letters and 0.51 logMAR for lower case letters (approximate Snellen equivalents of 6/26 and 6/21 respectively). In contrast, 9 point font used by Selenow et al. (2002) and Han et al. (2003ab) at 60cm (their working distance) represents an acuity demand of logMAR 0.3 (6/12). Jones et al. (1982) used 5, 6, 7 and 14 point font at 45cm, giving acuity demands of logMAR 0.18 (6/9 equivalent) and logMAR 0.3 (6/12 equivalent) for 5 and 7 point font respectively at 45cm; this working distance also needs an increased accommodative (or near addition) demand. All subjects were within the age range of 48-55 years and therefore presbyopic. Subjects may, however, have had sufficient remaining accommodation to allow the search targets to be viewed without using the added power of progressive zone of the PALs they used. Theoretical accommodative demand for 70 cm is 1.43D. Table 8.3 shows average, maximum, and minimum amplitudes of accommodation based on the formulae of Hofstetter (1950). Resultant amplitudes suggested by Hofstetter's formulae would have been sufficient to allow vision adequate to resolve the targets without use of the progressive corridor addition. Subjects' amplitudes of accommodation were not measured prior to the experiment. Legge et al. (1987) established the total depth of focus for a given acuity level in a group of 4 normal observers, who had accommodation paralysed and pupils dilated. For an acuity level of 6/18 (decimal acuity 0.3 in their study), total depth of focus was 3D (their Figure 10). This would mean that a subject with normal vision could read a 6/18 letter when defocused ±1.5D. In their experiment, pupils were dilated. In the current experiment, pupil size was natural which would increase the available depth of focus. For these reasons, subjects may have been able to perform the search task with the distance zone of their PAL lenses.

Age	Max amp	Ave amp	Min amp
48	5.8	4.1	3.0
49	5.4	3.8	2.75
50	5.0	3.5	2.5
51	4.6	3.2	2.25
52	4.2	2.9	2.0
53	3.8	2.6	1.75
54	3.4	2.3	1.5
55	3.0	2.0	1.25

Table 8.3 Theoretical amplitudes of accommodation for age ranges of subjects in experiment based on Hofstetter's formulae (1950). Max amp = maximum amplitude, ave amp = average amplitude, min amp = minimum amplitude.

If this was the case, any lateral field restrictions caused by the PAL corridor would not have affected head movement amplitudes across the measurement trials, which is suggested by the results found. Additionally, if subjects tended not use the progressive corridor of the lenses, variability across measures would represent variability in head movement behaviour rather than an effect of the PAL wear across measurement trials, which is also suggested by the results found.

Both sample size issues and the possibility above would serve to reduce the chance of a difference being found in head movement amplitudes in the experiment.

8.5.2 Head movement velocity

8.5.2.1 Average and peak velocity

Peak and average head movement velocities found in this experiment are consistent with those found in previous studies. Data for all subjects collated over all measurement conditions showed head movement average velocity to range from 1.25 deg/s to 68.6 deg/s; head movement peak velocity across all trials ranged from 2.92 deg/s to 112.1 deg/s. These values for peak velocity are similar to the range of peak velocities (up to 200 deg/s) found in a number of studies (Stark et al. 1980, Zangmeister et al. 1981, Uemura et al. (1980), Gresty 1974, Ron et al. 1993, Han et al. 2003b). Average velocities are similar to the range of head movement velocities quoted by Epelboim et al. (1995 ab, 1997, 1998).

The group means for subjects' median head movement average velocity and peak velocity increased across measures, indicating an effect of PAL wear on head movement velocity (Section 8.4). Group mean for subject's median head movement average velocity at baseline was 6.31 ± 1.29 deg/s; this increased to 7.35 ± 1.91 deg/s after 1 month of PAL wear. Group means for subjects' median peak velocity increased from 13.57 ± 3.41 deg/s at baseline to 16.38 ± 4.94 deg/s after 1 month of PAL wear (n.s.; p=0.214).

Head movement peak velocity during return sweep saccadic eye movements was investigated by Han et al. (2003b), for subjects wearing single vision lenses and two different PAL designs. The tasks required of subjects necessitated reading text on a single A4 page, and on two pages separated by 30º. Text size used required subjects to use the progressive power corridor of the lenses (see above). No significant differences between head movement peak velocity were found between the single vision lenses and the two PAL designs except between the single vision lenses and the PAL with a narrow progressive corridor when reading a single page (their Table 1). For the wider spaced pages, peak velocity of head movement with PALs was 75 deg/s (SEM ± 6.24) compared to 64 ± 8.77 (SEM) with single vision lenses. Whilst this is a specific type of head movement accompanying return sweep saccades, head movement velocity was not affected by PAL wear, as in the current experiment.

Interquartile and the 5th – 95th inter-percentile ranges of average and peak velocity also increased across measurement intervals; the differences also failed to reach statistical significance. Subjects showed wide inter-subject variability. For the visual task required in this experiment, head movement velocity or its variability was not influenced by PAL wear.

As discussed above, variability, sample size and the task not necessarily requiring full use of the progressive power zones of the lens would have reduced the chance of finding significant differences.

8.5.2.2 Main sequence relationships: velocity and head movement angle

Head movement average and peak velocity (when data are log transformed) show linear main sequence type relationships for log average velocity on log head movement angle, and for log peak velocity on log head movement angle, as was found in the first experiment (Section 7.5) and previously (Stark et al. 1980, Zangmeister et al. 1981). Slope of the main sequence regression line for both log average and log peak velocity on log head movement angle change minimally across the measurement conditions (Section 8.4.3, also Figure 8.12); this difference across measures was non-significant. For comparison, in the search task conducted in Experiment 1 (Chapter 7), the group mean of subjects' slopes for the log average velocity to log head movement angle was 0.446 ± 0.07 (see below).

Group mean of subjects' slope of the log peak velocity on log head movement angle main sequence differed minimally across measurement conditions; with mean slope at baseline was 0.586 ± 0.09, on collection of the PAL was 0.585 ± 0.07, and after 1 month of PAL wear was 0.601 ± 0.09. Measurement condition had no significant effect on slope of the log peak velocity to log head movement angle main sequence regression. The group mean of subjects' slopes for the log peak velocity to log head movement angle regression in the search task in Experiment 1 was 0.597 ± 0.09.

The small group standard deviations for both main sequence regression indicate that these slopes were similar between subjects under the three measurement conditions in this experiment. Bollen et al. (1993) in contrast have shown considerable intra-individual variability in two repeat measures of the saccadic eye movement peak velocity to amplitude main sequence. Less intra-subject variability existed in the head movement peak velocity to amplitude main sequence on repeat measures in the group of subjects participating in the current experiment. This was also found for a small sub-group of subjects in Experiment 1, who completed both tasks in that Experiment (Section 7.5).

Data for Experiment 1 was re-examined, and the group means for the subjects' regression line slopes for the main sequence of log average and log peak velocity on log head movement angle were calculated. For the copy task in Experiment 1, mean slope of the log average velocity on log angle regression was 0.678 ± 0.09. In the search task, this was 0.446 ± 0.07 (as noted above). For the log peak velocity to log angle regression, group mean for the copy task was 0.85 ± 0.08; and in the search task was 0.597 ± 0.09 (as noted above). Standard deviations for group means in Experiment 1 for both visual tasks are also small, indicating little difference between subjects for slope of velocity against angle, as in this experiment.

8.5.2.3 Peak to average velocity relationship

The slope of the main sequence for log peak velocity on log average velocity was calculated for each subject under each measurement condition. Group means of subjects' slopes did not significantly differ across measurement conditions (Section 8.4.3.1).

8.5.2.4 Ratio of peak to average velocity (velocity ratio)

The group mean of subjects' velocity ratio decreased on collection of PALs compared to the pre-PAL baseline and to velocity ratio after 1 month of PAL wear, at which time the velocity ratio had returned toward baseline (Section 8.4.3). This was due to an increase in average velocity in the second measure whilst peak velocity did not differ between baseline and PAL collection measures. Velocity ratio was 2.16 ± 0.06 at baseline, 2.02 ± 0.15 on PAL collection, and 2.11 ± 0.09 after 1 month. This change over measurement conditions was not significant.

Velocity ratio data were log-transformed due to the skewed distribution. Figure 8.16 shows that log velocity ratio was less in the PAL wearing conditions than at baseline; this was a significant effect of measurement condition. Post-hoc pairwise comparisons for log velocity ratio showed the mean difference between baseline and measure 2 (PAL collection) to be 0.027 with the 95% CI for the difference to be 0.19 to 0.034. These data relate to log-transformed data. Relating this to the raw data, velocity ratio on baseline was 1.047 *(i.e.* $10^{0.027}$*)* (CI: 1.044 *(i.e.* $10^{0.019}$*)* to 1.08 *(i.e.* $10^{0.034}$*)*) times higher than velocity ratio on collection of PALs. Whilst this difference is statistically significant, effectively velocity ratio is unchanged by PAL wear, and this is also not affected by head movement amplitude.

Velocity of head movement, whether this is considered as the average velocity of head movement (amplitude/duration) or peak velocity (maximum head movement amplitude in one sampling interval), is not significantly different in PAL wear as opposed to pre-PAL wear, in this group of first time PAL wearers. Variability of head movement velocity (interquartile and the 5^{th} – 95^{th} inter-percentile ranges) is not affected by PAL wear. PAL wear also did not affect the linear relationship of head movement velocity to head movement amplitude (slopes of the main sequence regression lines), or the ratio of peak to average velocity. Head movement velocity behaviour is robust in the presence of PALs, and therefore the hypothesis that PAL wear affects head movement behaviour cannot be supported by the data. The small sample size though will have increased the possibility of a type II error, given that there is wide variability within and between subjects for the amplitude and velocity measures used in the analysis. Repetition of the experiment with an increased number of subjects is required before the hypothesis that PAL wear increases head movement velocity and its variability can be rejected.

A repeat experiment should also include a search task that would require a higher visual demand so that subjects would be required to use the progressive corridor of PALs. An estimate of the variability of head movement behaviour on repetition of the task should also be made.

Chapter 9 Experimental methods 2: Motion detection thresholds

The perception of swim, or induced motion in the peripheral visual field, and other spatial distortions when wearing PALs is one of the causes for adaptation difficulties for PAL wearers. Some potential wearers are unable to adapt to this induced motion and distortion, and consequently are unable to wear PALs. This series of experiments aimed to investigate the relationships between motion detection thresholds in the central and peripheral visual field and head movement. Head movement is necessary when wearing PALs in order to utilize the power profile of the lens efficiently. Head movement may affect motion detection threshold so that previously undetectable motion may become apparent, thus producing swim. Alternately, the peripheral power profile of the PAL, which produces variable magnification across the lens surface, may similarly influence motion detection thresholds.

Motion detection thresholds were measured for central stimuli, and stimuli presented in the superior and inferior temporal visual field of the right eye, under two measurement conditions: with the subjects' head static and the subjects' head in approximate sinusoidal head movement. Minimum displacement thresholds were measured with a single vision lens as a control condition, and for three PAL designs worn as a crossover trial. The motion detection task in the experiments detailed in Sections 9.1 and 9.2 in this thesis is a measure of the minimum displacement threshold for random dot stimuli (Baker 1982, Bullimore, Wood and Swenson 1993, Wood and Bullimore 1995).

9.1 Stimuli for motion detection

Random dot stimuli were generated on 14" VGA monitors by a custom written computer programme (see Appendix B), controlled by a Coretech (Brisbane, Australia) computer using an 80486DX2 processor, and running MS-DOS 6.21 (Microsoft, USA). Screen display was set at 640 x 480 pixels, with a monitor raster display area of 260 x 195 mm. Resultant pixel size was 0.4 mm. Dot stimuli, 1 pixel in size, were randomly generated on the monitors by the software, which displayed

1000 dots (pixels) in random positions on the dark monitor background. Within this random dot display, a central patch of dots underwent coherent motion at random either up or down to create the motion stimulus. The patch size could be set as a percentage of the total screen raster area. For the experiments in this thesis, horizontal and vertical patch size was set at 40% of the total raster area, which produced a target subtending 0.98º at a fixation distance of 6.1m for central measures, and 3.97º at a fixation distance of 1.5 m for peripheral measures.

Apparent motion was obtained by the displacement of illuminated pixels within the central patch in the 200 ms exposure time. Individual pixels were initially illuminated, then extinguished and pixels, displaced from the first, were subsequently illuminated. The smallest number of pixels displaced (as a linear measure) within the exposure time producing apparent motion of the random dot array represented the minimum displacement threshold. For example, a 5 pixel sized displacement represents an angular displacement of 1.145 min arc at a fixation distance of 6.1 m, and a 4.655 min arc displacement at 1.5 m. All pixels moved coherently within the stimulus area, and all pixels that crossed the patch edge in displacement were wrapped to the opposite side.

A VGA monitor, viewed through a back-silvered plane mirror, was used as the target for central measures. This provided a 6.1 m fixation distance for central motion detection stimuli. For measures of central motion detection threshold, subjects fixated this monitor and the left eye was occluded during all experiments.

A distance fixation target was provided during measures of motion detection thresholds in the temporal visual field. Two VGA monitors were placed in the right temporal visual field so that stimuli could be presented in the superior and inferior halves of the temporal right visual field. The centres of the monitor display screens were located 30º temporal to the visual axis, at a distance of 1.5m from the subject. Monitors were placed so that the centre of one monitor's display area was 10º above the horizontal to subject's eye level; the second monitor was placed so that its centre was 10º below the horizontal. Each monitor was set to the same screen resolution, luminance and raster display area.

9.2 Threshold measures

The controlling computer, following button press responses for up/down apparent motion of the stimulus, recorded subject responses. Threshold measures commenced with a maximal displacement of 33 pixels for all trials, and following a correct response, displacement was reduced by a factor of 0.3 on subsequent stimulus presentations until the first reversal point (incorrect response) was recorded. Thresholding then continued with a 2 alternative forced choice (2AFC) procedure using a 2 down/1 up criterion with interval steps being increments of 1 pixel displacement up or down. Subjects were instructed not to guess, and to make no response if they could not determine direction of movement of the stimulus dots. Null responses were recorded as incorrect responses. Ennis, Anderson, Johnson (2002) have compared this thresholding strategy, termed the 2A-NonFC staircase, using a 1 up/1 down staircase, to more commonly used 3 up/1 down 2AFC, 1 up/1 down 2AFC and the method of constant stimuli (MOCS). This no-guessing thresholding protocol showed good agreement to both the MOCS and 3 up/1 down 2AFC procedures, but with a > 50% reduction in presentations for the same number of reversals. They concluded the new 1 up/1 down 2 A-NonFC performs as accurately as conventional staircases, and requires fewer than half of the number of stimulus presentations.

The controlling software allowed input of the number of reversals required to terminate the staircase; in these experiments, thresholding continued until 8 reversals occurred. Responses were recorded on line and saved as a comma-separated-values text file once the staircase procedure was completed. Table 9.1 shows a segment of a saved result file.

Trl	Cond	Correct	Pixels
0	3	Y	33
1	3	Y	21
2	3	Y	13
3	3	-	8
4	3	Y	10
5	3	Y	10
6	3	Y	9
7	3	Y	9
8	3	Y	8
9	3	-	8
10	3	-	9
11	3	Y	10
12	3	Y	10
13	3	Y	9
14	3	Y	9
15	3	Y	8
16	3	Y	8
17	3	Y	7
18	3	Y	7
19	3	-	6

Table 9.1 Extract of result file from thresholding staircase (Trl = trial, Cond = measurement condition, Pixels = no. of pixels displacement)

For each threshold staircase, approximately 45-50 trials were necessary to obtain 8 reversals. Time taken for each run of trials was 2-3 minutes for trials run with static head positions, and up to 7-8 minutes for trials run in conditions of head movement (see Section 9.4). Figure 9.1 (below) illustrates a typical thresholding staircase found during experimentation; this staircase results from the same experimental trial run as the data in Table 9.1.

The minimum displacement threshold was calculated as the arithmetic mean (in pixels) of the turnaround points (upward and downward) of the last five reversals of the staircase (i.e. 10 points), and converted from pixel values to min arc values using a spreadsheet calculation (Microsoft Excel 2000) in a look-up table.

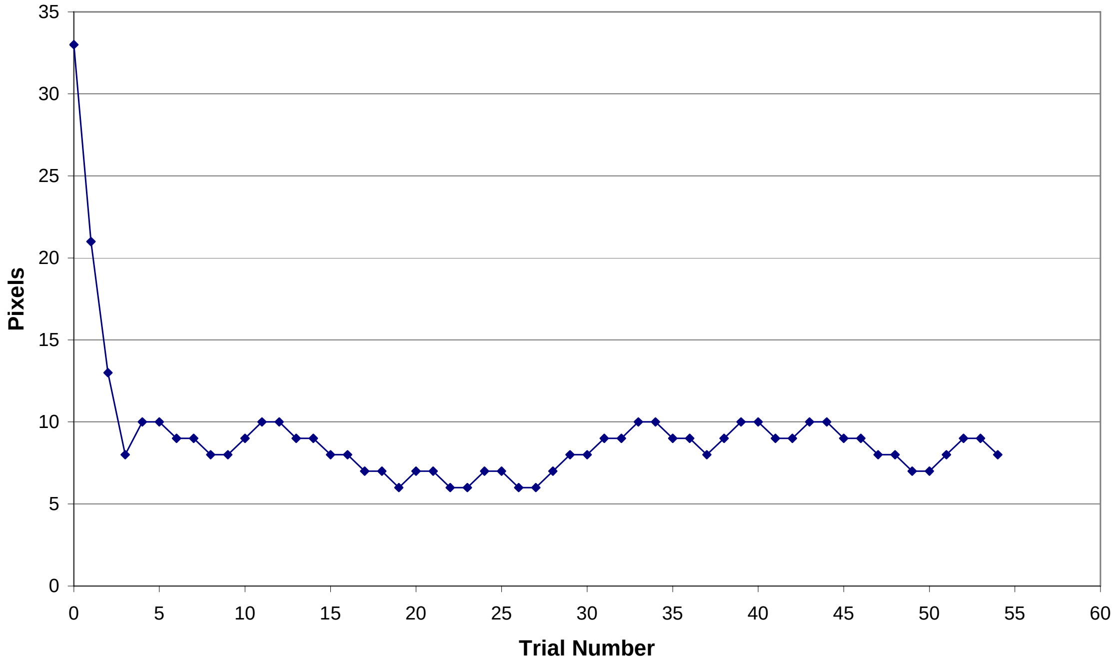

Figure 9.1 Example of a typical thresholding staircase

Order of presentation of stimuli in the three regions of the visual field (central, superior temporal and inferior temporal) and whether the first trial was conducted with the subject's head still or with head movement was randomised using a random number table generated by Microsoft Excel. An additional condition was that head still and head moving trials alternated to alleviate subject fatigue. Rest breaks were included at the request of the subject; not all subjects requested rest periods. The total time for experimental sessions involving measurement of minimum displacement thresholds for apparent motion approximated 90 minutes. CPU control over the VGA monitors displaying stimulus presentations was switched manually according to the random order of presentations.

9.3 Monitor calibration

Luminance of each monitor was measured for the full raster display area for red, green and blue output individually, and also for white and 50% grey output. Contrast and brightness settings for each monitor were adjusted so that luminance was equal on each monitor for each output. The settings for contrast and brightness on each monitor were then marked, and were unchanged throughout experimental sessions. Monitor luminances were rechecked at the start of each experimental session.

Luminance drift of monitors was checked by taking 5 measures for the red, green, blue, white and 50% grey fields before and after a 90 minute period where each monitor was left on.

9.4 Stimulus control with head movement

The experiments described in this thesis investigating motion detection thresholds measured the minimum displacement threshold in two conditions. In addition to threshold measures taken with the subject keeping their head still, subjects were required to make lateral angular head movements (yaw) about the vertical midline. The angular extent of the head movement was limited by stops equidistant from the vertical midline of the head, separated by the required head movement angle in degrees. To achieve the desired head movement velocity, subjects moved their heads in a yawing motion so that the angular limit of head movement was reached in time with a computer driven metronome beat. Head movement made in this manner approximated a sinusoidal movement.

Electrical resistance of the skin was used to record head touch to the limiting stops by the stimulus control software. A circuit powered by a 1.5V AA battery consisted of an electrode held in the subject's hand; the head movement limit stops were part of the circuit, and when the circuit was closed by the subject's head touching the limit stop, the closure of the circuit was recorded by the stimulus control software. When head movement velocity was such that the limit stops were reached within a 150 ms window centred around the metronome beat, control software recorded these as "in-time" touches. Stimuli were presented only when control software recorded a sequence of "in-time" head touches in a R-L-R sequence. Stimuli were presented following the second right side head touch, so that the subject's head was always moving in a right to left direction during stimulus presentations. Stimuli were presented 50 ms after the subject's head touched the right-hand limit stop, with a stimulus exposure time of 200 ms. A warning signal tone was given to indicate to subjects that a stimulus was about to be presented. Stimuli were thus presented at the same point within the sinusoidal head movements for all subjects. Figure 9.2 below illustrates the timing sequence for stimulus presentations where subjects' head movements met the criteria for acceptance.

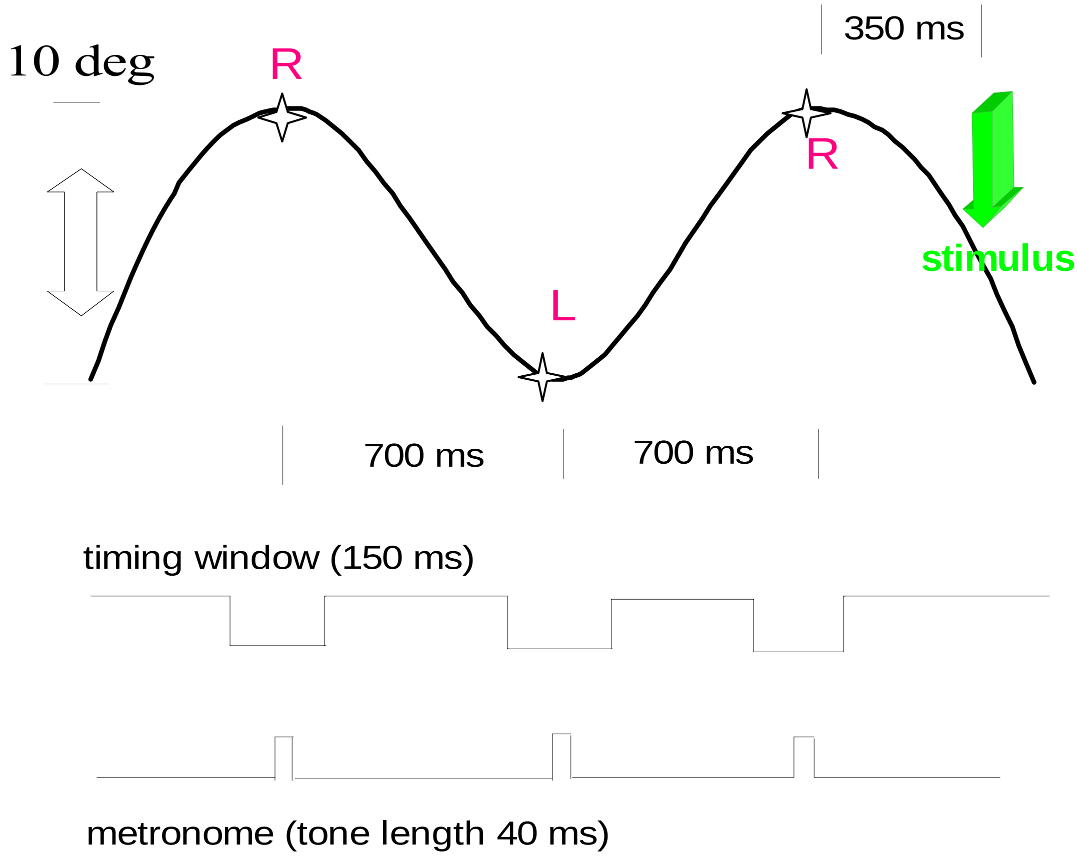

Figure 9.2 Timing sequence for stimulus presentations where head movement matched metronome timing. The stars at the extremes of the head excursion indicate circuit closure.

Where subjects' head movements did not reach the limit stops within the timing window surrounding the metronome tone, or did not make actual touch with the limit stops, stimuli were not presented (Figure 9.3 and 9.4)

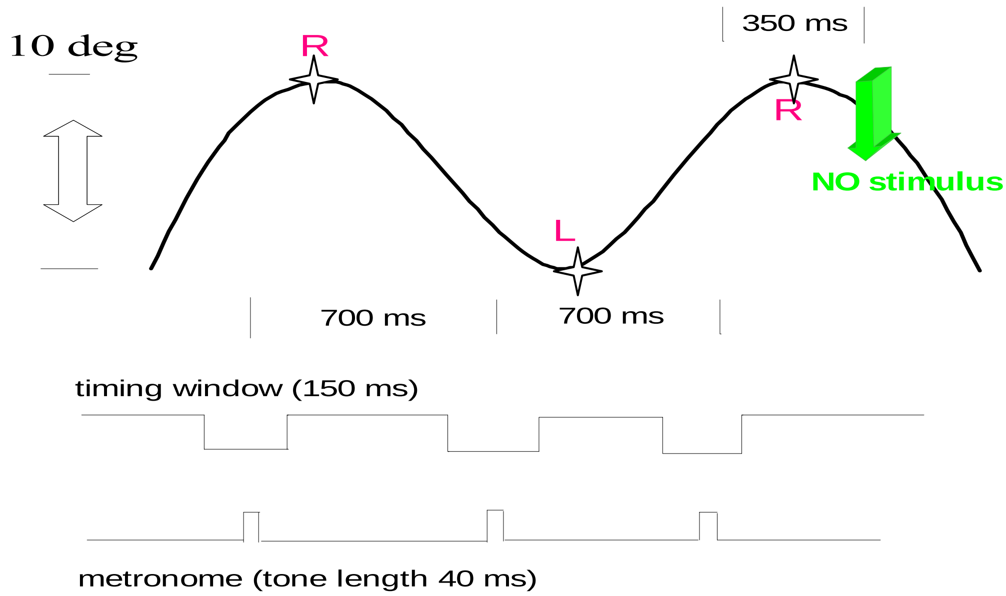

Figure 9.3 Stimulus not presented as head movement timing for reaching limit stops is incorrect. The stars at the extremes of the head excursion indicate circuit closure.

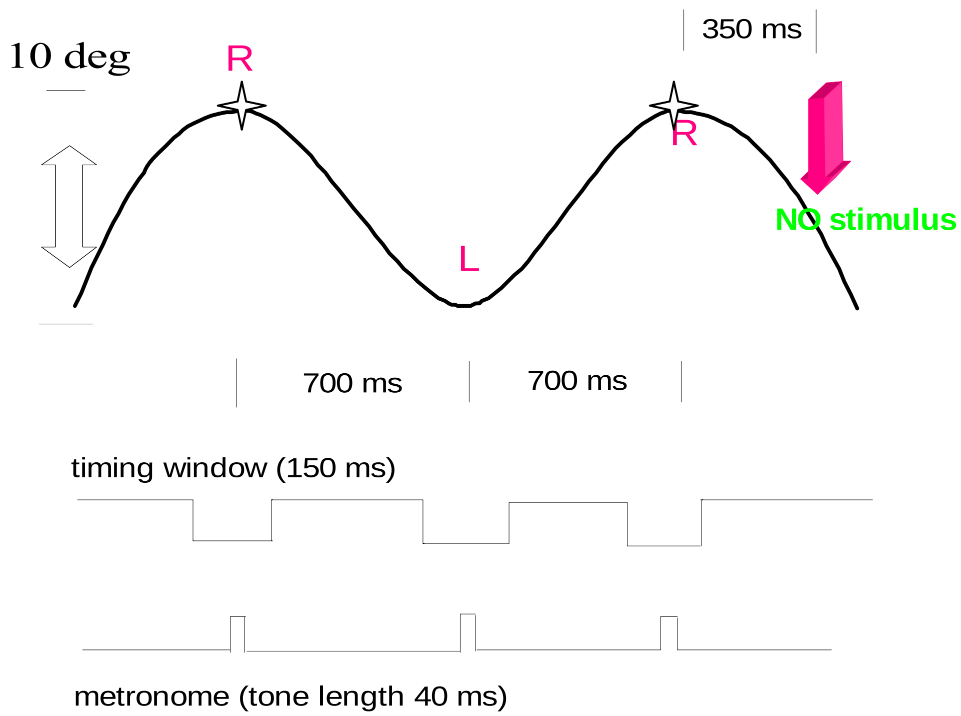

Figure 9.4 Stimulus not presented as head movement short of limit stops; although timing correct, head movement not recorded by control software as valid, as there is no circuit closure on the leftward head excursion, as indicated by the lack of a star here.

9.6 The effect of PAL peripheral design variations on motion threshold – clinical trial

Three experimental PALs were investigated as to their effect on motion detection thresholds. Each PAL had different peripheral power gradients and configuration. The PAL lenses used in this experiment were supplied by SOLA Holdings International Research Centre, Adelaide, Australia.

9.6.1 Method

Subjects wore these PAL lenses on a crossover basis, with three groups of subjects wearing lenses in differing orders (i.e. in the order of lens 1, lens 2, lens 3; or lens 2, lens 3, lens 1; or lens 3, lens 1, lens 2) to control for order effects. Subjects were previously successful PAL wearers, recruited from the Optometry Clinic of the Queensland University of Techology. The age range of subjects was restricted as the experimental PALs were available only in a near addition power range of +2.00 DS to +2.50 DS. Similarly, the spherical component of the distance refractive error was restricted to the range of -2.00 DS to +4.00 DS, due to manufacturing requirements for the experimental lenses.

The PALs for each subject were fitted to the same fitting characteristics (monocular distance PD, optical centre height). Monocular distance PD was measured with an Essilor pupillometer. Optical centre height was measured as the position of the corneal light reflex relative to the inside lower edge of the spectacle frame in the same vertical plane, with the examiner and subject at the same eye level. All measurements were taken by the same examiner. The same frame was used for each lens pair. The three pairs of lenses were edged to the frame at the same time in either the dispensing laboratory of the SOLA International Holdings Research Centre or the School of Optometry at the Queensland University of Technology. Subjects were assigned in random order to one of the three lens wear order groups. Each PAL pair was worn for two weeks, and then replaced with the next test lens pair. The investigator was masked as to the lens design criteria for the period of data collection.

Minimum displacement thresholds (head still and head moving) were measured using the methods described in Sections 9.2 to 9.4 above. A baseline measure was taken using the subject's distance prescription in a single vision correction at the time of delivery of the first test lens pair. Minimum displacement thresholds in the presence and absence of head movement through the PAL were assessed after 2 weeks of wear. The PALs were then changed to the next pair in sequence according to the experimental group to which the subject was assigned. Subjects also completed questionnaires relating to presence of spatial perception distortions (swim) with each lens design (see Chapter 11).

Results of this experiment are reported in Chapter 10. Data were analysed with a repeated measures ANOVA, with minimum displacement threshold as the dependent variable, and lens design as the independent factor, with wearing order group as the between subjects factor.

Chapter 10 Motion detection thresholds in a clinical trial of PAL wear

10.1 Introduction

One factor that influences successful adaptation to PALs is ‘swim’, which is an illusion of motion of objects visible through the peripheral zones of the PAL, induced by the non-uniform power profile of the peripheral zones of the lenses. Some potential wearers are unable to adapt to this induced motion and distortion, and consequently are unable to wear PALs.

Additionally, head movement is necessary when wearing PALs in order to utilize the power profile of the lens efficiently (e.g. Jones 1982, Guillon, Maissa and Barlow 1999, 2000, Han 2003ab). Head movement may affect motion detection threshold so that previously undetectable motion may become apparent, thus producing swim. Alternately, the peripheral power profile of the PAL, which produces variable magnification factors across the lens surface, may similarly influence motion detection thresholds.

This experiment aimed to investigate the relationships between motion detection thresholds in the central and peripheral visual field and head movement in subjects wearing three different PAL designs.

10.2 Methods in brief

Minimum displacement thresholds for random-dot stimuli (Baker 1982) were used as the measure of motion detection thresholds in this experiment. Stimuli were generated on 14” VGA monitors by a custom written programme. Dots, numbering 1000 in total and 1 pixel in size, were randomly generated on the screen raster area (260 x 195 mm); within this display, a central patch of dots underwent motion either up or down at random. Patch size was set at 40% of the total screen raster area for this experiment. This resulted in a target subtending 0.98º at a fixation distance of 6.1m for central measures, and 3.97º at a fixation distance of 1.5 m for peripheral measures. Monocular (right eye) only measures were taken at each location. The subjects' left eye was occluded with a black opaque occluder, placed behind the spectacle lens.

Stimuli were presented in three regions of the right visual field: central and 30º temporally, 10º above and below the horizontal meridian. Presentation order was randomized. The three monitors used to present stimuli were matched for luminance, raster area and screen resolution. Thresholds were estimated in one of two conditions, with the subject's head held steady, or with the subject's head moving in a sinusoidal motion in a horizontal plane (yaw), for the three areas of the visual field in a random order. Subjects had to make head movement in time with a computer generated metronome beat to reach limit stops which set the angular extent (and approximate velocity) of the head movement. Stimuli were presented only when head movement reached the limit stops within a 150 ms window centred on the metronome beat. Head motion (static vs moving) was also randomized for the first measurement trial in each session, after which the head moving conditions alternated for subsequent runs to minimise subject fatigue. For central measures, subjects were instructed to fixate the stimulus monitor directly; for peripheral measures fixation was directed to a small LED target presented centrally.

Thresholds were estimated with a 2 AFC staircase, but with subjects instructed not to guess, using a 2 down/ 1 up criterion, with a step size of 1 pixel. Null responses were recorded as incorrect responses. Staircases terminated after eight reversals, and threshold was calculated as the mean of the turnaround points (upward and downward) of the last five reversals of the staircase (i.e. 10 points). Pixel values were converted to angular values in min arc by using a spreadsheet look-up table.

Thresholds were measured with a single vision lens distance correction as baseline, and for three PAL designs, worn in a cross-over design wearing trial, after 2 weeks of wear of each PAL.

Subjects completed a questionnaire for each PAL which sought symptoms of distortion or illusory movement whilst wearing the PAL. Subjects also indicated preference ratings for the PAL designs in paired comparisons.

A full description of the experimental and data collection methods can be found in Chapter 9. Details of the questionnaire and data collection methods for symptoms of distortion and illusory movement with the PALs can be found in Chapter 11. Experimental methods were subject to ethical approval of the Queensland University of Technology's Human Ethics Research Committee. Subject selection criteria can be found in Chapter 6, Section 6.3.1. Age range of the subjects was restricted due to the availability of near additions (+2.00DS to + 2.50DS) in the PAL lenses used in the trial. Table 10.1 outlines demographic and refractive data for subjects included in the experiment. Mean age of subjects was 54.4 ± 3.2 years, mean previous PAL wearing experience was 2.7 ± 3.2 years.

Subject	Age	Sex	Prev Wear	R sph	R cyl	R axis	L sph	L cyl	L axis	Add
1	49	M	0.5	-2.00	-1.75	110	-1	-1.25	75	2.00
2	56	F	4	0.25	-0.75	15	0.25	-0.50	10	2.00
3	56	F	8	0.50			0.25			2.25
4	51	F	0	-0.50	-0.50	40	-0.50	-0.50	170	2.25
5	57	M	4	0.25	-0.50	30	plano	-0.50	155	2.25
6	57	F	0	1.75	-0.25	10	1.50	-0.25	5	2.25
7	54	F	4	1.25			1.25	-0.25	10	2.00
8	56	F	3	1.25			0.75			2.25
9	56	F	0.75	1.50	-0.75	5	1.75	-0.75	158	2.00
10	51	F	1	0.50	-0.50	100	0.75	-0.75	95	2.00
11	59	M	6	1.00	-0.50	40	plano	-0.50	40	2.50
12	55	F	5	plano	-0.25	175	plano	-0.25	20	2.00
13	58	F	3	2.25	-0.25	95	2.25			2.00
14	52	F	1	0.75	-0.25	45	0.75			2.00
15	48	F	2	plano	-0.50	75	0.75	-0.50	80	2.00
16	53	F	1	1.25			0.75			2.25
17	57	M	3	plano	-0.50	80	-0.25	-0.50	70	2.25
Mean	54.4		2.7							
SD	3.2		3.2							
Median	56.0		3.0							

Table 10.1 Subject demographic and refractive data. Columns headed 'Age' is age in years, 'Sex' is Male/Female, 'Prev Wear' is number of years of PAL wearing experience prior to the experiment. Mean, standard deviation and median values are shown for age and previous PAL wearing experience.

10.3 Minimum displacement thresholds

10.3.1 Central measures

The minimum displacement thresholds for central (foveal) measures with a stationary head position varied little across the four lens designs (single vision, and the three PAL lenses) and ranged from 1.60 ± 0.28 min arc to 1.66 ± 0.24 min arc across the different lens designs. Comparisons of the thresholds for the individual lenses are shown in Table 10.2 and Figure 10.1. Ranges of the thresholds varied across subjects within each lens design, as is shown in Table 10.2

When the head was stationary thresholds were only about 60% of those in the 'head moving' condition. In the head movement condition, minimum displacement threshold increased to a range of 2.57 ± 0.52 min arc to 2.71 ± 0.40 min arc, across the lens designs. Mean minimum displacement thresholds for central fixation elevated when subjects were making sinusoidal head movement as described above (Section 10.2) (Table 10.2, Figure 10.1). Variance for minimum displacement thresholds also increased with head movement (Table 10.2), indicating thresholds became more variable across subjects with head movement, whereas variance of thresholds in the head static condition was only about 60% of the value when the head was moving.

			Mean	Std Deviation	Variance	Minimum	Maximum
Central	head static	Single Vision	1.60	0.28	0.08	0.99	2.32
		PAL 1	1.63	0.19	0.04	1.28	1.94
		PAL 2	1.66	0.24	0.06	1.28	2.15
		PAL 3	1.63	0.29	0.08	1.11	2.10
	head moving	Single Vision	2.66	0.34	0.11	2.21	3.64
		PAL 1	2.71	0.35	0.12	2.31	3.52
		PAL 2	2.71	0.40	0.16	1.66	3.35
		PAL 3	2.57	0.52	0.27	1.69	3.40

Table 10.2 Descriptive statistics for mean minimum displacement thresholds (min arc) for a central target across four lens designs, in the static head and moving head conditions.

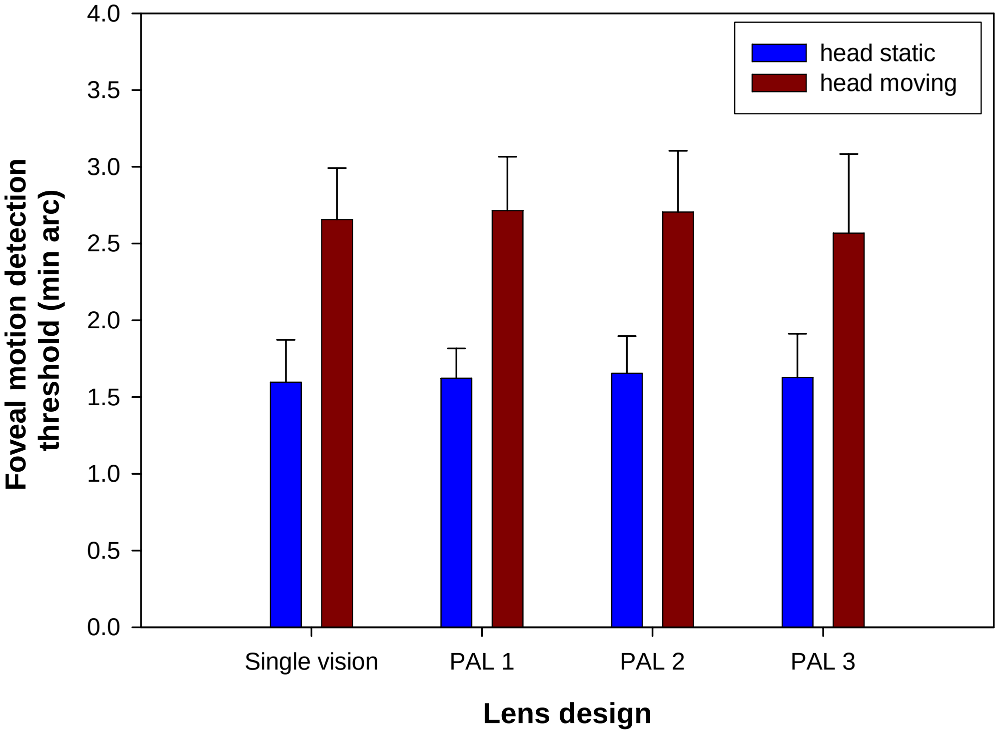

Figure 10.1 Mean minimum displacement thresholds (min arc) for a central target for four lens designs (Error bars are one standard deviation)

The effect of lens type and head movement on minimum displacement threshold for the central target was evaluated by a repeated measures analysis of variance, with minimum displacement threshold as the dependent variable, and lens type (4 levels: single vision, PAL 1, PAL 2, PAL 3) and head movement (2 levels: static and moving) as the independent factors. The order of wearing the different PAL designs was used as a between-subjects factor, to assess whether the order of PAL wear had an effect; as indicated above (Section 10.2), subjects wore the PAL lenses on a crossover basis, assigned at random. Three lens wear orders were used (1-2-3, 2-3-1 and 3-1-2).

Multivariate tests showed that lens type had no significant effect on the central minimum displacement threshold (Wilks' lambda = 0.830, $F_{3, 12} = 0.821$, $p = 0.507$). Within subjects contrasts ($F_{1, 12} = 0.044$, $p = 0.836$) also showed no effect of lens type on central measures of minimum displacement threshold. The interaction of order of PAL wear with lens type also had no effect (Wilks' lambda = 0.847,

$F_{6, 24} = 0.345$, $p = 0.906$; within subjects contrasts: $F_{2, 14} = 0.311$, $p = 0.739$).

Head movement had a significant effect on the minimum displacement threshold (Wilks' lambda = 0.016, $F_{1,14} = 846.95$, $p < 0.0005$). This was not unexpected, as Table 10.2 shows an approximate 60% increase in threshold in the presence of head movement (see also Figure 10.1). Post hoc comparisons by paired t-tests show a significant difference for all lens designs between the head static threshold and the head moving threshold, with significance adjusted by a Bonferroni adjustment for multiple comparisons (adjusted $p = 0.0125$) (Table 10.3).

	Mean	Std Deviation	Std Error	95% CI of difference		t	df	p (2 tail)
				Lower	Upper			
Single vision	-1.060	0.311	0.075	-1.220	-0.900	-14.062	16	<0.0005
PAL 1	-1.085	0.354	0.086	-1.267	-0.903	-12.626	16	<0.0005
PAL 2	-1.050	0.306	0.074	-1.207	-0.893	-14.166	16	<0.0005
PAL 3	-0.941	0.450	0.109	-1.172	-0.709	-8.616	16	<0.0005

Table 10.3 Paired comparisons (head static – head moving) for central minimum displacement thresholds for lens designs. All differences are significant at a significance level adjusted for multiple comparisons (Bonferroni, $p = 0.0125$). For all designs, minimum displacement threshold is higher in head movement (negative differences)

The mean difference in threshold is approximately 1 min arc for all lens designs, with the threshold in head movement being the higher. The standard deviation of the differences is high compared to the mean difference; wide inter-subject variability in the difference between the head static and head moving minimum displacement thresholds existed. The 95% confidence limits for the distribution of the difference are also quite wide in comparison to the mean difference.

The interaction of head movement with PAL wearing order was not significant ($F_{2, 14} = 2.311$, $p = 0.136$). The interaction of lens design and head movement had no significant effect on the central minimum displacement threshold ($F_{1,14} = 1.014$, $p = 0.331$). The interactions of lens design, head movement and PAL wearing order also had no significant effect on central minimum displacement thresholds

($F_{2, 14}$ = 1.109, p = 0.357). PAL wearing order also had no effect as a between subjects factor ($F_{2,14}$ = 0.526, p = 0.602).

The minimum displacement threshold was increased by head movement across lens designs. This increase was not affected by the type of lens worn, nor the order in which the PALs were worn.

10.3.2 Minimum displacement thresholds in the infero-temporal visual field

Mean minimum displacement threshold in the head static condition in the infero-temporal visual field of the right eye was 6.63 ± 1.1.40 min arc with single vision lenses. Minimum displacement thresholds with the PALs were 6.84 ± 1.11 min arc with PAL 1, 7.03 ± 1.28 min arc with PAL 2, and 6.79 ± 1.06 min arc with PAL 3 (Figure 10.2). The range of threshold measures with the different lens designs is shown in Table 10.5. As shown in Table 10.4, variance was highest with the single vision lenses, and lowest with PAL 3.

			Mean	Std Deviation	Variance	Minimum	Maximum
Infero-temporal	head static	Single Vision	6.63	1.40	1.95	2.95	9.45
		PAL 1	6.84	1.11	1.22	4.58	8.49
		PAL 2	7.03	1.28	1.63	4.08	9.11
		PAL 3	6.79	1.06	1.13	4.66	8.43
	head moving	Single Vision	9.54	2.76	7.60	4.58	15.88
		PAL 1	10.06	1.79	3.19	7.03	13.23
		PAL 2	10.98	2.01	4.03	7.11	14.22
		PAL 3	10.11	1.94	3.75	7.23	12.94

Table 10.4 Descriptive statistics for minimum displacement thresholds in the infero-temporal visual field of the right eye, in four lens types.

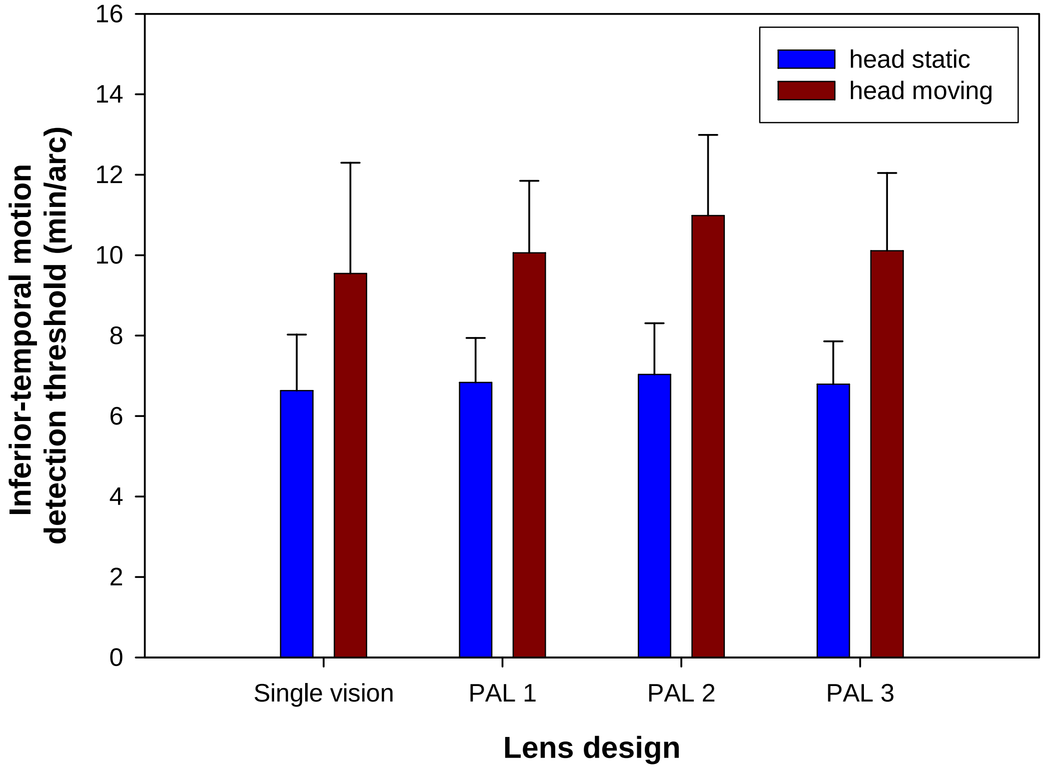

Figure 10.2 Mean minimum displacement thresholds (min arc) for an infero-temporal target for four lens designs (Error bars are one standard deviation)

When subjects made approximately sinusoidal head movement, minimum displacement thresholds increased by about 50% in the infero-temporal visual field compared to when the head was static (Table 10.4, Figure 10.2). Threshold for single vision lenses became 9.54 ± 2.76 min arc, for PAL 1 10.06 ± 1.79 min arc, PAL 2 10.98 ± 2.01 min arc and for PAL 3 10.11 ± 1.94 min arc. Variance of threshold increased markedly with head movement, which indicated increased variability between subjects.

Minimum displacement thresholds were not affected by lens type (Wilks' lambda = 0.785, $F_{3, 12}$ = 1.093, p = 0.39, within subjects contrasts: $F_{1,14}$ = 1.302, p = 0.273). The interaction of lens type and PAL wearing order also had no effect on minimum displacement threshold (Wilks' lambda = 0.691, $F_{6, 24}$ = 0.811, p = 0.572; within subjects contrasts: $F_{2,14}$ = 0.779, p = 0.478).

Head movement had a significant effect on the minimum displacement threshold in the infero-temporal field (Wilks' lambda = 0.691, $F_{1,14}$ = 297.42, p < 0.0005); mean threshold was approximately 3 min arc higher in the head moving condition (Table 10.4). Post-hoc paired t-tests showed significant differences for all lens designs on paired comparisons of the head static to head moving thresholds (Table 10.5).

	Mean	Std Deviation	Std Error	95% CI of difference Lower	Upper	t	df	p (2 tail)
Single vision	-2.911	1.915	0.465	-3.896	-1.927	-6.267	16	<0.0005
PAL 1	-3.221	1.396	0.339	-3.939	-2.503	-9.515	16	<0.0005
PAL 2	-3.951	1.213	0.294	-4.575	-3.328	-13.433	16	<0.0005
PAL 3	-3.312	1.892	0.459	-4.285	-2.340	-7.219	16	<0.0005

Table 10.5 Paired comparisons (paired t-tests, post-hoc) for minimum displacement thresholds in head static – head moving conditions, for four lens designs, infero-temporal field. All paired comparisons are significant at a significance level adjusted for multiple comparisons (Bonferroni, p = 0.0125)

The difference between threshold in head static and head moving conditions was greatest in PAL 3 at -3.951 ± 1.213 min arc (head moving condition greater); other lens designs showed differences of the order of 3 min arc between head static and head moving conditions, with the head moving condition threshold higher than the head static threshold. Once more, standard deviations of the differences were high in relation to the mean.

The interaction of head movement with PAL wearing order had no significant effect on minimum displacement threshold ($F_{2,14}$ = 0.354, p = 0.708). Lens design and head movement together had no significant interaction effect on minimum displacement threshold ($F_{1,14}$ = 0.619, p = 0.445). The interaction of lens design, head movement and PAL wearing order had no significant effect on minimum displacement threshold ($F_{2,14}$ = 0.015, p = 0.085). The between subject effect of PAL wearing order had no significant effect ($F_{2,14}$ = 0.752, p = 0.49).

Minimum displacement threshold in the infero-temporal field was increased in PAL lenses compared to a single vision lens. One PAL design (PAL 2) produced a greater increase in minimum displacement threshold compared to other PAL designs, although this was not significant. Head movement significantly increased minimum displacement threshold in the infero-temporal visual field; this was not affected significantly by lens design or by PAL wearing order.

10.3.2 Minimum displacement thresholds in the superior-temporal field

The mean minimum displacement threshold in the superior-temporal visual field was 6.79 ± 1.78 min arc with single vision lenses in the head static condition. Threshold with the head static with PAL designs was slightly higher than with single vision lenses. Mean minimum displacement threshold for PAL 1 was 7.10 ± 1.55 min arc, for PAL 2 mean threshold was 7.04 ± 1.86 min arc, and for PAL 3 was 7.30 ± 1.64 min arc (Table 10.6, Figure 10.3).

			Mean	Std Deviation	Variance	Minimum	Maximum
Supero-temporal	head static	Single Vision	6.78	1.78	3.17	2.91	10.80
		PAL 1	7.10	1.55	2.40	3.43	8.99
		PAL 2	7.04	1.86	3.46	3.78	11.15
		PAL 3	7.30	1.64	2.69	3.80	9.95
	head moving	Single Vision	10.05	2.06	4.24	3.68	13.04
		PAL 1	11.38	2.77	7.68	5.79	16.11
		PAL 2	11.56	2.10	4.39	8.57	16.20
		PAL 3	11.05	2.69	7.22	4.69	15.03

Table 10.6 Descriptive statistics for minimum displacement thresholds (min arc) for a target in the superior-temporal visual field, for four lens designs, in head static and head moving measurement conditions.

Standard deviations and the variance in the head static condition were high in relation to the mean for all lenses. This indicated high inter-subject variability which is supported by the range of thresholds.

Mean minimum displacement thresholds are increased by head movement for all lens designs (Table 10.6, Figure 10.3). Mean minimum displacement threshold in the head moving condition was 10.05 ± 2.06 min arc with single vision lenses. With the PAL designs, mean threshold was 11.38 ± 2.77 min arc with PAL design 1; increased slightly with PAL 2 to 11.56 ± 2.10 min arc, and was slightly lower at 11.05 ± 2.69 min arc with PAL 3. Variance in the threshold was higher in the head movement condition than in the head static condition; variability in threshold increased with head movement.

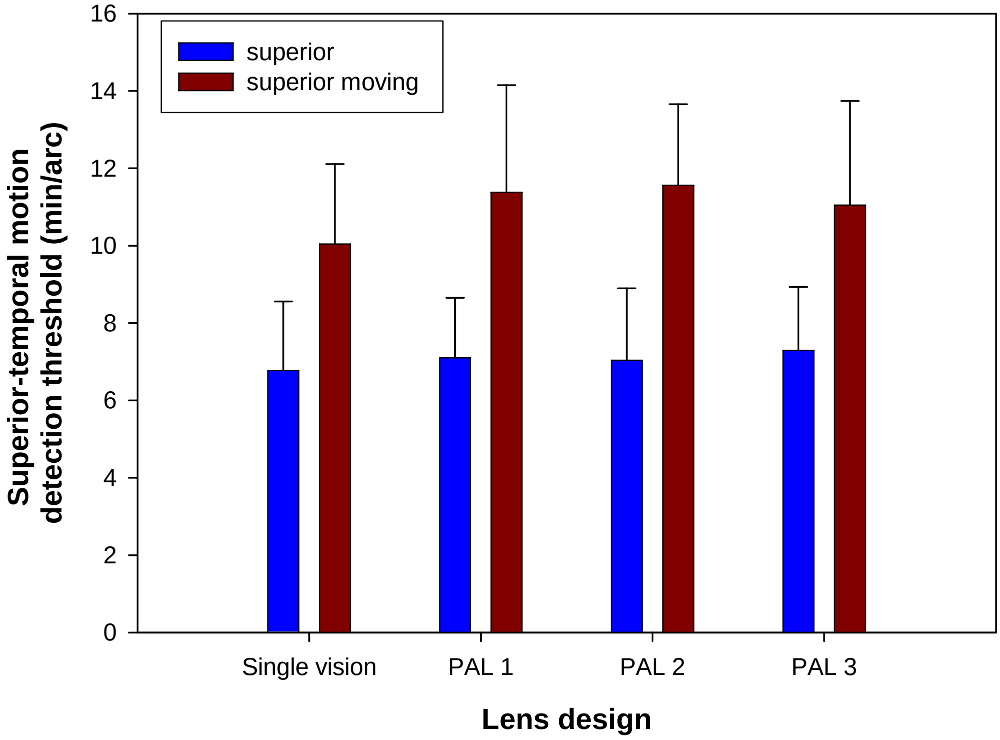

Figure 10.3 Mean minimum displacement thresholds (min arc), for four lens designs, supero-temporal visual field. (Error bars are one standard deviation).

The effect of lens type and head movement on minimum displacement thresholds in the supero-temporal field was investigated by a repeated measures analysis of variance, with threshold as the dependent variable and lens type (4 levels) and head movement (2 levels) as the independent factors, and PAL wearing order (3 levels) as a between subjects factor.

Minimum displacement thresholds were not affected by lens type (Wilks' lambda = 0.609, $F_{3,12}$ = 2.566, p = 0.10). The interaction of lens type and PAL wearing order also had no significant effect on the supero-temporal minimum displacement threshold (Wilks' lambda = 0.772, $F_{6,24}$ = 0.554, p = 0.762).

Head movement, as was expected given the increase in mean threshold across lens designs (Figure 10.3, Table 10.6), had a significant effect on minimum displacement threshold in the supero-temporal field (Wilks' lambda = 0.052, $F_{1,14}$ = 255.57, p < 0.0005,). Post-hoc paired t-tests showed significant differences in minimum displacement threshold between head static and head moving conditions for all lens designs (significance level adjusted for multiple comparisons, p = 0.0125, Bonferroni adjustment) (Table 10.7)

	Mean	Std Deviation	Std Error	95% CI of difference		t	df	p (2 tail)
				Lower	Upper			
Single vision	-3.271	1.744	0.423	-4.168	-2.374	-7.731	16	<0.0005
PAL 1	-4.277	1.685	0.409	-5.144	-3.411	-10.469	16	<0.0005
PAL 2	-4.526	1.815	0.440	-5.459	-3.593	-10.285	16	<0.0005
PAL 3	-3.755	1.983	0.481	-4.775	-2.735	-7.807	16	<0.0005

Table 10.7 Post-hoc paired t-tests for head static – head moving differences in minimum displacement threshold in the supero-temporal visual field, for four lens designs. All paired comparisons are significant (adjusted for multiple comparisons, at p = 0.0125, Bonferroni adjustment).

Minimum displacement threshold was increased 3.27 to 4.52 min arc on average by head movement across all lens designs; the single vision lens showed the least increase (3.27 ± 1.74 min arc) and PAL 2 the greatest increase (4.53 ± 1.82 min arc). Wide variability, evidenced by the standard deviations and 95% confidence intervals for the mean difference, was present.

The interaction of lens type with head movement was non-significant (Wilks' lambda = 0.760, $F_{3,12}$ = 1.262, p = 0.331). There was also no interaction effect for head movement and PAL wearing order (Wilks' lambda = 0.826, $F_{2,14}$ = 1.47, p = 0.263,). The interaction of lens design, head movement and PAL wearing order had no effect on minimum displacement threshold (Wilks' lambda = 0.66, $F_{6,24} = 0.923$, p = 0.496,). The between subject effect of wearing order was not significant ($F_{2,14}$ = 0.942, p = 0.413).

Minimum displacement threshold in the superior temporal field was increased by head movement. Threshold was not affected by lens design or wearing order of the PAL lenses.

10.4 Ratio of threshold measures

Results above show that head movement caused a significant increase in minimum displacement threshold for measures at the fovea and at two peripheral locations in the visual field, across four lens designs. Minimum displacement thresholds measured with the head static or with the head moving in approximate sinusoidal movement however were not significantly different between lens designs. Change in minimum displacement threshold from baseline was investigated by analyzing the ratio of the minimum displacement threshold obtained with head movement to the minimum displacement threshold with the head static. In effect, the head static threshold is the baseline for each subject. Ratios of minimum displacement thresholds for head moving/head static were calculated for the single vision lens and the 3 PAL designs, for foveal, inferior temporal and superior temporal measures.

Mean ratio of head movement thresholds ranged from 1.44 ± 0.29 to 1.69 ± 0.29 across the lens designs and locations. (Table 10.8, Figure 10.4). Head movement increased minimum displacement threshold from 44% to 70% on average compared to baseline head static measures across all conditions of measurement.

The effect of lens design and location of displacement threshold measurement within the field of vision on the ratio of minimum displacement thresholds was investigated by a repeated measures analysis of variance, with the ratio of the minimum displacement thresholds as the dependent variable, and lens design (4 levels) and location of measurement (3 levels) as the independent factors, and PAL wearing order (3 levels) as the between subjects factor.

	Central (foveal)	Inferior temporal	Superior temporal
Single Vision	1.69 ± 0.29	1.44 ± 0.30	1.54 ± 0.40
PAL 1	1.68 ± 0.27	1.48 ± 0.23	1.61 ± 0.21
PAL 2	1.64 ± 0.20	1.57 ± 0.18	1.72 ± 0.42
PAL 3	1.59 ± 0.29	1.51 ± 0.32	1.54 ± 0.37

Table 10.8 Mean ratio of minimum displacement threshold in head moving condition / head static condition

Lens design had no effect on the ratio of minimum displacement thresholds (Wilks' lambda = 0.834, $F_{3,12} = 0.797$, p = 0.519). There was no effect for the interaction of lens design and PAL wearing order (Wilks' lambda = 0.651, $F_{6,24} = 0.958$, p = 0.474).

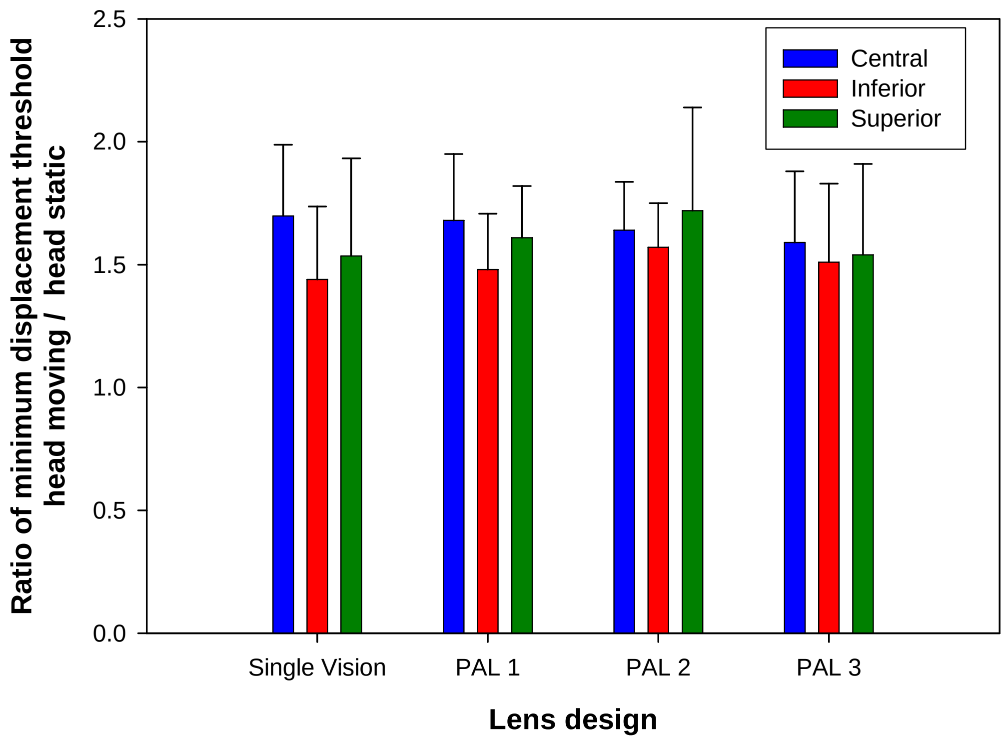

Figure 10.4 Mean ratio of minimum displacement thresholds in head moving/head static conditions for four lens designs. Error bars are one standard deviation.

Location of the threshold measurements had a significant effect on the ratio of minimum displacement thresholds (Wilks' lambda = 0.368; $F_{2,13}$ = 11.168, p = 0.002). Post-hoc t-tests showed this to be due to a significant difference between the ratio of minimum displacement thresholds centrally and inferiorally (Table 10.9). The mean ratio of minimum displacement thresholds centrally was 1.66 ± 0.26, inferiorally was 1.50 ± 0.26 and superior was 1.6 ± 0.36. Table 10.10 shows descriptive statistics for the ratio of minimum displacement thresholds at each measurement location, collated for all designs. The ratio of minimum displacement thresholds was significantly greater centrally than inferiorally, with the mean difference in ratio being 0.154 ± 0.35 (Table 10.9). Differences between the ratio of minimum displacement thresholds centrally to superiorally, and inferiorally to superiorally were not significantly different. Standard deviations of the differences were high in relation to the mean difference, indicating wide variability.

	Mean	sd	95% CI difference		t	df	p
Comparison	difference		upper	lower			
Central - Inferior	0.154	0.35	0.834	-0.52	3.419	134	0.0008*
Central - Superior	0.05	0.38	0.795	-0.68	1.026	134	0.307
Inferior - Superior	-0.099	0.41	0.71	-0.9	-1.826	134	0.07

Table 10.9 Post-hoc paired t-tests for ratio of minimum displacement thresholds in three locations of visual field. * = significant at p = 0.0167, Bonferroni adjustment for multiple comparisons.

	Mean	sd	95% CI		Minimum	Maximum
			lower	upper		
Central	1.66	0.26	1.14	2.17	1.12	2.45
Inferior	1.50	0.26	0.99	2.01	1.07	2.42
Superior	1.60	0.36	0.89	2.30	0.96	2.91

Table 10.10 Descriptive statistics for the ratio of minimum displacement thresholds at three measurement locations.

The interaction of lens wearing order with the location of threshold measurements had no significant effect on the ratio of minimum displacement thresholds (Wilks' lambda = 0.758, $F_{4, 26}$ = 0.965, p = 0.443). Lens design and location of threshold measurement also showed no interaction effect (Wilks' lambda = 0.644, $F_{6,9}$ = 0.828, p = 0.576). The combined interaction between lens design, location of threshold measurement and PAL wearing order also had no significant effect on the ratio of minimum displacement thresholds (Wilks' lambda = 0.569, $F_{12, 18}$ = 0.488, p = 0.896).

The ratio of minimum displacement threshold measured with the head moving to that measured with the head static was not affected by lens design, indicating that head movement affected minimum displacement threshold by a similar factor across all lens designs. Head movement increased minimum displacement thresholds by a factor of approximately 1.5 to 1.6 for each lens design tested. The ratio of minimum displacement threshold measured with head movement to head static was significantly greater for central measures than inferior temporal measures; this difference is in the order of 15% on average.

10.5 Single vision lens to PAL differences

In the analysis above, the three PAL designs were considered individually within the analysis. To investigate if there is an effect of PAL wear on minimum displacement thresholds, data for the three PAL designs were grouped, and compared to data for the single vision control lens in a series of independent t-tests, with a Bonferroni adjustment to control for type II errors in multiple comparisons. This gave a group size of 17 for the single vision lens group, and 51 for the PAL group. Data for minimum displacement thresholds in the inferior and superior temporal field with the head static and head moving and for the ratio of the minimum displacement threshold with head movement to the head static minimum displacement threshold were compared in this manner.

10.5.1 Minimum displacement thresholds

Mean minimum displacement threshold with the head static with a single vision lens for the inferior temporal visual field was 6.63 ±1.40 min arc, and for the superior temporal visual field was 6.78 ± 1.78 min arc. For the grouped PAL data, mean minimum displacement threshold in inferior temporal visual field was 6.89 ± 1.13 min arc, and in the superior temporal field 7.15 ± 1.66 min arc. Table 10.11 shows descriptive statistics for minimum displacement thresholds for the single vision lens compared to the grouped PAL data.

Mean minimum displacement thresholds increased in both inferior and superior field with head movement, with single vision lenses or with a PAL (Table 10.11, Figure 10.5). Mean minimum displacement thresholds were increased by approximately 40-60% with head movement in both the inferior and superior temporal visual fields for single vision lenses and for the grouped PAL data. The increase in minimum displacement threshold with head movement when wearing a PAL was greater than that occurring with a single vision lens. Variance in minimum displacement thresholds and in the range of values was also increased by head movement (Table 10.11)

		Mean	Std Deviation	Variance	Minimum	Maximum
Single Vision	Inferior	6.78	1.78	3.17	2.91	10.80
	Inferior moving	9.54	2.76	7.60	4.58	15.88
	Superior	6.78	1.78	3.17	2.91	10.80
	Superior moving	10.05	2.06	4.24	3.68	13.04
PALs grouped	Inferior	6.89	1.13	1.29	4.08	9.11
	Inferior moving	10.38	1.92	3.69	7.03	14.22
	Superior	7.15	1.66	2.75	3.43	11.15
	Superior moving	11.33	2.49	6.22	4.69	16.20

Table 10.11 Descriptive statistics for minimum displacement thresholds (min arc), single vision lens and all PAL data grouped, inferior temporal and superior temporal visual fields. (Inferior/superior = threshold with head static, inferior moving/superior moving = threshold with head movement).

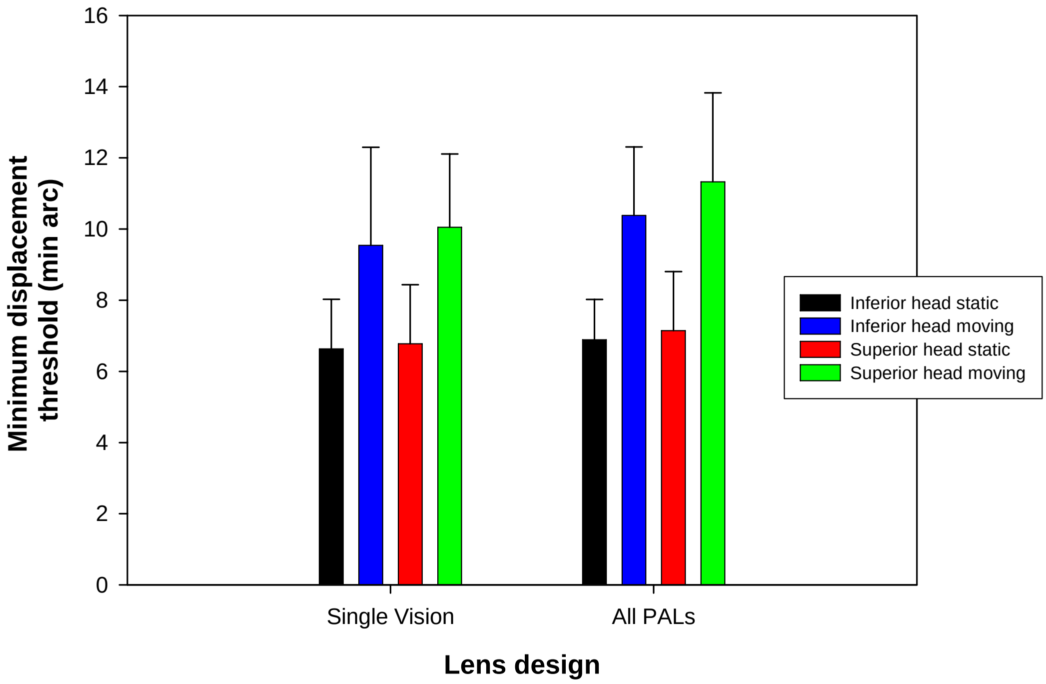

Figure 10.5 Mean minimum displacement thresholds (min arc) for single vision lens and grouped data for PALs. Error bars are one standard deviation.

The differences in minimum displacement threshold between the single vision lens and the grouped PAL data for inferior and superior temporal regions of the peripheral visual field were not significantly different (at $p < 0.0125$, Bonferroni adjustment for multiple comparisons) on independent t-tests, for both head static and head moving conditions (Table 10.12, also Figure 10.5). Levene's test for equality of variances showed a non-significant value for F for each comparison, indicating the assumption of equality of variances for the independent t-test is met.

Mean difference in minimum displacement threshold between the single vision lens and PAL is -0.26 min arc inferiorally with the head static, and -0.84 min arc with the head moving, with the PAL group showing the higher threshold. For the superior temporal zone of the visual field, the PAL group also shows a higher threshold, with the mean difference compared to single vision lenses being -0.37 min arc in the head static condition, and -1.28 min arc in the head moving condition. The 95% confidence intervals for the difference are wide compared to the mean difference, with positive upper bounds, indicating large variability in the difference.

	Mean	SEM	95% CI	of difference			
	difference		Lower	Upper	t	df	p
Inferior	-0.26	0.37	-0.93	0.41	-0.767	66	0.446
Inferior moving	-0.84	0.60	-2.05	0.36	-1.39	66	0.168
Superior	-0.37	0.47	-1.31	0.57	-0.78	66	0.438
Superior moving	-1.28	-0.67	-2.62	0.05	-1.91	66	0.06

Table 10.12 Independent t-tests, single vision – PAL for minimum displacement threshold (min arc) in inferior and superior temporal visual field, in head static and head moving conditions. (inferior/superior = head static condition, inferior moving/superior moving = head moving condition). No difference between lens designs is significant at $p<0.0125$, Bonferroni adjustment for multiple comparisons.

Minimum displacement thresholds are not significantly different with PAL wear compared to single vision lenses, although PAL wear shows a tendency to result in higher minimum displacement thresholds.

10.5.2 Ratio of minimum displacement threshold measures

The ratio of minimum displacement thresholds for head moving/head static were calculated for the single vision lens and the data for the PALs combined into one group, for inferior temporal and superior temporal measures. This ratio represents the increase in minimum displacement threshold caused by head movement compared to the head static baseline (Section 10.4 above).

Mean ratio of minimum displacement thresholds, head moving condition/head static condition for the single vision lens and the PAL group is shown in Table 10.13 and Figure 10.6 (below). The mean ratio of minimum displacement thresholds is similar between the two groups for both inferior and superior temporal measures, ranging from 1.44 ± 0.30 for the inferior temporal measure with single vision lenses, to 1.62 ± 0.35 for the superior temporal measure in the PAL group. Variance is approximately a factor of 2 times greater for superior temporal measures in either head static or head movement conditions in both groups, indicating increased variability between subjects in measures of the minimum displacement thresholds in this region of the visual field.

		Mean	Std Deviation	Variance	Minimum	Maximum
Single Vision	Inferior	1.44	0.30	0.09	1.12	2.42
	Superior	1.54	0.40	0.16	0.96	2.86
PALs grouped	Inferior	1.52	0.25	0.06	1.07	2.26
	Superior	1.62	0.35	0.12	1.20	2.91

Table 10.13 Descriptive statistics of the ratio of minimum displacement thresholds (min arc), head moving condition/head static condition, for single vision lens compared to all PAL data combined.

The ratio of minimum displacement thresholds for inferior temporal and superior temporal measures were not significantly different between single vision lenses and PALs: inferior temporal: $t = -1.11$, $df = 66$, $p = 0.27$; superior temporal: $t = -0.854$, $df = 66$, $p = 0.39$.

The ratio of head moving/head static minimum displacement thresholds is not significantly different between a single vision lens and PALs. This indicates head movement increases the minimum displacement threshold to a similar degree for either lens design. The ratio is higher in the superior temporal visual field in both lens designs; variability is also increased in the superior temporal field. Further investigation is warranted with more subjects to determine if this represents an inherent behaviour of the superior temporal visual field.

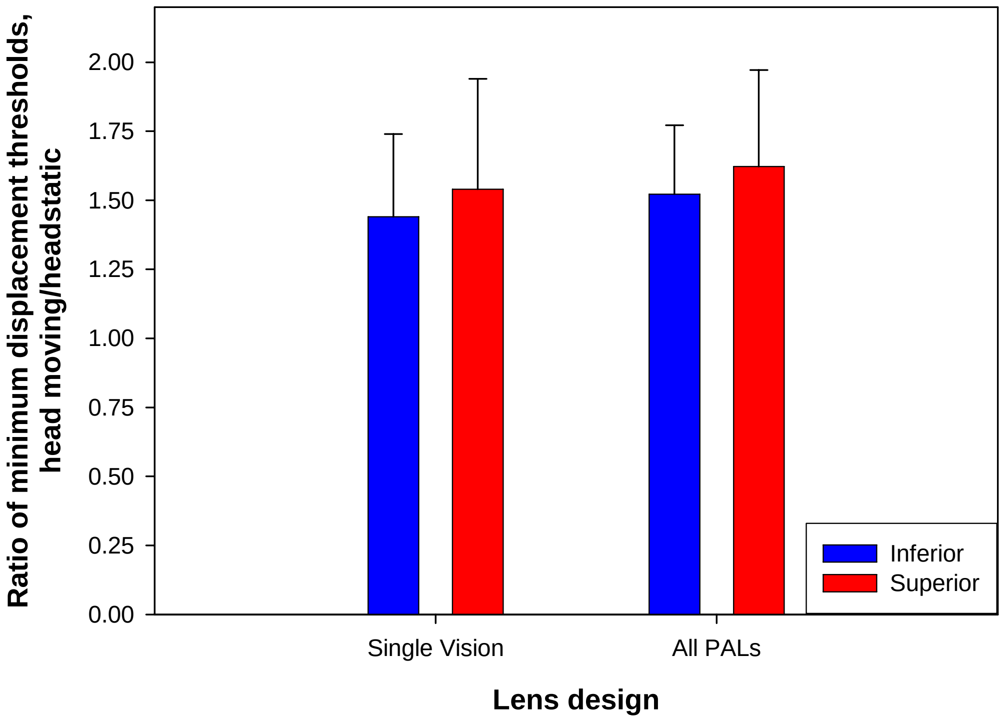

Figure 10.6 Mean ratio of minimum displacement thresholds (min arc) for thresholds in head movement/thresholds in head static conditions. Error bars are one standard deviation.

10.6 Discussion

10.6.1 Minimum displacement thresholds without head movement

Minimum displacement thresholds for eccentric targets significantly increased in relation to minimum displacement thresholds for a central target, in both the superior and inferior temporal visual fields for targets at 30º temporal in the visual field and ± 10º above and below the horizontal midline. Minimum displacement thresholds for central targets ranged from 1.60 min arc to 1.66 min arc for a single vision lens and 3 different PAL designs. Minimum displacement thresholds ranged from 6.63 to 7.03 min arc inferiorly and 6.87 to 7.30 min arc superiorly. Minimum displacement thresholds for 30º temporal eccentricity are roughly 4 times higher than central thresholds.

Displacement thresholds for a small luminous spot were measured by Legge and Campbell (1981). They used a 1.0mm diameter white spot, which subtended 0.45 min arc at a viewing distance of 760 cm. The target spot was displayed in a uniform, unstructured dark field, and underwent random movement either left or right. Displacement thresholds obtained with this protocol ranged from 1.05 min arc to 2.17 min arc for five observers. These displacement thresholds are similar to those obtained for central measures in this study, albeit with a different target configuration (Table 10.2). Wood and Bullimore (1995) measured minimum displacement thresholds in normal observers, using a random dot stimulus which subtended 2.9º at their viewing distance of 3.2m. Dot density of their stimulus was greater (1%) than dot density of the stimulus used in this experiment (0.33%). They obtained minimum displacement thresholds of -0.52 ± 0.18 log min arc for 14 normal subjects aged 50 – 59 years, a similar age range to that of subjects in this experiment. The threshold they obtained equates to 0.3 min arc. This is considerably smaller than the threshold for central measures (approximately 1.6 min arc) found in the current experiment; the difference is most likely due to stimulus size (2.9º in Wood and Bullimore's experiment, 0.98º in the current experiment), and the luminance difference in stimuli caused by differing dot (pixel) densities.

Studies investigating motion detection or displacement thresholds for peripheral vision have used different target configurations (eg lines, random dot stimuli), varying stimulus exposure durations, and different methods of scaling stimuli to account for peripheral sensitivity and the change in receptive field size in the peripheral retina. Post and Johnson (1986) indicated that motion sensitivity for a 1º square white target was approximately 1 min arc centrally and 3 min arc at 30º eccentricity (from inspection of their graphed data). Fixation distance is not specified in their report. Johnson and Scobey (1980) assessed foveal and peripheral displacement thresholds for moving line stimuli as a function of stimulus duration, length and luminance. Displacement thresholds at the fovea were 1 to 1.5 min arc, and were not affected by stimulus length in min arc, nor by stimulus durations between 5-500 ms. Peripheral displacement thresholds measured at 18º eccentricity in the nasal field were dependent upon stimulus size, with displacement thresholds of 8 – 10 min arc with a 5 min arc stimulus, and 3.5 min arc with a larger 120 min arc stimulus.

Studies using sinusoidal gratings, with superimposed oscillation of the grating (Buckingham and Whitaker 1985, 1986, 1987ab) have shown minimum displacement thresholds ranging from 0.8-1 min arc to 2 min arc at the fovea dependent upon luminance and frequency of target oscillation. Threshold increased as target luminance decreased. Bedell and Johnson (1995) have shown a similar minimum displacement threshold at the fovea of 0.8 min arc with a 2Hz oscillation frequency of their stimulus. Threshold increased to 5 min arc at 25º in the right visual field.

Baker and Braddick (1985) used random dot stimuli to investigate thresholds for minimum and maximum displacement at different eccentricities. Stimuli were scaled for eccentricity, with stimulus size increasing as eccentricity increased – ie for a stimulus to be presented at 10º eccentricity, stimulus size was twice the eccentricity (20º). Minimum displacement thresholds increased by a factor of 2 to 4 in four subjects at 10º eccentricity compared to central targets (0.4º eccentricity). They indicate that the minimum displacement threshold shows an increase with eccentricity consistent with the variation of cortical magnification with eccentricity. For their four subjects, minimum displacement thresholds at 10º eccentricity ranged from 80 to 200 sec arc, with a stimulus size of 20 x 20º.

Other studies have also indicated peripheral motion detection thresholds equate to foveal measures when stimuli are scaled according to the cortical magnification factor (McKee and Nakayama 1984, Koenderink et al. 1985, van de Grind et al. 1983). Using random dot stimuli, van de Grind et al. (1983) calculated signal to noise ratios as a determinant of stimulus velocity, and showed that motion detection performance was essentially invariant across the temporal visual field to a 48º eccentricity, when stimuli were scaled to obtain equivalent cortical sizes and velocities. McKee and Nakayama (1984) showed that the target size necessary to produce the lowest differential motion threshold (analogous to minimum displacement threshold as used in this experiment) is large, ranging from 1º at the fovea to 20º at 40º eccentricity. When they normalized thresholds for differential motion sensitivity against the fovea, differential motion threshold was linearly related to eccentricity.

Peripheral minimum displacement thresholds measured in this experiment, with a stimulus subtending 4º at a distance of 1.5m, were of the order of 6 – 7 min arc (Tables 10.4 and 10.6). Peripheral minimum displacement thresholds, either at 30º horizontal and 10 º vertical eccentricities in the inferior or superior temporal visual field, were not affected by lens design (Sections 10.3.2 and 10.3.3). Direct comparison to results of other studies is difficult due to stimulus differences. Additionally, stimulus size in the current experiment may not have been sufficient to measure the absolute minimum detection threshold in these areas of the field, given the findings of McKee and Nakayama (1984). As measurement conditions were the same for all measurement trials the experiment would however have been sensitive to between lens differences. Stimulus size used in this experiment for peripheral measures was 3.97º, and for central measures was 0.98º (Chapter 9). This represents a 4.06 times difference in stimulus size for peripheral measures compared to foveal measures. Calculated values for the ratio of inferior and superior minimum displacement thresholds to central minimum displacement thresholds are shown in Table 10.14 below. Mean value for this ratio ranges from 3.58 ± 0.92 to 4.94 ± 1.20 min arc, across all measurement conditions. Peripheral minimum displacement thresholds obtained in this experiment are approximately 4 times greater than central thresholds, consistent with the ratio of stimulus size difference.

Peripheral minimum displacement thresholds compared to central threshold measures are increased, on average, by a factor equivalent to the increase in target size between the two measurement conditions, consistent with other studies using spatially scaled stimuli (McKee and Nakayama 1984, Koenderink et al. 1985, van de Grind et al. 1983).

			Mean	sd	Variance	Minimum	Maximum
Inferior temporal	Head static	SV	4.22	1.06	1.12	2.41	7.31
		PAL 1	4.19	0.45	0.20	3.29	4.97
		PAL 2	4.32	0.98	0.96	2.61	5.79
		PAL 3	4.23	0.63	0.39	2.99	6.03
	Head moving	SV	3.58	0.92	0.85	1.91	5.52
		PAL 1	3.75	0.75	0.56	2.23	5.17
		PAL 2	4.14	0.95	0.89	2.63	6.31
		PAL 3	4.01	0.79	0.62	2.75	5.99
Superior temporal	Head static	SV	4.25	0.84	0.70	1.72	5.86
		PAL 1	4.31	0.61	0.37	2.67	4.98
		PAL 2	4.94	1.20	1.43	2.24	6.58
		PAL 3	4.59	1.12	1.25	1.86	6.57
	Head moving	SV	3.79	0.75	0.56	1.66	5.29
		PAL 1	4.30	0.80	0.65	3.09	5.90
		PAL 2	4.32	0.77	0.60	3.23	5.93
		PAL 3	4.41	1.27	1.63	1.98	7.22

Table 10.14 Ratio of peripheral minimum displacement thresholds to central displacement thresholds (min arc) across 4 lens designs for head static and head movement measurement conditions. (SV = single vision lens, sd = standard deviation)

In the current experiment, minimum displacement threshold was not significantly different between a single vision lens and three PAL designs, for central measures and in the superior and inferior temporal visual field (Section 10.3.1 to 10.3.3). When data for all PALs was grouped as one data set, minimum displacement thresholds were not significantly different between the PAL group and the single vision lens group. (Section 10.5.1, Table 10.12).

10.6.2 Minimum displacement thresholds with head movement

Minimum displacement threshold is significantly increased by head movement in a single vision lens and in three PAL designs for both central and peripheral minimum displacement thresholds (Tables 10.3, 10.5 and 10.7; also Figures 10.1 to 10.3). Minimum displacement thresholds were from 0.94 ± 0.45 to 1.085 ± 0.35 min arc higher with head movement than head static measures at the fovea.

Minimum displacement thresholds were increased by head movement in the inferior temporal field (Table 10.5). Head movement increased threshold by between 3 and 4 min arc on average across all lens designs; threshold increased by approximately 50% when the head moved in approximate sinusoidal movement. Minimum displacement thresholds in the superior temporal field were increased 3.27 to 4.52 min arc on average across all lens designs (Table 10.7). Threshold in the superior temporal field also increased by approximately 50% with head movement compared to the head static measures. Whilst head movement significantly increased minimum displacement threshold, threshold was not significantly different between lens designs on repeated measures ANOVA (Section 10.3.2 and 10.3.3). Minimum displacement threshold was also not significantly different between a single vision lens and all PALs considered as one group (Section 10.5.1, Table 10.12).

The effect of head movement on minimum displacement threshold was further investigated by reviewing the ratio of the minimum displacement threshold in the head moving condition to the minimum displacement threshold in the head static condition (Section 10.4). This ratio represents the percentage increase in threshold caused by head movement. The mean ratio of minimum displacement thresholds ranged from 1.44 ± 0.29 to 1.72 ± 0.42 across the four lens designs and visual field locations (Table 10.8). Lens design had no significant effect on this ratio, indicating head movement increased minimum displacement threshold in a uniform manner irrespective of the measurement condition. This ratio was also compared for the single vision lens, and for all PAL data combined as one group (Section 10.5.2). Again, this was not significantly different between the PAL group and the single vision group at both inferior and superior temporal visual field. Mean ratio of minimum displacement thresholds was 1.44 ± 0.30 and 1.54 ± 0.40 for single vision lenses at the inferior temporal and superior temporal locations respectively. In the PAL group, the equivalent values are 1.52 ± 0.25 and 1.62 ± 0.35. Head movement, at a frequency of 0.7Hz, increases minimum displacement threshold by 40-60% compared to head static measures. The ratio is also higher with PALs than with a single vision lens, although this difference is not statistically significant. The ratio is highest in the superior temporal field, and variance is also highest in the superior temporal field (Table10.13), indicating threshold was more variable in this region of the field. Investigation with a larger number of subjects would determine if this represents an inherent behaviour of the superior temporal visual field as opposed to a possible effect of subject variability in the current experiment. A larger number of subjects in a comparison of displacement thresholds in single vision lenses and PALs would also increase the power of the analysis to detect a difference in motion threshold between these two groups.

Minimum displacement thresholds in the current experiment were measured in three localised regions of the visual field in both head static and head moving conditions. Results show that these localised measures of minimum displacement thresholds were not affected by PAL design. This would suggest that any motion effects induced by PALs are not a local field phenomenon, but a more global response of the motion system; hence they were not captured in this experiment.

In an experiment reported as a conference abstract, Patel and Bedell (2002) investigated motion detection with a 3.3 sq. deg. field random dot target which underwent horizontal motion in one of two fields. Subjects were required to indicate in which field the target underwent motion. Motion detection thresholds were measured with and without voluntary 1.5 Hz head movement. Mean motion threshold increased from approximately 0.7 deg/s when the head was stationary to approximately 1.5 deg/s during head movement. In the Patel and Bedell (2002) experiment, voluntary head movement increased motion detection threshold by a factor of 2, compared with an approximate 50% increase in the current experiment, where head movement occurred in time with a metronome beat, with a frequency of approximately 0.7Hz. Rate of increase in motion detection threshold thus appears dependent on head movement frequency; further investigation with a range of head movement frequencies is warranted to investigate possible relationships between head movement frequency and minimum displacement thresholds.

A number of studies have investigated vision function in the presence of head movement. Stereopsis is unaffected by head movement for head movement frequencies of up to 2 Hz (Westheimer and McKee 1978, Patterson and Fox 1984, Steinman et al. 1985). Westheimer and McKee (1978) also showed that Landolt C and vernier acuity are not affected by retinal image speeds of up to 2-3 deg/s. Barnes and Smith (1981) and Demer (1994) similarly found visual acuity to be relatively unaffected by retinal image movement of between 2-4 deg/s. Retinal slip, the movement of an image on the retina, caused by head and eye movement, is one factor that may be influenced by PAL wear, owing to the peripheral power variations found in these lens designs. Grossman et al. (1989) reported retinal image slip velocities of less than 4 deg/s when subjects were walking or standing. Demer et al. (1997) reported horizontal and vertical retinal image velocities were always less than 4 deg/s for targets beyond 4m. Medendorp et al. (2000) also showed retinal image velocities below 2 deg/s for head movement frequencies of 0.25 to 1.5 Hz, with head movements measured in darkness with and without a fixation target. Retinal image speeds of 4 deg/s were also found by Steinman and Collewijn (1980) for head movement frequencies of 0.25 to 5 Hz. Gain of the VOR acts to stabilize retinal image position during head movement, by allowing compensatory eye movements equal and opposite to head movement. In the studies of Grossman et al. (1989) and Demer et al. (1997), VOR gain was around 1.0, indicating eye movement and head movement extent and velocity were matched.

VOR gain was not measured in the current experiment. Likely VOR gain in the current experiment can be estimated from the literature. In the current experiment, head rotations occurred in the horizontal plane, while fixating a stationary distance target (6.1m). Experiments were also conducted in reduced room illumination. Experimental studies of the VOR in darkness showed that VOR gain approached 1.0 in studies where subjects were passively or actively rotated, while fixating a stationary target (Gauthier and Vercher 1990, Barr et al. 1976, Cheung et al. 1996, Vercher and Gauthier 1990, Demer et al. 1987, Takahashi et al. 1980, 1989). This suggests that VOR gain in the current experiment would be around 1.0, and that accordingly, retinal image speeds would be kept within the ranges above. If this were the case, it would be expected that minimum displacement thresholds would be similar with head movment and head static conditions. As head movement significantly increases minimum displacement threshold, and this increase appears to be greater in PALs, the power profile of the PAL may introduce variation in velocity of the retinal image as objects are viewed through peripheral regions of the PAL. Optical blur decreased displacement detection with random dot stimuli for dot displacements of less than 16' arc (Barton et al. 1996), with the effect of blur depending on the displacement of dots with the random dot stimulus, not the velocity of displacement. The current experiment showed wide variability in minimum detection thresholds, possibly in part due to the experimental conditions (see Section 10.6.3 below).

10.6.3 Variability of measures

The experimental protocol (Chapter 9) required subjects to make voluntary 10º head movement in an approximate sinusoidal manner in time with a computer driven metronome, and to time their head movement with the metronome to reach a limiting stop within a fixed time interval to generate a motion stimulus. In addition, they had to steadily fixate a distant target, and attend to a peripheral target to perceive the stimuli. Subjects were thus performing a number of simultaneous tasks when experimental measures were being made, particularly in the head movement condition. This experimental protocol was used to control the time within the head movement that the stimulus was presented, to ensure that stimuli were presented in the same location of the visual field on each presentation.

The human information processing system can be thought of as having a finite capacity, and allocation of processing resources to a second task can affect performance on the primary task (Navon and Gopher 1979, Britten et al. 1978, Britten and Price 1981, Williams 1982, Schroiff 1984, Madden and Allen 1989, Rayner and Morris 1990, Crossley and Hiscock 1992). Variance of the minimum displacement thresholds was greater in head movement measurement conditions, increasing by up to a factor of 2 times. The demand of the experimental task undertaken by subjects may have increased variability in the measurement of minimum displacement threshold due to attentional effects.

The experimental protocol also used vertical stimulus movement in the measurement of minimum displacement thresholds, with stimuli moving randomly up or down during the staircase procedure. Naito et al. (2000) have reported an investigation of magnetic response imaging of the extrastriate visual cortex for five subjects exposed to an apparent motion stimulus. They report that the extrastriate cortex has a directional preference for downward movement versus upward movement in the upper visual field whereas no directional preference was seen in the lower visual field. This effect may have biased subject responses in trials when downward stimulus motion occurred, potentially acting as source of variability.

Experimental data collection sessions also took 90 minutes plus to complete on occasion, with subjects on some trials not able to correctly time their head movement to allow presentation of the stimulus, thus either prolonging the trial and creating fatigue, or at times necessitating restarting the staircase procedure, also increasing subject fatigue.

In future experiments investigating motion thresholds, it is recommended that any head movement be induced by methods other than subjects' actively rotating their head. This may be, for example, by using a treadmill to generate self motion and recording head movement extent and velocity (thus frequency) on line, and presenting stimuli when the desired conditions are met.

The variability, evidenced by the large standard deviations and 95% confidence intervals for the differences between measurement conditions, in the data collected also reduced the power of the ANOVA to detect significant differences. A larger number of subjects would be needed to increase the power of the analysis, preferably under experimental conditions which reduced processing load of the subjects and the likelihood of fatigue.

10.6.4 Statistical analyses

The design of this experiment, where subjects used 3 designs of PAL worn in different wearing orders, and a single vision lens, with the same variables measured for each lens design, warranted a within subjects and between groups repeated measures analysis. For this reason, the parametric within subjects between groups (or mixed) repeated measures ANOVA was used as no non-parametric alternative test could be used. ANOVA is robust to violations of its assumptions (Pallant 2002, Tabachnik and Fidell 2001), although the power of these experiments is reduced because of the variances in the minimum displacement threshold measures studied; greater sample sizes would have been preferred for increased power, as noted above.

Alpha level was adjusted to allow for multiple comparisons to reduce the possibility of type II errors.

Chapter 11 Experimental methods 3: PAL design differences, preference ratings and distortion scores

Manufacturers of PAL designs illustrate design features of their lenses using iso-cylindrical contour plots. These plots show contours linking areas of the lens which have similar astigmatic powers, comparable to contour lines as traditionally seen in mapping, or isobars seen in weather maps. These iso-cylindrical plots demonstrate to clinicians where zones of maximal astigmatism occur, and how progressive corridors and reading zones of the PAL designs are placed on the lens surface.

The experiments described in this chapter, and also in Chapter 9, were performed using three experimental PAL designs supplied by SOLA Holdings International Research Centre, Adelaide, Australia. Iso-cylinder plots are shown below (Figure 11.1 to 11.3, below) for each of the lens designs used in the experiments. The plots are for a right lens, with a back vertex power of 0.00D (plano), with a +2.00 sph near addition, superimposed with a 75mm diameter lens blank template. The nasal aspect of the lens is to the right hand side of the figure. The lowest astigmatic power contour in each plot is 0.50D (indicated by pale grey-green), incrementing in 0.50D steps.

The plots indicate PAL 1 and PAL 3 concentrate higher degrees of peripheral astigmatism in the lower quadrants of the lens, whereas PAL B has its higher power astigmatic contours higher on the lens surface nasally and temporally. PAL 1 and PAL 3 also show a steeper gradient (or rate of change) of astigmatic power closer to the boundaries of the near zone, where PAL 2 shows a flatter gradient of astigmatic power change adjacent tp the near zone.

In order to make comparisons between lens designs and their optical factors, and to relate lens design factors to subjective ratings of distortion (Section 11.2), back vertex power of the lenses was measured and converted to power vectors (Thibos, Wheeler and Horner 1997, Thibos and Horner 2001), in the manner described in Section 11.1 (below).

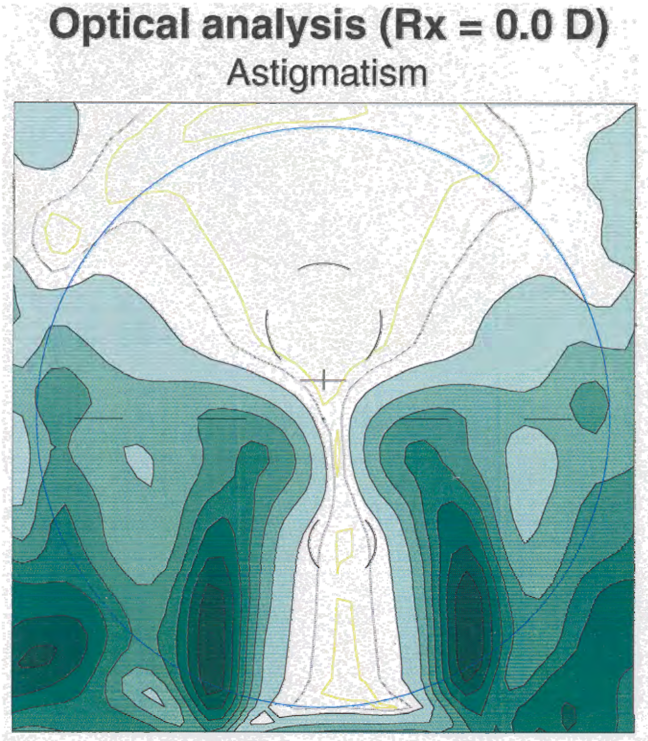

Figure 11.1 Iso-cylindrical contour plot for PAL 1.

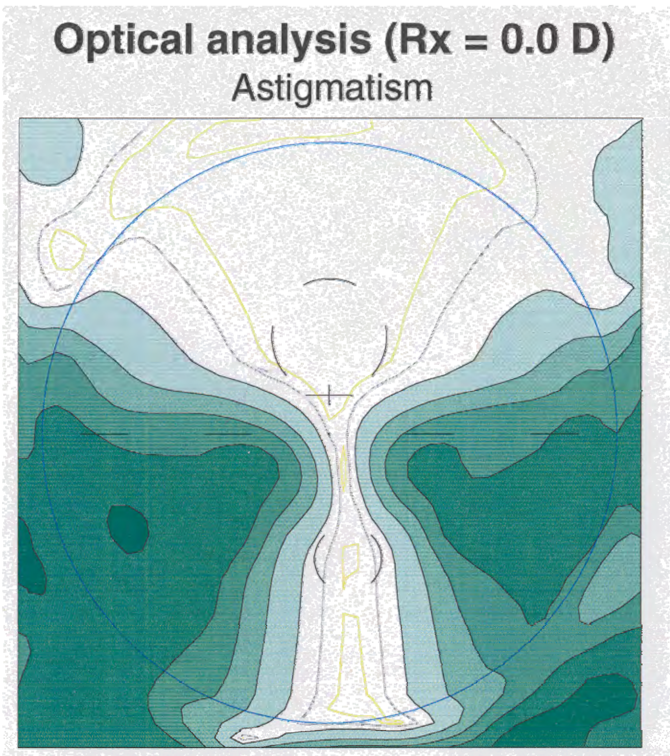

Figure 11.2 Iso-cylindrical contour plot for PAL 2

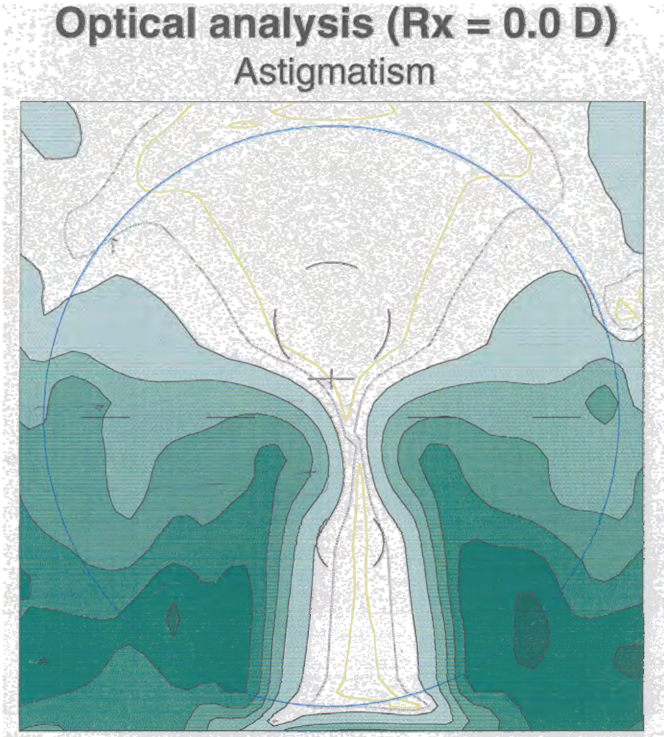

Figure 11.3 Iso-cylindrical contour plot for PAL 3.

11.1 PAL design differences

Back vertex power of the PALs used in the experimental trials outlined in the previous sections was measured at three locations on the PAL, corresponding to the points on the lens surface through which the motion threshold target would be imaged. One location corresponded to the distance viewing portion of the PAL; back vertex power was taken as the power measured through the distance power circle of the PAL, and corresponds to the distance subjective refraction of the subject. Back vertex power was also measured at two peripheral points on the PAL. Position of these points on the PAL surface was calculated assuming a spectacle plane to centre of ocular rotation distance of 27mm, and referenced to the fitting cross position of the PAL, as this was fitted to pupil centre. Targets for measurement of peripheral minimum displacement thresholds were positioned 30º temporal to the visual axis; assuming a spectacle plane to centre of rotation distance of 27mm, this represents an area 15.6mm temporal to the fitting cross of the PAL in the spectacle plane (Figure 11.2).

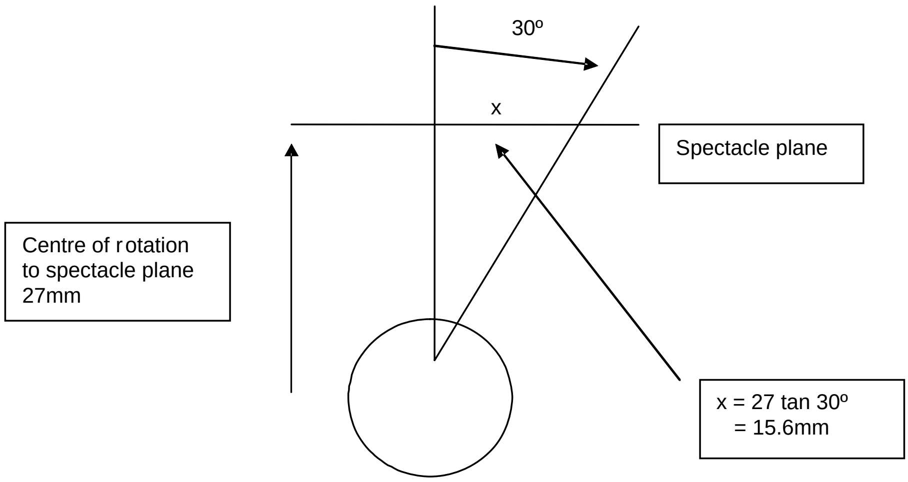

Figure 11.2 Measurement in spectacle plane of distance on PAL surface through which peripheral targets viewed.

The targets for peripheral motion thresholds in the temporal field of the right eye were positioned 10º above and below a horizontal line equivalent to eye level for the subject. Figure 11.3 shows this positioning referenced to the spectacle plane of the subject; the points 10º above and below the horizontal midline translate to a measurement of 2.75mm on the PAL surface.

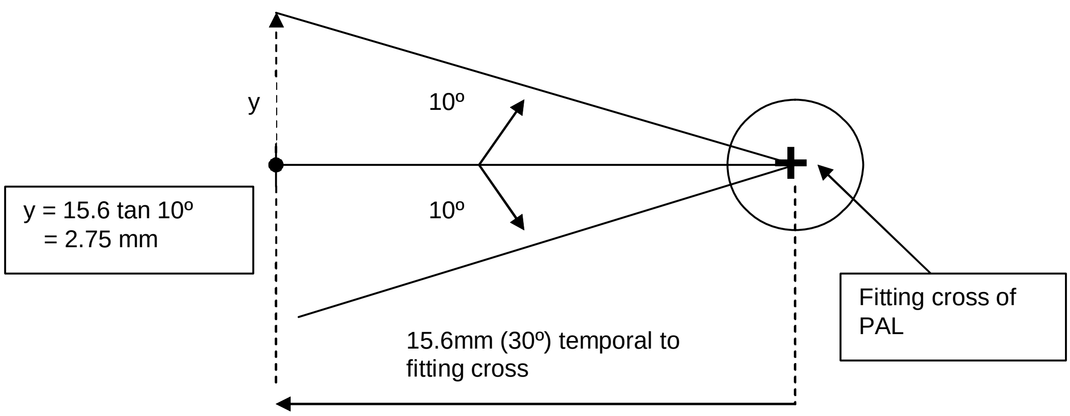

Figure 11.3 Vertical position of points on PAL surface at the spectacle plane

A template was made to allow measurement of back vertex power at the two peripheral locations on the PAL surface. This was centred on the nasal and temporal reference engravings of the PAL, and a 3mm aperture was centred on the points 15.6mm horizontal and 2.75 mm vertical to the PAL fitting cross (see Figure 11.4). Back vertex power was then measured with a Topcon LM 6 vertometer using the small vertometer aperture stop, with the PAL manually positioned by lateral displacement so that the template apertures overlaid the vertometer aperture stop. A prism compensator was used to align the vertometer mire centrally for measurement of back vertex power. Back vertex power was measured as the principal powers and axis orientation.

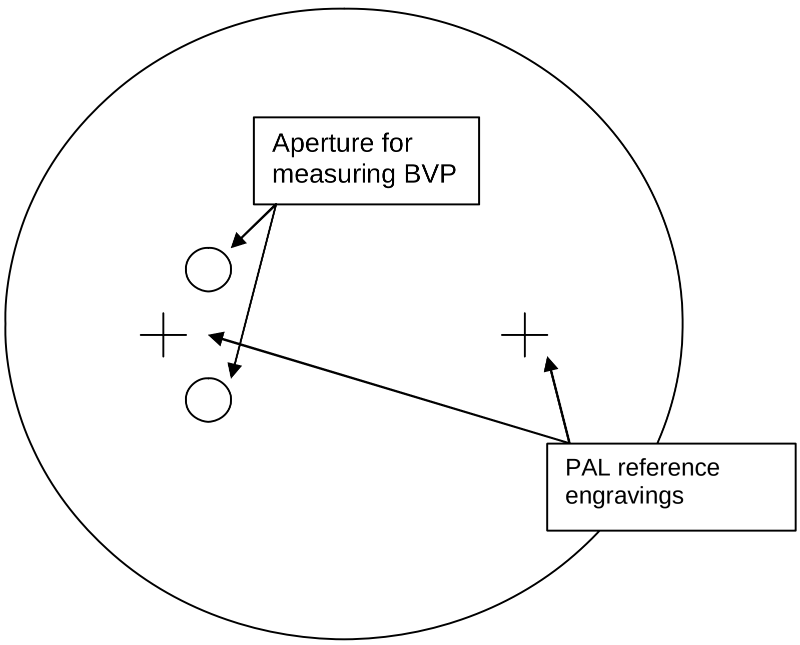

Figure 11.4 Diagram of overlay template used in back vertex power measurements of peripheral areas of PALs. (BVP = back vertex power)

Measurement of back vertex power in the two peripheral positions of the PAL by lateral displacement does not incorporate the effect of the small increase in back vertex distance and oblique view through the periphery of the lens that would occur in the natural viewing environment. Simonet et al. (1986), Sheedy et al. (1987) and Atchison (1987) have used rotating lens mounts in their studies of PALs to account for this. Fowler and Sullivan (1988) have evaluated three methods of measuring PAL peripheral powers: lateral displacement across the vertometer, a rotational mount and a surface reflection technique. Fowler and Sullivan (1988) indicated that the three methods gave essentially similar readings of peripheral astigmatism for lenses of low distance power. PALs used in the experiments in this thesis were all of low distance power (see Table 10.1). The method of laterally displacing the lenses across the vertometer aperture was also used as this is a method that can be readily employed in standard clinical situations.

Back vertex powers for the distance power zone and the two temporal peripheral locations were tabulated in negative cylinder form. To allow statistical analysis of differences between the PAL designs, and to investigate relationships between PAL peripheral powers and preference scores and minimum displacement thresholds, the clinical expressions of back vertex power in sphero-cylinder form were transposed to power vectors (Thibos, Wheeler and Horner 1997, Thibos and Horner 2001) as M, J_0 and J_{45} powers. The Pythagorean length of the power vector, termed 'blur strength' by Thibos and Horner (2001) was also calculated. This is equivalent to the scalar vector "dioptric strength" of Harris (1994) in his matrix form of refractive power analysis. (Transposition of lens forms was aided by the electronic appendix to the paper of Thibos, Wheeler and Horner (1997)[2].

11.2 The effect of PAL peripheral design variations on spatial distortions – clinical trial

Three experimental PALs were investigated as to their effect on motion detection thresholds (Chapter 9 and 10) and whether the psychophysical motion detection threshold can be related to the wearers' subjective impression of swim and spatial distortions. Each PAL had different peripheral power gradients and configuration.

[2] http://research.opt.indiana.edu/Library/PowerVectors/pv.html

The PAL lenses used in this experiment were supplied by SOLA Holdings International Research Centre, Adelaide, Australia.

11.2.1 Method

Subjects wore these PAL lenses on a crossover basis, with three groups of subjects wearing lenses in different orders to control for order effects. Subjects were previously successful PAL wearers, recruited from the Optometry Clinic of the Queensland University of Techology. The age range of subjects was restricted as the experimental PALs were available only in a near addition power range of +2.00 DS to +2.50 DS. Similarly, the spherical component of the distance refractive error was restricted to the range of -2.00 DS to +4.00 DS, due to manufacturing requirements for the experimental lenses.

Each of the PALs were fitted using the same fitting parameters (monocular distance PD, optical centre height). Monocular distance PD was measured with an Essilor pupillometer. Optical centre height was measured as the position of the corneal light reflex relative to the inside lower edge of the spectacle frame in the same vertical plane, with the examiner and subject at the same eye level. All measurements were taken by the same examiner. The same frame was used for each lens pair. The three pairs of lenses were edged to the frame at the same time in either the dispensing laboratory of the SOLA International Holdings Research Centre or the School of Optometry at the Queensland University of Technology. Each lens pair was then removed from the frame, and separately labelled as Pair 1, 2 or 3. Subjects were randomly assigned to one of the three lens wear order groups. Each PAL pair was worn for two weeks, and then changed to the next pair in sequence according to the experimental order to which the subject was assigned.. The investigator was masked as to the lens design criteria for the period of data collection.

Subjects completed a symptoms questionnaire to investigate subjective impressions of spatial distortions at the end of each two-week wearing period. The questions were constructed with Likert scales to allow for determination of adaptive effects and differences between PAL designs (Section 11.2.2 below).

11.2.2 Distortion questionnaire

Questionnaires consisted of 6 questions related to different spatial distortions, with the set of six questions repeated in sub-sections for spatial distortions noticed with distance vision, intermediate vision and near vision. A copy of the questionnaire appears as Appendix C.

The six spatial distortion questions were:

- a feeling that objects in the sides of your vision were distorted?
- difficulty judging distance or position from other objects?
- things in your field of vision seeming to move up and down?
- things in your field of vision seeming to move side to side?
- things in your field of vision seeming to sway or tilt?
- things in your field of vision seeming to move to and fro?

Subjects were required to score whether the distortion was present on a five point scale, on how annoying the distortion was using a seven point scale, and if the distortion was more noticeable when moving about using a five point scale. A three level rating for distortions was used as a subject may or may not notice a particular spatial distortion, then if this distortion is present it may prove annoying or not annoying to the subject, and lastly the spatial distortion may be aggravated or more noticeable when the subject is moving about.

Figure 11.5 shows an extract from the distortion questionnaire, illustrating how the questionnaire appeared to the subject. This format was repeated for each of the distortion questions as above, and for distance, intermediate and near vision tasks.

Subjects were then scored for distortion based on their response to the 6 questions in each of the 3 vision areas (18 score values in total). Subjects were also scored for distance, intermediate and near vision separately. Scores for the three levels of each question were multiplied together to calculate 2 distortion scores (SCORE A: presence x annoyance; SCORE B: SCORE A x effect of motion).

The scoring method is described below.

11. A feeling that objects in the sides of your vision were distorted?

Always	Frequently	Sometimes	Infrequently	Never
☐	☐	☐	☐	☐
5	4	3	2	1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐	☐	☐	☐	☐	☐	☐
7	6	5	4	3	2	1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐	☐	☐	☐	☐
5	4	3	2	1

Figure 11.5 Extract from distortion questionnaire

11.2.3 Questionnaire scoring

If a subject did not experience the particular distortion symptom, he/she would check the NEVER box as shown in Figure 11.6.

Always	Frequently	Sometimes	Infrequently	Never
☐	☐	☐	☐	X
5	4	3	2	1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐	☐	☐	☐	☐	☐	X
7	6	5	4	3	2	1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐	☐	☐	☐	X
5	4	3	2	1

Figure 11.6 Spatial distortion questionnaire extract showing “perfect” score

If the subject did not notice the spatial distortions for all sections of the questionnaire, the questionnaire would total to a score of 18. This represents the "perfect case", where distortions are not noticed.

Alternatively, if a subject experienced the distortion symptom constantly to the point of being very annoying, and it was very much more noticeable when moving about, this would be completed as in Figure 11.7, and would score 175.

Always	Frequently	Sometimes	Infrequently	Never
X				
5	4	3	2	1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
X						
7	6	5	4	3	2	1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
X				
5	4	3	2	1

Figure 11.7 Distortion questionnaire extract showing worst possible score

To obtain the total for each subject, scores for each question were added for distance, intermediate and near independently.

11.2.4 The DISTORTION score

A distortion score was derived as a variable for subjective distortion to use in analysis. This was calculated for distance, intermediate and near vision independently, and the total score. The distortion score was calculated as:

$$\textbf{distortion score} = \frac{\textbf{subject score}}{\textbf{perfect score}}$$

Considering the total distortion score, this reflects effectively a distance from the perfect case of no spatial distortions:

- in "perfect case" situation = 1 (18/18)

- in "worst case" scenario = 175 (3150/18)

Distortion scores therefore ranged between 1 and 175 for questionnaire total score, and similarly ranged from 1 to 175 for distance, intermediate and near vision when considered separately.

11.2.5 Preference scores

Subjects were required to make forced choice paired comparisons of the PALs worn, by indicating whether they preferred pair1 vs pair 2, pair 1 vs pair 3, and pair 2 vs pair 3. For each forced choice comparison, they also indicated the relative strength of their preference, as shown in Figure 11.8.

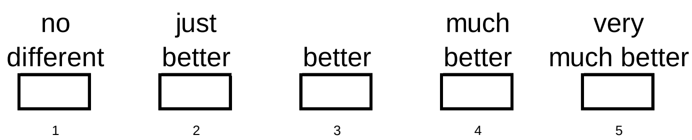

Figure 11.8. PAL preference rating scale.

To create a variable for lens preference, the following scheme was adopted. For each forced choice comparison, a score value was given to the preferred lens choice based on the subject's preference rating for that lens. For example, in a forced choice comparison a subject preferred lens 1 over lens 2, and rated lens 1 as much better. In this instance, lens 1 was awarded a score of 5, and lens 2 a score of 1. Figure 11.9 (below) illustrates a completed forced choice comparison. In this example, lens 1 is preferred to lens 2, and rated much better. Lens 1 is given 5 score points, lens 2 one point. In the second comparison, lens 1 is preferred to lens 3, and rated just better. Lens 1 is given 3 score points, lens 3 one. In the final comparison, lens 3 is preferred to lens 2, and rated just better. Lens 3 is therefore given 3 score points, lens 2 one point. These point scores are totalled across all forced choice comparisons, resulting in total lens rating scores as in Table 11.2.

Lens design	Total preference rating
Design 1	8
Design 2	2
Design 3	4

Table 11.2 Example of lens preference rating, calculated from the example shown in Figure 11.9 (below), as described in text above.

1 vs 2

1	2
X	
1	2

What was the strength of your preference. My preferred pair was…

no different	just better	better	much better	very much better
			X	
1	2	3	4	5

1 vs 3

1	3
X	
1	2

What was the strength of your preference. My preferred pair was…

no different	just better	better	much better	very much better
	X			
1	2	3	4	5

2 vs 3

2	3
	X
1	2

What was the strength of your preference. My preferred pair was…

no different	just better	better	much better	very much better
	X			
1	2	3	4	5

Figure 11.9 Sample completed forced choice comparisons for PAL preference

PAL preference ratings were calculated in this manner for all subjects, and collated across all subjects to result in an overall lens preference score as a variable.

11.3 Data analysis

Data for all subjects was pooled. A repeated measures analysis of variance with preference score and distortion score as dependent variables, lens design and order as independent variables was performed to determine the effect of PAL peripheral design on lens preference and subjective rating of swim distortions. Linear regressions were performed to investigate the relationship between blur strength, preference and distortion scores.

Chapter 12 Results: PAL design differences, distortion and preference scores

Introduction

Many of the studies investigating PALs have reported clinical trials of wearer acceptance of PALs in preference to other lens designs, or to other progressive lenses (Wittenberg 1978, Chapman 1978, Hitzeman and Brookman 1980, Spaulding 1981, Borish and Hitzeman 1983, Augsburger et al. 1984, Hitzeman and Myers 1985, Borish, Brookman, Hall and Jensen 1988, Wittenberg et al. 1989, Sullivan and Fowler 1989a, Cho et al. 1991, Bachman 1992, Fowler et al. 1994, Young and Borish 1994, Boroyan et al. 1995). These investigations have generally taken the form of clinical wearer trials with crossover designs where subjects have been asked to determine their preference for one lens design over another.

This experiment aimed to determine if PAL wearers' perceptions of spatial distortion with PALs and their preference for one PAL design over another as determined in a crossover clinical wearing trial showed a relationship to optical parameters measured at two areas on the lens surface. This experiment formed part of a clinical wearer trial of three PAL designs and measurement of peripheral motion detection thresholds in the presence and absence of head movement while wearing PALs (Chapter 9 and 10). The hypothesis under test is that ratings of spatial distortion observed subjectively with PALs are related to peripheral back vertex powers and also resultant blur, where higher ratings of spatial distortion are related to lower scores for lens design preference and increased blur.

Experimental methods are outlined in Chapter 11. In summary, subjects participating in an experiment measuring motion detection threshold with PALs (chapter 9 and 10) wore three different PAL designs in a crossover clinical wearing trial, with each lens design worn for two weeks. Subjects rated their perception of spatial distortions on a questionnaire with Likert scales, and also rated whether any distortions noted were annoying or not, and whether they were more noticeable with movement. Scores for perception of distortion were derived from these scales and used as dependent variables in the analysis detailed in this chapter. Subjects also indicated subjective preference for one PAL design over another in paired forced choice comparisons. A score for subject preference was calculated from these preferences, and used as a dependent variable in subsequent analyses.

12.1 PAL Back vertex powers

Back vertex powers for the three measures for each PAL were transposed to power vector forms using the method described by Thibos, Wheeler and Horner (1997) (see Section 11.1). Back vertex power data were available for analysis from 15 subjects, with data excluded for subject 1 owing to the prescription of an incorrect near addition (see Section 12.2.1 Distortion scores: see below); data for 14 subjects were therefore included in the subsequent analyses referring to PAL design differences. Data were incomplete for 2 subjects.

For distance back vertex power (equivalent to distance refraction), mean M vector power was 0.51 ± 0.81 D, mean J_0 vector power was 0.016 ± 0.18 D, and mean J_{45} vector power was 0.08 ± 0.11 D. As the three PAL designs used in the experiment were made to the same distance prescription for each individual subject, these values were constant between lens designs. PAL 2 showed increased spherical and astigmatic vector component powers for the infero-temporal point compared to the PAL 1 and PAL 3 designs (Table 12.1, Figure 12.1). The means of the M, J_0 and J_{45} components were similar across PAL designs for superior-temporal measures (Table 12.1, Figure 12.1).

		M	J_0	J_{45}
Superior	PAL 1	0.88 ± 0.72	0.001 ± 0.19	0.28 ± 0.11
	PAL 2	0.89 ± 0.73	0.08 ± 0.22	0.29 ± 0.12
	PAL 3	0.89 ± 0.7	-0.06 ± 0.22	0.32 ± 0.17
Inferior	PAL 1	1.28 ± 0.75	-0.48 ± 0.2	0.45 ± 0.19
	PAL 2	1.62 ± 0.72	-0.62 ± 0.23	0.76 ± 0.2
	PAL 3	1.37 ± 0.67	-0.60 ± 0.19	0.53 ± 0.22

Table 12.1 Mean values for M, J_0 and J_{45} vector component powers across PAL designs for supero- and infero-temporal locations (in dioptres, *M = spherical power, J components = cylindrical power*)

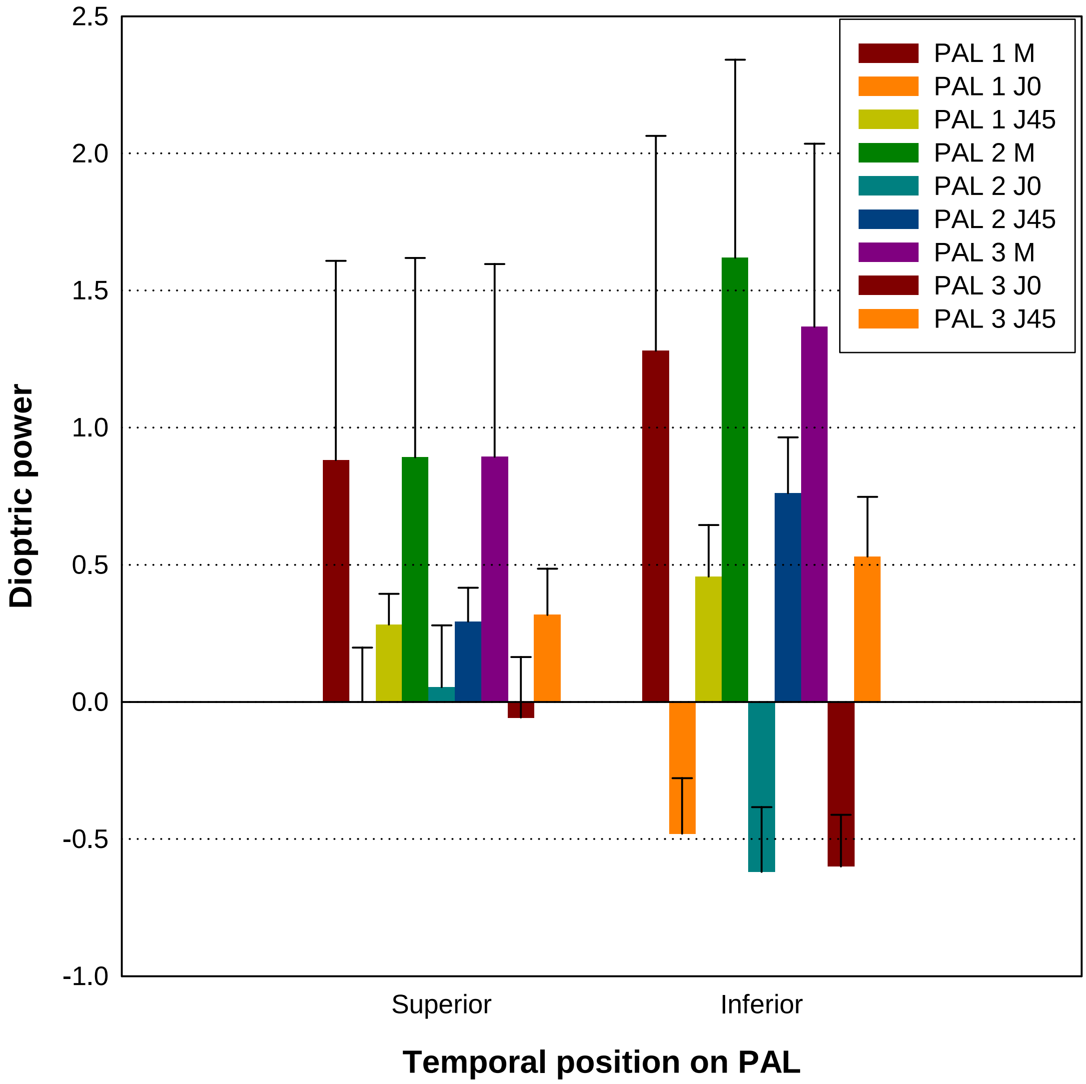

Figure 12.1 Mean vector component powers for three PAL designs for back vertex powers measured in the superior and inferior temporal aspect of the right lens. Error bars are one standard deviation.

To determine if the three vector components for each lens were different between the PAL designs, a series of one-way repeated measures ANOVAs were performed separately for the superior and inferior temporal positions with each of the vector component powers as the dependent variable. A Bonferroni correction was applied due to the multiple comparisons, with a modified *p* value of 0.008 applying (*p* of 0.05/6). For vector component powers measured in the superior temporal zone of the lens, there was a significant difference between lenses for the J_0 component (Wilks' Lambda = 0.48, $F_{2,12}$ = 6.50, p = 0.012), but not for the *M* and J_{45} power components

(*M* component: Wilks' Lambda = 0.984, $F_{2,12}$ = 0.162, p = 0.852; J_{45} component: Wilks' Lambda = 0.875, $F_{2,12}$ = 0.859, p= 0.448).

The three PAL designs differed significantly for the power vector components in the inferior temporal zone of the lenses: *M* component: Wilks' Lambda = 0.221, $F_{2,12}$ = 21.18, p = 0.0005; J_0 component: Wilks' Lambda = 0.443, $F_{2,12}$ = 7.55, p = 0.008; J_{45} component: Wilks' Lambda = 0.116, $F_{2,12}$ = 45.51, p = 0.0005. Paired t-tests show this to be due to PAL 2 having significantly greater *M* and J_{45} component powers than both PAL 1 and PAL 3, and PAL 1 a significantly greater J_0 component than PAL 3 (Table 12.2, also Figure 12.1).

		Mean	SD	95% CI difference		t	df	Sig.
				Lower	Upper			(2-tailed)
M	PAL 1 - PAL 2	-0.339	0.225	-0.469	-0.209	-5.626	13	0.0005*
	PAL 1 - PAL 3	-0.088	0.360	-0.296	0.120	-0.912	13	0.378
	PAL 2 - PAL 3	0.251	0.270	0.095	0.407	3.483	13	0.004*
J0	PAL 1 - PAL 2	0.140	0.135	0.061	0.218	3.858	13	0.002*
	PAL 1 - PAL 3	0.119	0.137	0.040	0.199	3.259	13	0.006*
	PAL 2 - PAL 3	-0.020	0.123	-0.091	0.051	-0.612	13	0.551
J45	PAL 1 - PAL 2	-0.303	0.116	-0.370	-0.237	-9.807	13	0.0005*
	PAL 1 - PAL 3	-0.073	0.190	-0.182	0.037	-1.427	13	0.177
	PAL 2 - PAL 3	0.231	0.191	0.121	0.341	4.523	13	0.001*

Table 12.2 Paired t-test comparisons for M, J_0 and J_{45} components in the inferior temporal zone of PALs (* significant at p = 0.005, Bonferroni adjustment for multiple comparisons). (95% confidence intervals calculated from standard error of mean).

12.1.2 Blur strength vector

The power vector expressions of M, J_0 and J_{45} in the analysis above are considered to represent *x,y and z* Cartesian coordinates of 3 lenses which in combination create a sphero-cylindrical spectacle lens power (Thibos, Wheeler and Horner 1997, Thibos and Horner 2001). If these coordinates are interpreted geometrically as the coordinates of a point in 3-dimensional dioptric space, the Pythagorean length of the power vector from origin to the *x,y,z* Cartesian coordinates for a given sphero-cylindrical lens is a measure of the overall blurring strength of the sphero-cylindrical lens, or refractive error (Harris 1994, Raasch 1995, Thibos, Wheeler and Horner 1997, Thibos and Horner 2001). This has been termed blur strength (Thibos, Wheeler and Horner 1997, Thibos and Horner 2001) and dioptric strength by Harris (1994) in the matrix form of refractive power analysis.

Blur strength has been calculated from the M, J_0 and J_{45} power vectors for the inferior and superior temporal zones for each PAL design used, using the method described by Thibos, Wheeler and Horner (1997), where blur strength (B) is defined as $B = \sqrt{(M^2 + J_0^2 + J_{45}^2)}$. Blur strength vector power was then used as the dependent variable in one-way repeated measures ANOVAs performed separately for the superior and inferior temporal positions, with lens design (3 levels) as the independent variable.

For blur strength vector power in the superior-temporal zone of the lenses, there was no significant difference between the three PAL designs (Wilks' Lambda = 0.864, $F_{2,12} = 0.943$, $p = 0.417$). PAL 1 has mean blur strength in the superior-temporal zone of 1.039 ± 0.581 D, PAL 2: 1.063 ± 0.574 D and PAL 3: 1.067 ± 0.561 D (Figure 12.2).

Mean blur strength vector power in the inferior temporal zone is PAL 1: 1.52 ± 0.662 D, PAL 2: 1.96 ± 0.59 D and PAL 3: 1.66 ± 0.513 D. The three PAL designs differed significantly for blur strength power vector in the inferior-temporal zone (Wilks' Lambda = 0.124, $F_{2,12} = 42.24$, $p = 0.0005$). Post-hoc comparisons show this to be due to PAL 2 having significantly greater blur strength vector power in the inferior-temporal zone than both PAL 1 and PAL 3; whereas PAL 1 and PAL 3 are not significantly different (Table 12.3, Figure 12.2).

	mean difference	SD	95% CI for difference		p
			upper	lower	
PAL 1 - PAL 2	-0.439	0.186	-0.07	-0.8	0.0005*
PAL 3 - PAL 2	-0.299	0.293	0.27	-0.87	0.0005*
PAL 1 - PAL 3	-0.14	0.344	0.53	-0.81	0.456

Table 12.3 Post-hoc comparisons for blur strength vector power (in dioptres) for the inferior temporal zone (* = significant at $p < 0.016$, Bonferroni adjustment for multiple comparisons).

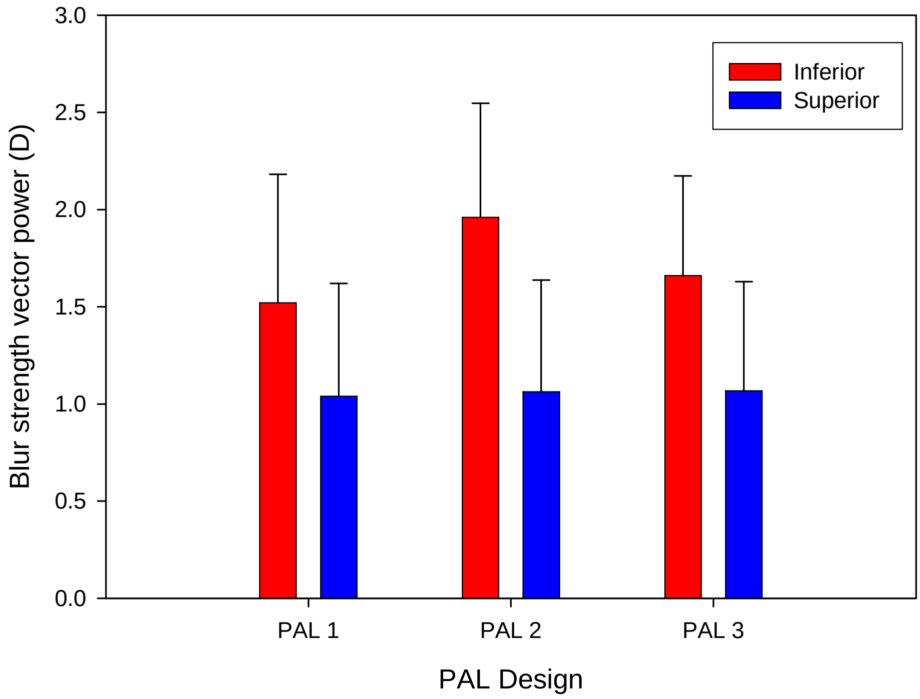

Figure 12.2 Mean blur strength vector power for PAL designs, superior-temporal and inferior temporal zones, in dioptres. Greater blur strength is found in inferior temporal zone than superior for all lens designs. Error bars are one standard deviation.

PAL 2 therefore creates significantly more blur in the inferior-temporal zone than the two other PAL designs, PAL 1 and PAL 3. The mean difference however clinically is small, being 0.50D more blur on average compared to PAL 1, and 0.25 D more blur compared to PAL 3.

Blur strength vector power in both superior and inferior temporal zones of the PAL designs is also used as the independent variable in regression analysis of distortion scores (Section 12.3.1) and preference scores (Section 12.3.2) as dependent variables.

12.2 Distortion scores and preference ratings of PAL designs

12.2.1 Distortion scores

Subjects completed a questionnaire consisting of six questions relating to the perception of distortion and 'swim' in distance, intermediate and near vision for each of the PAL lenses worn (see Section 11.2). All subjects (n = 17) participated in this experiment. Subject demographic data can be seen in Table 10.1. The questions asked how often a symptom of distortion or illusory movement was noticed, if present how annoying it was, and whether this was more noticeable if the subject was moving about. Response scales were structured so that high scores represented constancy of the distortion, high level of annoyance and the symptom being very much more noticeable when moving about. The lowest score represented absence of a distortion. Question scales are illustrated in Figure 12.3.

11. A feeling that objects in the sides of your vision were distorted?

Always	Frequently	Sometimes	Infrequently	Never
5	4	3	2	1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
7	6	5	4	3	2	1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
5	4	3	2	1

Figure 12.3 Response scale of distortion questionnaire (duplicate of Figure 11.4)

Responses were collated for each question. Responses were allocated to 2 variables for each question. Score A for each question represented the *presence x annoyance* scores for the distortion. Score B represented *Score A x the effect of the subject moving about*. Score B therefore indicated the effect of movement on Score A; no change in Score B compared to Score A indicated movement did not increase awareness of the distortion. A total distortion score for distance, intermediate and near vision was derived as 'TOT DISTN A' and "TOT DISTN B'. These were the sum of individual questions Score A and B respectively, divided by 6 (the total for distance, intermediate or near if no distortions were noted). These two scores therefore reflect distortions as a ratio to the 'perfect no distortion score'.

Six distortion questions were evaluated:
Q1: a feeling that objects in the sides of your vision were distorted?
Q2: difficulty judging distance or position from other objects?
Q3: things in your field of vision seeming to move up and down?
Q4: things in your field of vision seeming to move side to side?
Q5: things in your field of vision seeming to sway or tilt?
Q6: things in your field of vision seeming to move to and fro?

Four questions (Q3-Q6) sought symptoms of illusory movement, and two questions sought more generic distortion symptoms.

Collated results for distance, intermediate and near vision are shown in Figures 12.4 to 12.6. Data shown are group mean and standard deviation. Variables Q1SCORA etc are the distortion scores for the individual questions as outlined above. TOT DISTN A and B are the summed total of the 6 question scores. The variable 'MOVT EFFECT' is the total distortion (TOT DISTN) score B divided by score A. This ratio reflects the overall effect of the subject moving about on their perception of the distortions at distance, intermediate or near; as noted above, a unit value for this ratio indicates distortions are not more perceptible when the subject is moving around.

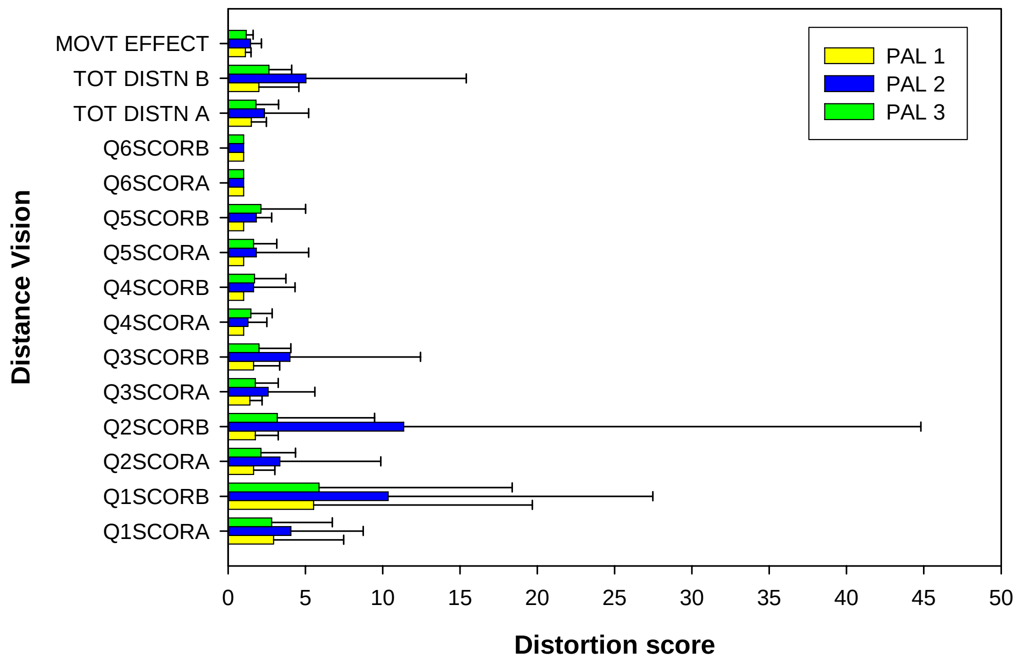

Figure 12.4 Group means and standard deviation for distortion scores in distance vision for individual questions (SCORA and SCORB), and collated for all questions (TOT DISTN A and B) – see text. Error bars are one standard deviation.

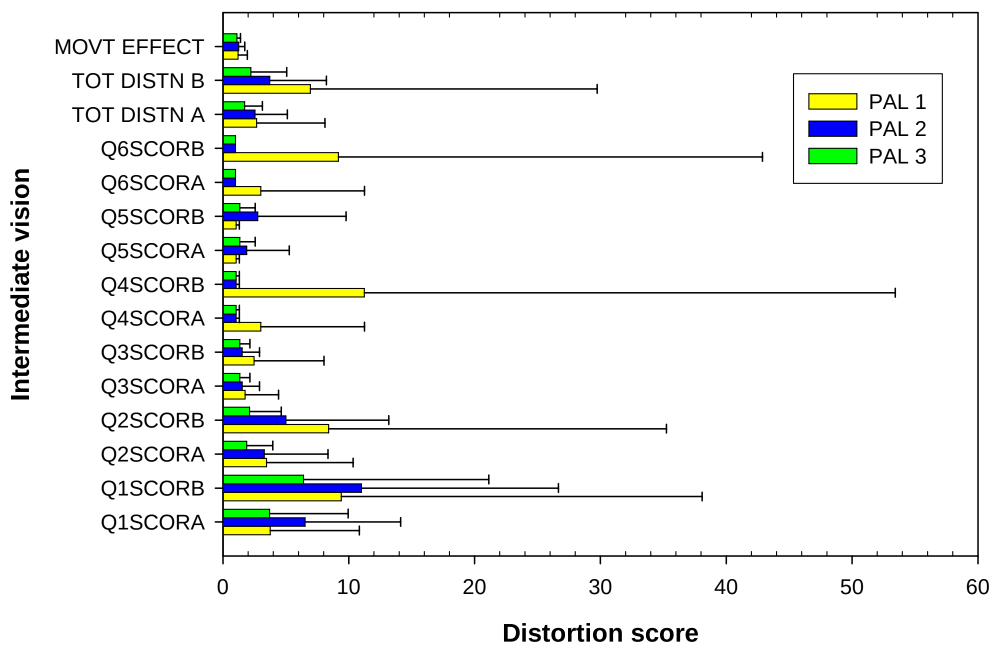

Figure 12.5 Group mean and standard deviation of distortion scores for intermediate vision, for each distortion question and for question totals (see text). Error bars are one standard deviation.

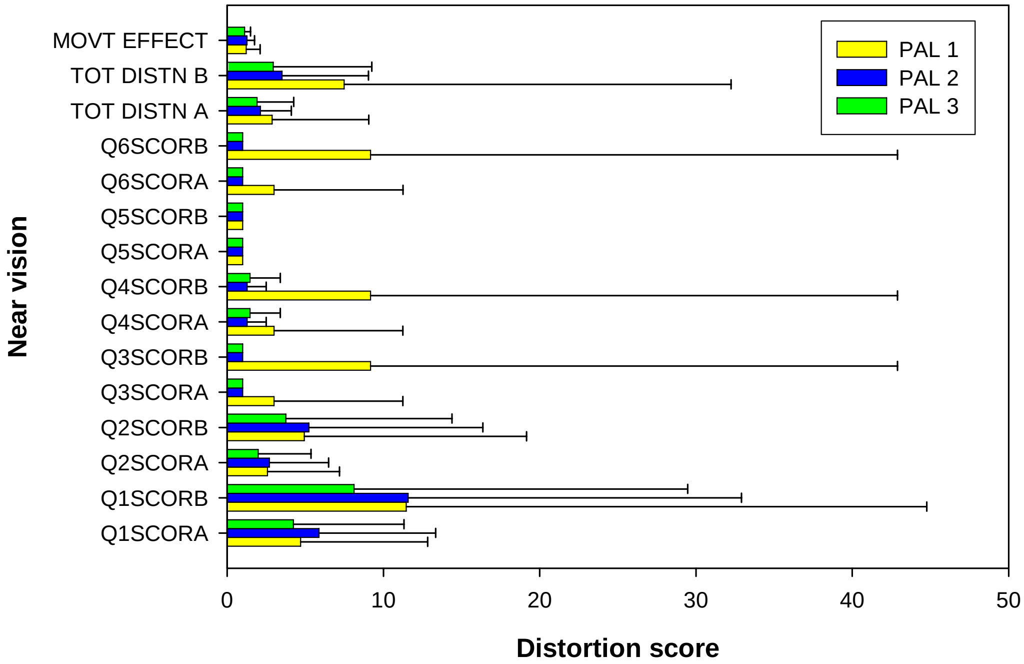

Figure 12.6 Group mean and standard deviation of distortion scores for near vision for each distortion question and for question totals (see text). Error bars are one standard deviation.

Figures 12.4 to 12.6 indicate that distortion increased with the PAL 1 design in intermediate and near vision compared to other lenses. Inspection of the completed questionnaires showed this to be due to one subject, who was severely bothered by distortions at intermediate and near vision with all designs, but particularly PAL 1. Near addition for this subject had been increased compared to the subject's previous prescription, and it was found that the subject preferred a longer working distance than the revised add provided, thus the subject tended to use the progressive corridor for most near tasks, with resultant visual field restrictions. Analysis of data for distortion and preference ratings presented hereafter does not include this subject. Revised plots of distortion scores are shown below as Figures 12.7 to 12.9. Mean scores and standard deviations are lessened after treating this subject as an outlier.

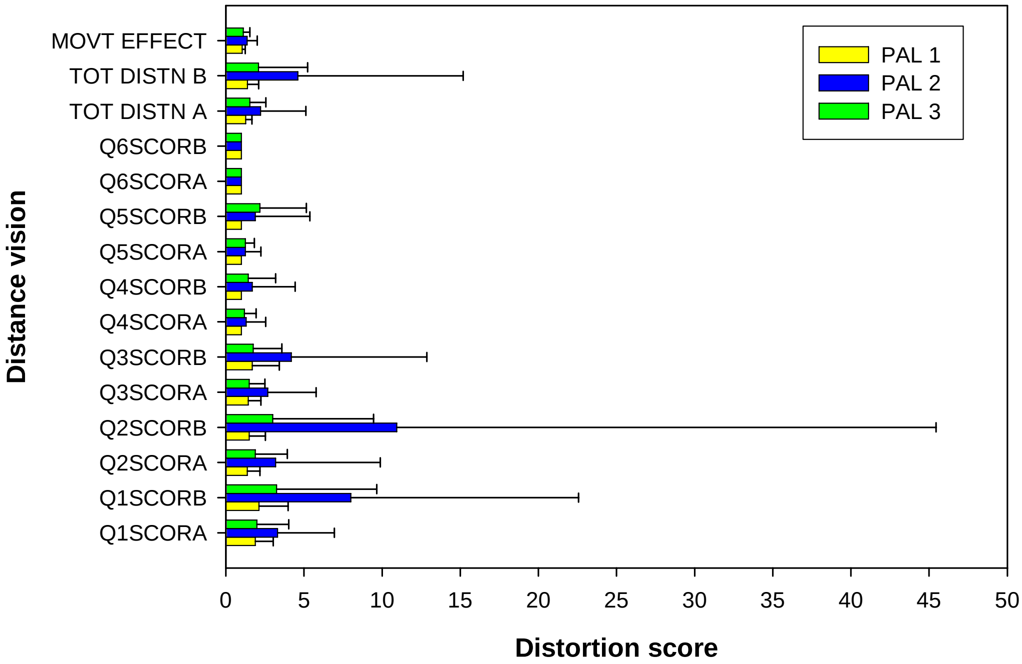

Figure 12.7 Revised group means and standard deviations of distortion scores for distance vision, after removal of one subject as an outlier. Error bars are one standard deviation.

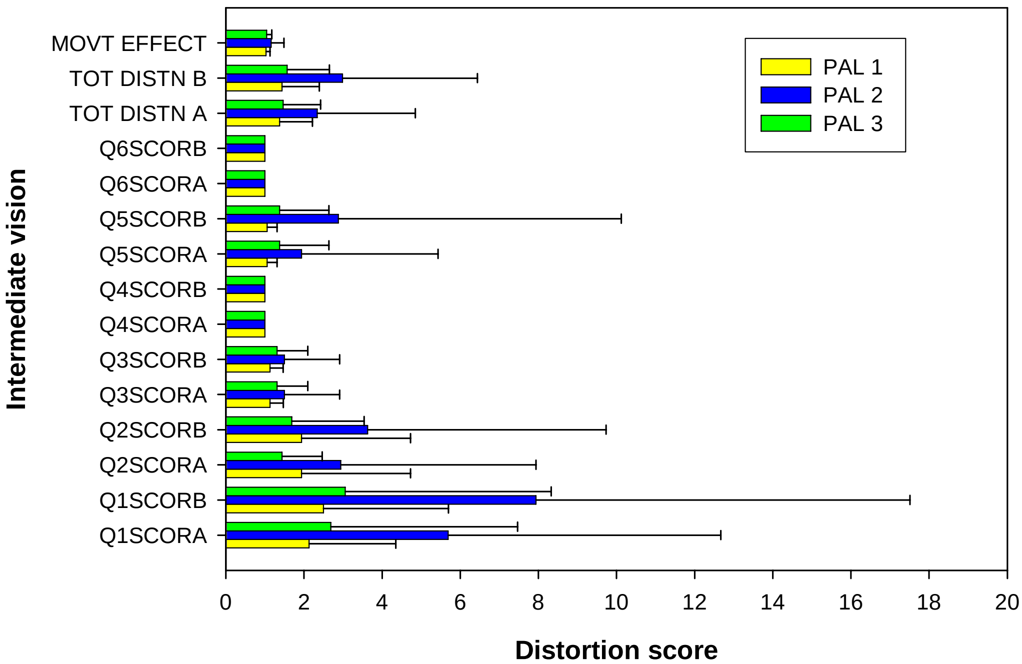

Figure 12.8 Revised group means and standard deviations for distortion scores in intermediate vision, after one subject treated as an outlier.

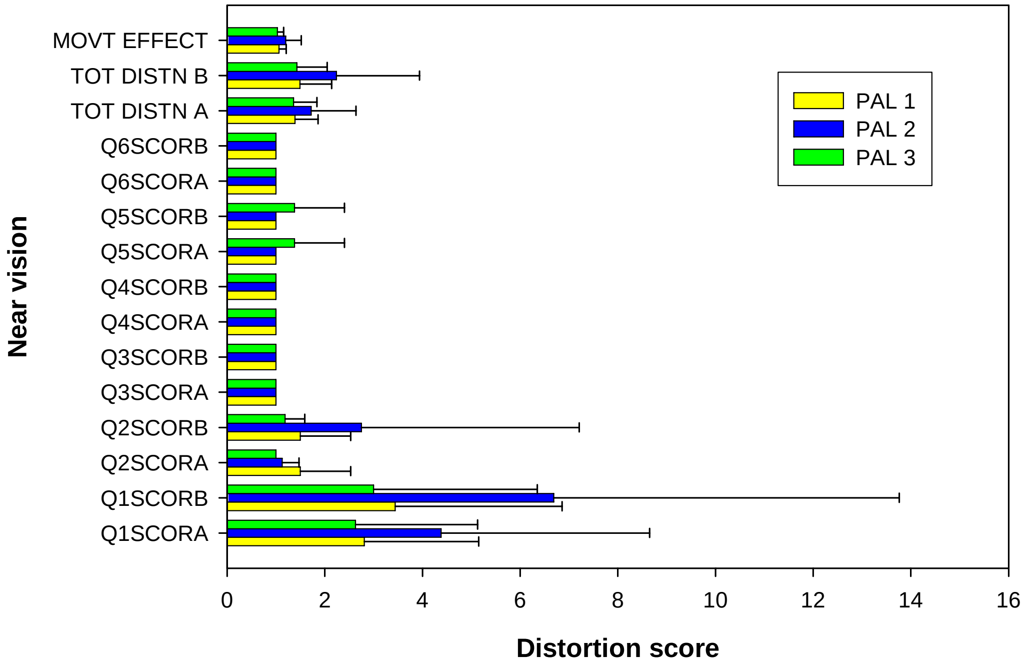

Figure 12.9 Revised group means and standard deviations for distortion scores in near vision, after data for one subject treated as an outlier. Error bars are one standard deviation.

Figures 12.7 to 12.9 indicate that no subjects reported objects in their visual field moving to and fro (question 6 in questionnaire) for distance, near and intermediate vision. Mean score for this question (Q6SCORA and B in the figures) was 1, with no variance. This was also the case for distance vision, with the outlier subject included (Figure 12.4).

Unit scores without variance were also found for the questions regarding objects moving side to side in the visual field (Q4SCORA and B) and for objects moving up and down (Q3SCOR A and B) for near vision (Figure 12.8) in all lens designs, and for the ‘moving side to side’ question (Q4) for intermediate vision (Figure 12.9). These symptoms of ‘swim’, or induced illusory movement, were not apparent to this subject group during near or intermediate vision.

Tables 12.4 to 12.6 following show descriptive statistics for the distortion score variables, listed for each PAL design for distance, intermediate and near.

(text continues after Tables following)

PAL Design		Mean	Std Deviation	Minimum	Maximum
1	Q1SCORA	1.88	1.15	1	4
	Q1SCORB	2.13	1.86	1	8
	Q2SCORA	1.38	0.81	1	4
	Q2SCORB	1.50	1.03	1	4
	Q3SCORA	1.44	0.81	1	4
	Q3SCORB	1.69	1.74	1	8
	Q4SCORA	1	0	1	1
	Q4SCORB	1	0	1	1
	Q5SCORA	1	0	1	1
	Q5SCORB	1	0	1	1
	Q6SCORA	1	0	1	1
	Q6SCORB	1	0	1	1
	TOT DISTN A	1.28	0.39	1	2.17
	TOT DISTN B	1.39	0.72	1	3.83
	Movteffect	1.05	0.19	1	1.77
2	Q1SCORA	3.31	3.63	1	15
	Q1SCORB	8.00	14.57	1	60
	Q2SCORA	3.19	6.70	1	28
	Q2SCORB	10.94	34.50	1	140
	Q3SCORA	2.69	3.09	1	12
	Q3SCORB	4.19	8.68	1	36
	Q4SCORA	1.31	1.25	1	6
	Q4SCORB	1.69	2.75	1	12
	Q5SCORA	1.88	3.50	1	15
	Q5SCORB	1.88	3.50	1	15
	Q6SCORA	1	0	1	1
	Q6SCORB	1	0	1	1
	TOT DISTN A	2.23	2.90	1	12.83
	TOT DISTN B	4.61	10.57	1	44.00
	Movteffect	1.37	0.65	1	3.43
3	Q1SCORA	2	2.03	1	9
	Q1SCORB	3.25	6.41	1	27
	Q2SCORA	1.88	2.06	1	9
	Q2SCORB	3.00	6.45	1	27
	Q3SCORA	1.50	1.03	1	4
	Q3SCORB	1.75	1.84	1	8
	Q4SCORA	1.19	0.75	1	4
	Q4SCORB	1.44	1.75	1	8
	Q5SCORA	1.69	1.54	1	6
	Q5SCORB	2.19	2.97	1	12
	Q6SCORA	1	0	1	1
	Q6SCORB	1	0	1	1
	TOT DISTN A	1.54	1.03	1	5.17
	TOT DISTN B	2.10	3.15	1	13.83
	Movteffect	1.12	0.42	1	2.68

Table 12.4 Descriptive statistics for distortion scores for distance vision

PAL Design		Mean	Std Deviation	Minimum	Maximum
1	Q1SCORA	2.13	2.22	1	9
	Q1SCORB	2.50	3.20	1	12
	Q2SCORA	1.94	2.79	1	12
	Q2SCORB	1.94	2.79	1	12
	Q3SCORA	1.13	0.34	1	2
	Q3SCORB	1.13	0.34	1	2
	Q4SCORA	1	0	1	1
	Q4SCORB	1	0	1	1
	Q5SCORA	1.06	0.25	1	2
	Q5SCORB	1.06	0.25	1	2
	Q6SCORA	1	0	1	1
	Q6SCORB	1	0	1	1
	TOT DISTN A	1.38	0.84	1	4.17
	TOT DISTN B	1.44	0.95	1	4.17
	Movteffect	1.03	0.10	1	1.4
2	Q1SCORA	5.69	6.98	1	28
	Q1SCORB	7.94	9.57	1	28
	Q2SCORA	2.94	5.00	1	20
	Q2SCORB	3.63	6.10	1	20
	Q3SCORA	1.50	1.41	1	6
	Q3SCORB	1.50	1.41	1	6
	Q4SCORA	1.00	0.00	1	1
	Q4SCORB	1.00	0.00	1	1
	Q5SCORA	1.94	3.49	1	15
	Q5SCORB	2.88	7.24	1	30
	Q6SCORA	1	0	1	1
	Q6SCORB	1	0	1	1
	TOT DISTN A	2.34	2.51	1	11.00
	TOT DISTN B	2.99	3.45	1	13.50
	Movteffect	1.16	0.33	1	2.23
3	Q1SCORA	2.69	4.78	1	20
	Q1SCORB	3.06	5.27	1	20
	Q2SCORA	1.44	1.03	1	4
	Q2SCORB	1.69	1.85	1	8
	Q3SCORA	1.31	0.79	1	4
	Q3SCORB	1.31	0.79	1	4
	Q4SCORA	1.00	0.00	1	1
	Q4SCORB	1.00	0.00	1	1
	Q5SCORA	1.38	1.26	1	6
	Q5SCORB	1.38	1.26	1	6
	Q6SCORA	1	0	1	1
	Q6SCORB	1	0	1	1
	TOT DISTN A	1.47	0.96	1	4.67
	TOT DISTN B	1.57	1.08	1	4.67
	Movteffect	1.05	0.13	1	1.40

Table 12.5 Descriptive statistics for distortion scores for intermediate vision

PAL Design		Mean	Std Deviation	Minimum	Maximum
1	Q1SCORA	2.81	2.34	1	9
	Q1SCORB	3.44	3.42	1	12
	Q2SCORA	1.50	1.03	1	4
	Q2SCORB	1.50	1.03	1	4
	Q3SCORA	1	0	1	1
	Q3SCORB	1	0	1	1
	Q4SCORA	1	0	1	1
	Q4SCORB	1	0	1	1
	Q5SCORA	1	0	1	1
	Q5SCORB	1	0	1	1
	Q6SCORA	1	0	1	1
	Q6SCORB	1	0	1	1
	TOT DISTN A	1.39	0.47	1	2.33
	TOT DISTN B	1.49	0.65	1	3.00
	Movteffect	1.06	0.15	1	1.5
2	Q1SCORA	4.38	4.27	1	15
	Q1SCORB	6.69	7.07	1	18
	Q2SCORA	1.94	2.14	1	9
	Q2SCORB	2.75	4.46	1	18
	Q3SCORA	1	0	1	1
	Q3SCORB	1	0	1	1
	Q4SCORA	1	0	1	1
	Q4SCORB	1	0	1	1
	Q5SCORA	1	0	1	1
	Q5SCORB	1	0	1	1
	Q6SCORA	1	0	1	1
	Q6SCORB	1	0	1	1
	TOT DISTN A	1.72	0.92	1	3.67
	TOT DISTN B	2.24	1.72	1	6.67
	Movteffect	1.20	0.32	1	1.82
3	Q1SCORA	2.63	2.50	1	9
	Q1SCORB	3.00	3.35	1	12
	Q2SCORA	1.19	0.40	1	2
	Q2SCORB	1.19	0.40	1	2
	Q3SCORA	1	0	1	1
	Q3SCORB	1	0	1	1
	Q4SCORA	1	0	1	1
	Q4SCORB	1	0	1	1
	Q5SCORA	1.38	1.02	1	4
	Q5SCORB	1.38	1.02	1	4
	Q6SCORA	1	0	1	1
	Q6SCORB	1	0	1	1
	TOT DISTN A	1.36	0.48	1	2.33
	TOT DISTN B	1.43	0.62	1	3.00
	Movteffect	1.03	0.13	1	1.50

Table 12.6 Descriptive statistics for distortion scores for near vision

12.2.1.1 Overall distortion score

An overall distortion score was then calculated for each subject by combining the total distortion scores (TOT DISTN A and B separately) for distance, intermediate and near, then dividing this by 3 to reflect this score as a ratio to a perfect no distortion score. This generated two variables, OVDIST A and OVDIST B. The former of these indicates the overall *presence x annoyance* of distortions, and the latter the overall effect on this score of the subject moving about. The ratio of the two overall distortion scores again indicates the overall movement effect; a unit ratio indicates the subject felt distortions present at distance, intermediate and near were not affected by his/her movement.

Group mean overall distortion score A (OVDIST A: presence x annoyance) for PAL 1 was 1.35 ± 0.42 (range 1.00 to 2.44); for PAL 2 this was 2.10 ± 1.977 (range 1.00 to 9.06) and for PAL 3 was 1.46 ± 0.69 (range 1.00 to 3.78).

Mean overall distortion score B (OVDIST B: OVDIST A x effect of subject movement) was 1.44 ± 0.53 (range 1.00 to 2.56) for PAL 1, 3.28 ± 4.75 (range 1.00 to 20.28) for PAL 2 and 1.70 ± 1.38 (range 1.00 to 6.67) for PAL 3.

Subjects reported more distortions with PAL 2 than the other lens designs; these became more noticeable with subject movement in PAL 2 than in the other PAL designs. To investigate this effect of lens design on perception of distortions, the overall distortion and movement scores, as outlined above, formed the dependent variables in a series of one-way repeated measures analysis of variance, with PAL design (3 levels) as the independent factor, with PAL wearing order as the between subjects factor. As the raw data for distortion scores showed positively skewed distributions, data for distortion score A and B, and the ratio of distortion scores, were log-transformed prior to the repeated measures analysis of variance; the log transformed scores thus were the dependent variables in the analysis. Descriptive statistics for the log-transformed variables are shown in Table 12.7 (see below).

PAL design had an effect on the *presence x annoyance* of distortions (log overall score A) (Wilks' lambda = 0.615, $F_{2,12} = 3.75$, p = 0.054), although this effect just failed to reach significance at the p = 0.05 level. The interaction of PAL design with wearing order had no significant effect on overall distortion score A (Wilks' lambda = 0.639, $F_{4,24}$ = 1.50, p = 0.233). Post-hoc pairwise comparisons (with a Bonferroni adjustment for multiple comparisons) indicated this effect is caused by an increase in the log overall distortion score A in PAL 2 compared to the other two designs. PAL 2 showed a significantly greater log distortion score A than PAL 1 (mean difference = 0.111, SE 0.039, p = 0.041, 95% CI 0.004 to 0.219). PAL 2 also showed a greater log overall distortion score A than PAL 3, but this was non-significant (mean difference 0.093, SE 0.038, p = 0.082, 95% CI -0.1 to 0.196). Overall distortion score A was not significantly different between PAL 1 and PAL 3 (mean difference -0.018, SE 0.017, p = 0.994).

		Mean	sd	Variance	Minimum	Maximum
Distortion Score A	PAL 1	0.112	0.113	0.015	0	0.388
	PAL 2	0.226	0.261	0.068	0	0.957
	PAL 3	0.134	0.152	0.023	0	0.577
Distortion Score B	PAL 1	0.133	0.146	0.022	0	0.407
	PAL 2	0.317	0.367	0.134	0	1.307
	PAL 3	0.135	0.21	0.044	0	0.824
Ratio of scores	PAL 1	0.021	0.047	0.002	0	0.158
	PAL 2	0.091	0.112	0.013	0	0.35
	PAL 3	0.031	0.065	0.004	0	0.247

Table 12.7. Descriptive statistics for log transformed variables overall distortion score A, overall distortion score B and ratio of ScoreB/Score A

PAL design had a significant effect on log overall distortion score B (presence x annoyance x effect of movement) (Wilks' lambda = 0.575, $F_{2,12}$ = 4.437, p = 0.036). The interaction of PAL design with PAL wearing order had no significant effect on overall distortion score B (Wilks' lambda = 0.614, $F_{4,24}$ = 1.654, p = 0.193). Post-hoc pairwise comparisons, with a Bonferroni adjustment for multiple comparisons, indicated the effect PAL design was caused by the log overall distortion score B for PAL 2 being significantly greater than the distortion score in both PAL 1 and PAL 3 (PAL 2 – PAL 1: mean difference 0.18, SE 0.062, 95% CI for difference 0.009 to 0.351, p = 0.038; PAL 2 – PAL 3: mean difference 0.154, SE 0.05, 95% CI for difference 0.16 to 2.91, p = 0.027). PAL 1 and PAL 3 were not significantly different (PAL 1 – PAL 3 mean difference -0.026, SE 0.03, 95%CI for difference -0.11 to 0.057, p = 1.000). As with other measures of PAL performance, variability was high.

12.2.1.2 Ratio of distortion scores

The ratio of the overall distortion scores (score B/score A) indicated whether distortions were made more noticeable if the subject was moving around. A unit value for this ratio indicated subject movement did not make distortions more noticeable. Movement ratio in PAL 1 was 1.06 ± 0.13 (range 1.0 to 1.4). This ratio was similar with PAL 3 (1.09 ± 0.19, range 1.0 to 1.77). The movement ratio was higher in PAL 2 (1.28 ± 0.38, range 1.0 to 2.24). As noted above, raw data for the ratio of distortion scores was log-transformed prior to the repeated measures ANOVA. Lens design had a significant effect on this ratio (Wilks' lambda = 0.48, $F_{2,12}$ = 6.497, p = 0.012). The interaction of PAL design and wearing order had no significant effect on the ratio of distortion scores (Wilks' lambda = 0.687, $F_{4,24}$ = 1.241, p = 0.32).

Post-hoc pairwise comparisons, with a Bonferroni adjustment for multiple comparisons, showed the effect of PAL design to be due to a significant increase in the log of the ratio of scores with PAL 2 compared to PAL 1 and PAL 3. Mean difference between PAL 2 and PAL 1 was 0.068 (SE 0.026, 95% CI for the difference -0.002 to 0.139, p = 0.06). Mean difference between PAL 2 and PAL 3 was 0.06 (SE 0.016, 95% CI for the difference 0.016 to 0.115, p = 0.007). The ratio of overall distortion scores was not significantly different between PAL 1 and PAL 3 (mean difference -0.008, SE 0.019, 95% CI for difference -0.06 to 0.043, p = 1.000).

Both the combined distortion scores for distance, intermediate and near vision (Score A), and the distortion score incorporating the effect of subject movement (Score B) were highest in PAL 2. This difference between PAL 2 and the other two PAL designs just failed to reach significance when considering the presence and annoyance of distortions (Score A), but was statistically significant when the effect of subject self movement was included (Score B or the ratio of distortion scores). Wearing order of the PAL designs had no effect on distortion score. Overall distortion scores are significantly increased by subject movement in PAL 2; subjective distortions are more noticeable with this PAL design when subjects are moving about. Distortion scores which include the effect of subject self movement on symptoms of distortion (distortion score B and the ratio of distortion scores) show a significant effect for PAL design on the score, indicating that it is the effect of subject self movement on symptoms which is the discriminator between lenses, more so than the presence of symptoms themselves.

12.2.2 Subjective preference ratings for PAL designs

Subjects were required to make paired comparisons between PAL pairs to indicate which PAL design they preferred in a paired comparison, and the strength of this preference (Section 11.2.5). The results of the paired comparisons were summed for each lens, and a preference score was generated from these paired ratings. With this scoring method, the higher the score the more the subject preferred a lens across paired lens comparisons.

Mean preference score for PAL 1 was 6.50 ± 2.39 (range 2 – 11), for PAL 2 this was 3.06 ± 1.48 (range 2 – 6) and for PAL 3 was 4.94 ± 1.88 (range 2 – 10). Preference scores for individual subjects are indicated in Table 12.8.

	Preference Score		
Subject	PAL 1	PAL 2	PAL 3
2	5	2	10
3	6	6	6
4	11	2	4
5	10	5	2
6	7	2	5
7	8	2	5
8	8	2	5
9	7	2	4
10	5	2	7
11	2	5	7
12	8	2	5
13	4	4	4
14	7	2	4
15	8	2	4
16	4	5	3
17	4	4	4

Table 12.8 Preference scores across lens designs for individual subjects

The effect of PAL design on preference score was investigated by a repeated measures analysis of variance, with preference score as the dependent variable, and PAL design (3 levels) as the independent factor, and PAL wearing order as the between subjects factor. Raw data for preference scores were log transformed, with the log data for preference score used as the dependent variable in this analysis.

PAL design had a significant effect on preference score (Wilks' lambda = 0.455, $F_{2,12}$ = 7.184, p = 0.009). The interaction of PAL design with wearing order was not significant (Wilks' lambda = 0.647, $F_{4,24}$ = 1.486, p = 0.238).

Post-hoc pairwise comparisons show the effect of PAL design to be caused by lower preference scores for PAL 2 compared to the other PAL designs. Preference scores for PAL 2 are significantly lower than for PAL 1 (PAL 1 – PAL 2 mean difference: 0.332, SE 0.084, 95% CI for difference 0.10 to 0.564, p = 0.005, Bonferroni adjustment for multiple comparisons). Preference scores for PAL 2 are also significantly lower than for PAL 3 (PAL 3 – PAL 2 mean difference: 0.224, SE 0.075, 95% CI for difference 0.019 to 0.429, p = 0.03, Bonferroni adjustment). Preference scores for PAL 1 and PAL 3 are not significantly different (PAL 1 – PAL 3 mean difference: 0.108, SE 0.063, 95% CI for difference -0.06 to 0.28, p = 0.0328, Bonferroni adjustment).

Subjects overall preferred PAL designs 1 and 3 to PAL design 2. Preference scores for PALs 1 and 3 however were not significantly different. For wearers with higher preference scores for PAL 1 and 3 than for PAL 2, 10 wearers preferred PAL 1 to PAL 3, and 3 wearers preferred PAL 3 to PAL 1. Three wearers showed no difference in preference score across all three lens designs, and one wearer (subject 16) gave PAL 2 the highest preference score (Table 12.8).

12.2.3 Can distortion scores predict preference scores?

To determine whether the distortion scores (Score A: *presence x annoyance,* Score B: *presence x annoyance x effect of subject movement)* or the ratio of distortion scores for each PAL design are able to predict preference scores for the design, linear regression analysis was conducted with preference score as the dependent variable, and total distortion score as the independent variable. This was performed separately for each lens design, with the log-transformed data as the variables as outlined.

Scatterplots for the linear regression analysis are shown in Figures 12.10 to 12.12. Figures show scatterplots for log preference score plotted against log distortion score A and B (top two graphs in each Figure), and against the log of the ratio of distortion scores (bottom graph in each figure). Non linear relationships are evident in these figures. The lack of a linear relationship between preference scores and distortion score for each PAL design was supported by the regression ANOVA performed by SPSS, where F ratios were not significant for each lens design (Table 12.9 - below).

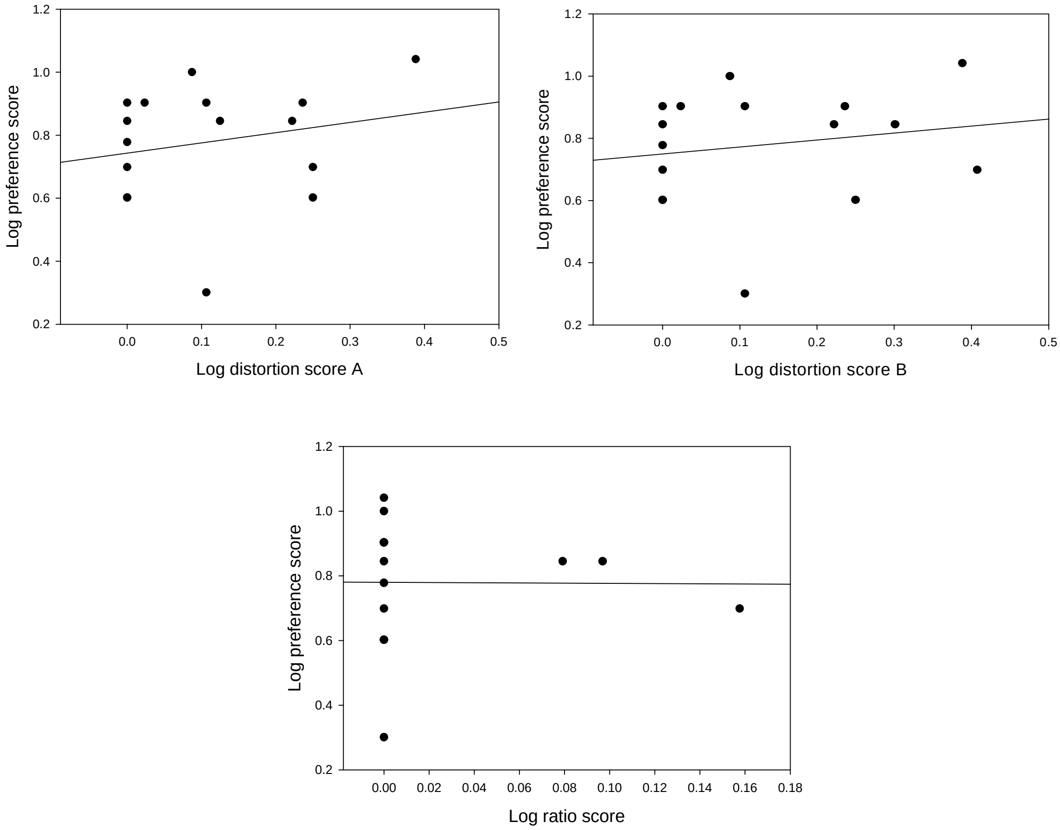

Figure 12.10 Scatterplots of preference scores against distortion scores and ratio score for PAL 1. Non linear relationships exist between preference score and distortion scores.

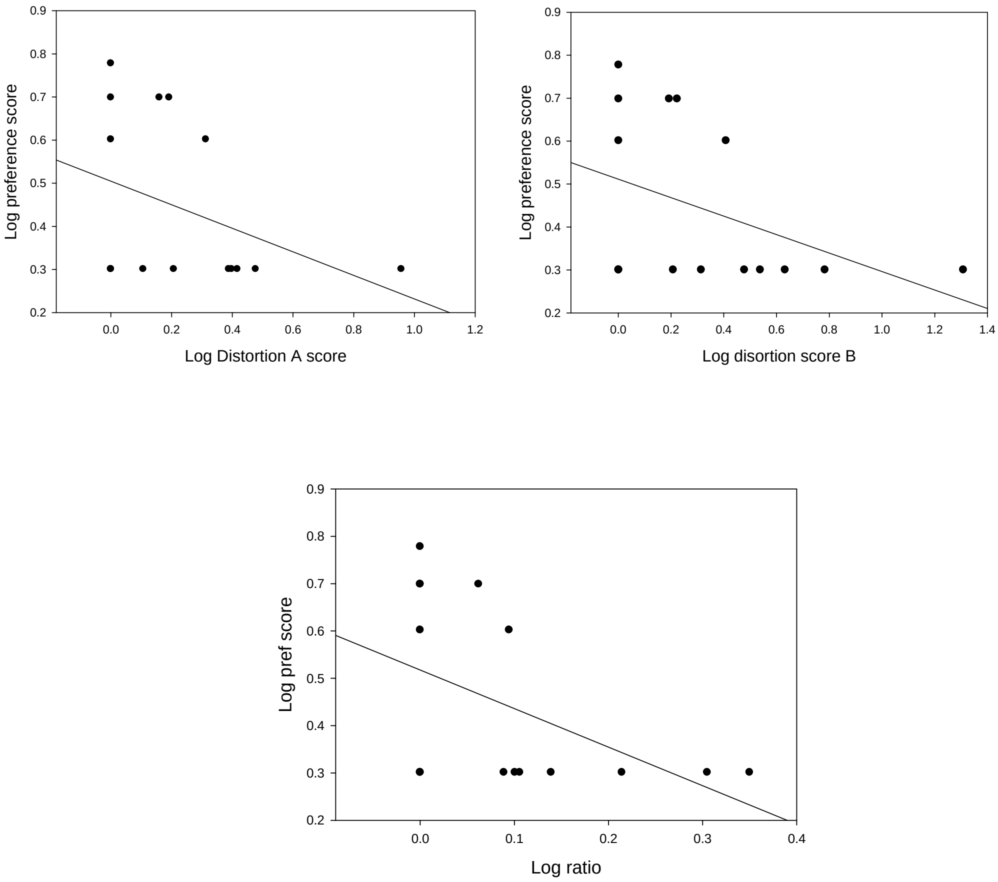

Figure 12.11 Scatterplots of preference score against total distortion scores and ratio score for PAL 2. Preference score for PAL 2 decreases as distortion or ratio score increases. Note scale difference on *x-axes* compared to Figure 12.10 and 12.12; distortion scores and ratio scores are greatest with the PAL 2 design.

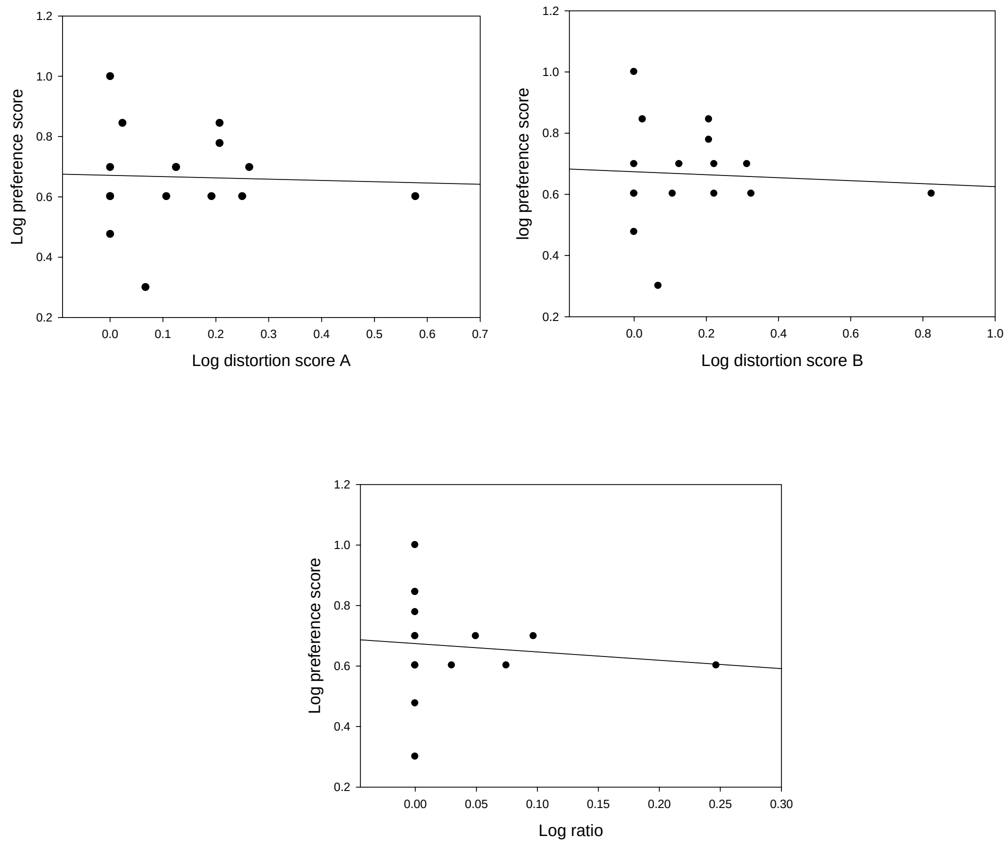

Figure 12.12 Scatterplots of preference score against total distortion scores and ratio score for PAL 3. Non-linear relationships are shown.

Regression equations and coefficients are shown in Table 12.9. Correlation coefficients are non-significant. Poor correlation existed between preference score, distortion scores and ratio score for each of the PAL designs. Distortion score, with or without the effect of subject movement, does not predict lens preference scores, within a particular lens design.

Distortion Score A

	regression equation	r	r^2	$F_{1,14}$	p
PAL 1	logpref = 0.33 logdistort A + 0.74	0.213	0.045	0.664	0.429
PAL 2	logpref = -0.27 logdistort A + 0.51	0.369	0.136	2.203	0.16
PAL 3	logpref = -0.04 logdistort A + 0.68	0.112	0.013	0.178	0.679

Distortion Score B

	regression equation	r	r^2	$F_{1,14}$	p
PAL 1	logpref = 0.22 logdistort B + 0.75	0.175	0.031	0.443	0.516
PAL 2	logpref = -0.22 logdistort B + 0.51	0.408	0.166	2.79	0.117
PAL 3	logpref = -0.05 logdistort B + 0.67	0.064	0.004	0.058	0.814

Ratio of Distortion Scores

	regression equation	r	r^2	$F_{1,14}$	p
PAL 1	logpref = -0.03 logratio + 0.78	0.009	0.00008	0.001	0.975
PAL 2	logpref = -0.81 logratio + 0.52	0.473	0.224	4.04	0.064
PAL 3	logpref = -0.28 logratio + 0.67	0.112	0.013	0.178	0.679

Table 12.9 Regression equations for preference score as a function of total distortion score and ratio score for each PAL design. Regression ANOVA is non-significant for each regression.

12.2.3.1 Preference and distortion scores across lens designs

The results discussed above show that, for an individual PAL design, subjects' preference for the lens design is not related to the distortion scores the subject gave to the particular lens design. To investigate this across all designs, data for each lens design was grouped for the log transformed preference score, distortion score A and B, and the ratio of scores. Linear regression was performed on this grouped data, with preference score as the dependent variable, and distortion score A and B and ratio of scores as the independent variable. Whilst grouping the data for individual lens designs means linear regression is not performed on wholly independent measures, this approach was taken to increase the power of the experiment.

Regression equations for the grouped data are shown in Table 12.10 below. Regression ANOVA shows significant linear relationships exist for preference score and distortion score B, and preference score with the ratio of distortion scores. The relationship between preference score and distortion score A just fails to reach significance. Scatterplots of the regression analysis are shown in Figures 12.13 to 12.15.

regression equation	r	r^2	$F_{1,47}$	p
logpref = -0.32 logdistort A + 0.68	0.269	0.073	3.596	0.064
logpref = -0.28 logdistort B + 0.69	0.33	0.107	5.514	0.023
logpref = -1.13 logratio + 0.68	0.421	0.177	9.897	0.003

Table 12.10 Regression equations for grouped PAL data. Significant relationships exist for preference score with distortion score B and the ratio of distortion scores.

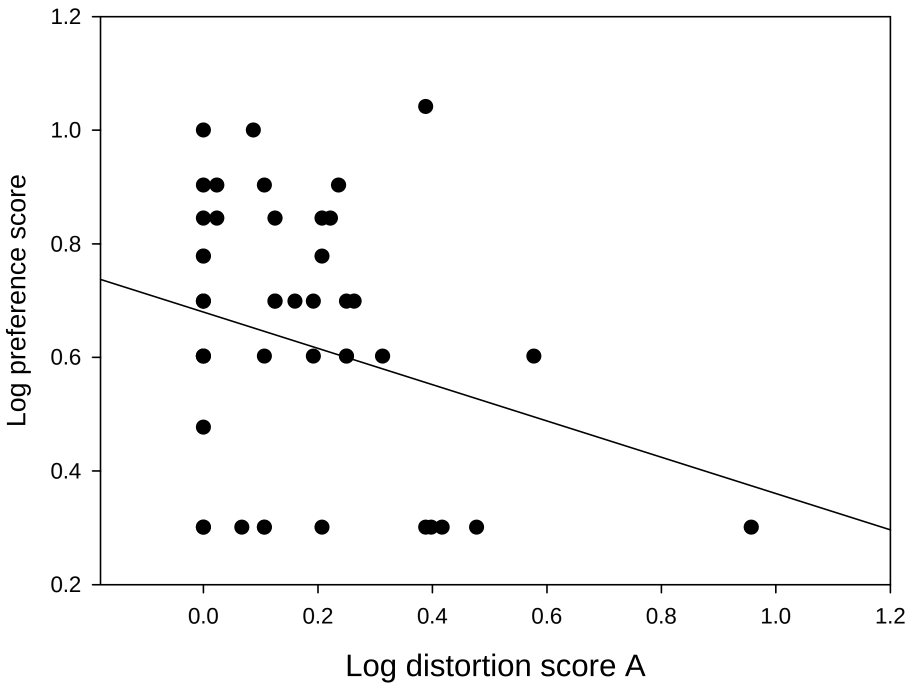

Figure 12.13 Regression scatterplot for preference score against distortion score A, grouped PAL data

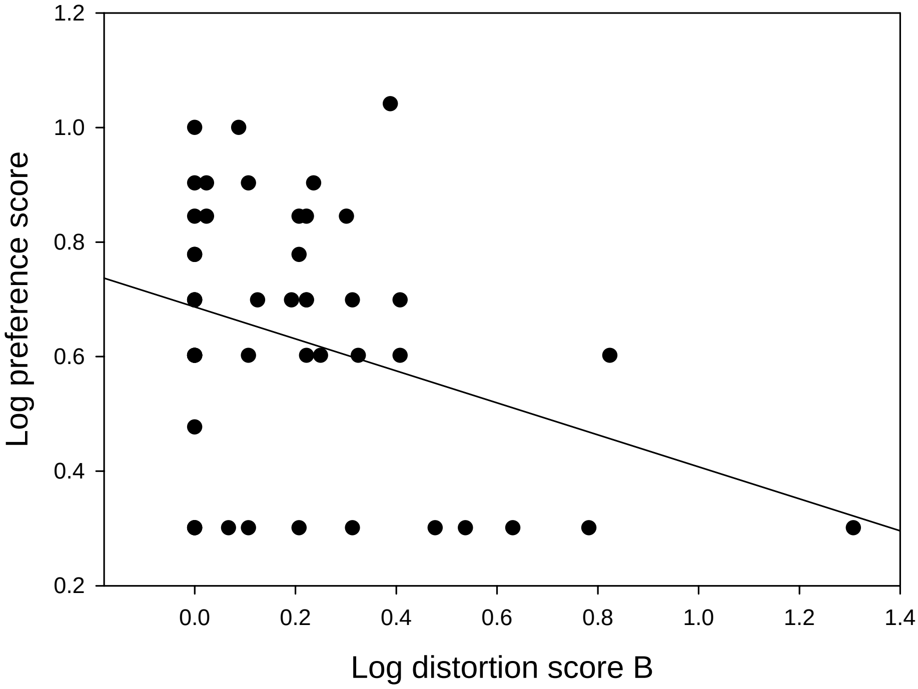

Figure 12.14 Regression scatterplot for preference score against distortion score B, grouped data

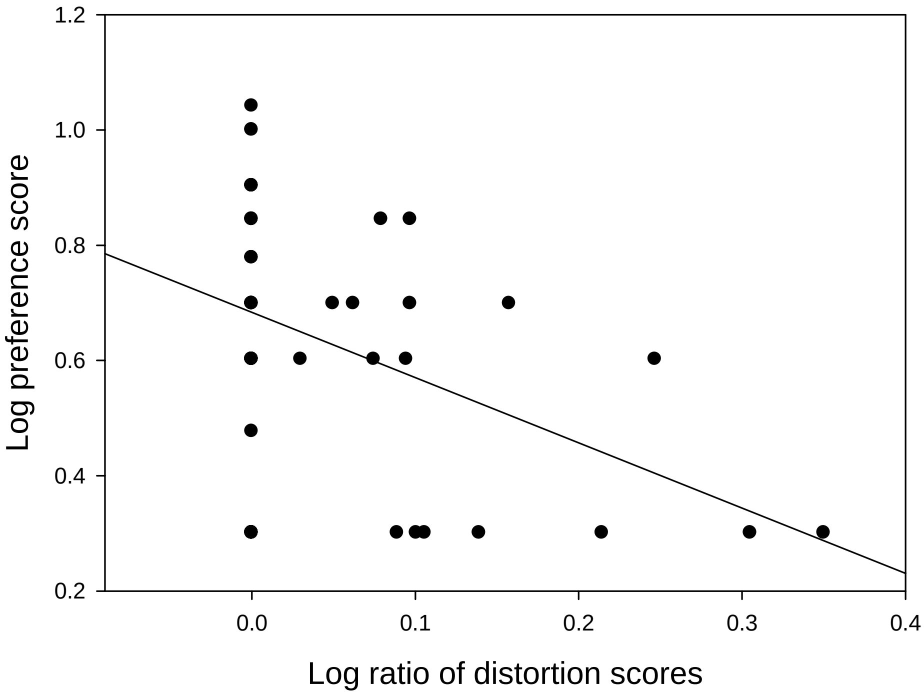

Figure 12.15 Regression scatterplot for preference score on the ratio of distortion scores. The effect of movement on symptoms of distortion is predictive of subject preference score across lens designs

Figures 12.13 to 12.15 show an outlier, the point with the lowest preference score and highest score for distortion and ratio. This subject reported marked difficulties with PAL 2 when playing tennis in comparison to the other two designs, and accordingly gave PAL 2 higher distortions scores than the other two lenses. To remove the effect of this outlier on the regression equations in Table 12.10, regression equations were recalculated with this outlier removed from the analysis. Results of the repeated regression analysis are shown in Table 12.11.

regression equation	r	r^2	$F_{1,46}$	p
logpref = -0.26 logdistort A + 0.67	0.18	0.032	1.484	0.229
logpref = -0.28 logdistort B + 0.69	0.25	0.064	3.107	0.085
logpref = -1.15 logratio + 0.68	0.37	0.14	7.19	0.01

Table 12.11 Regression equations for preference score on distortion scores and ratio of distortion scores after removal of outlier subject. In comparison to Table 12.10, a significant linear relationship is shown only for preference score on the ratio of distortion scores.

Linear regression after removal of the outlier (Table 12.11) shows preference score has a significant inverse linear relationship to the ratio of the distortion scores, with non-significant relationships for each of the two distortion score ratings; contrast this to Table 12.10 which includes the outlier subject. This indicates lens design preference relates to the effect of subject self movement on symptoms, more so than to the presence of symptoms themselves, as suggested above in Section 12.2.1.

12.3 Preference ratings, distortion scores and design differences

12.3.1 Distortion Scores and PAL design differences

Linear regression was performed to determine if any relationship existed between subjects' perceptions of spatial distortions and the dioptric powers of the three PAL designs in the superior and inferior zones of the lenses. Perception of spatial distortion was represented by the total distortion score (distortion score B; Sections 11.2.2 and 12.1.1), or the ratio of the distortion scores as the dependent variable, and inferior and superior blur strength vector power in dioptres (Section 11.1 and 12.1.2) as the independent variable. Linear regression was separately performed for each PAL design.

Scatter plots of the linear regression analysis of distortion score B and blur strength vector are shown in Figure 12.16 and Figure 12.17. Points for the individual lenses are shown on each graph. Each point represents data for one subject for each PAL design. The scatterplots show that no relationship exists between the subject's perceptions of spatial distortions and the blur strength vector power in each of the PAL designs. This lack of a linear relationship is supported by the regression ANOVA, where F ratios were non-significant for each PAL design (Table 12.12)

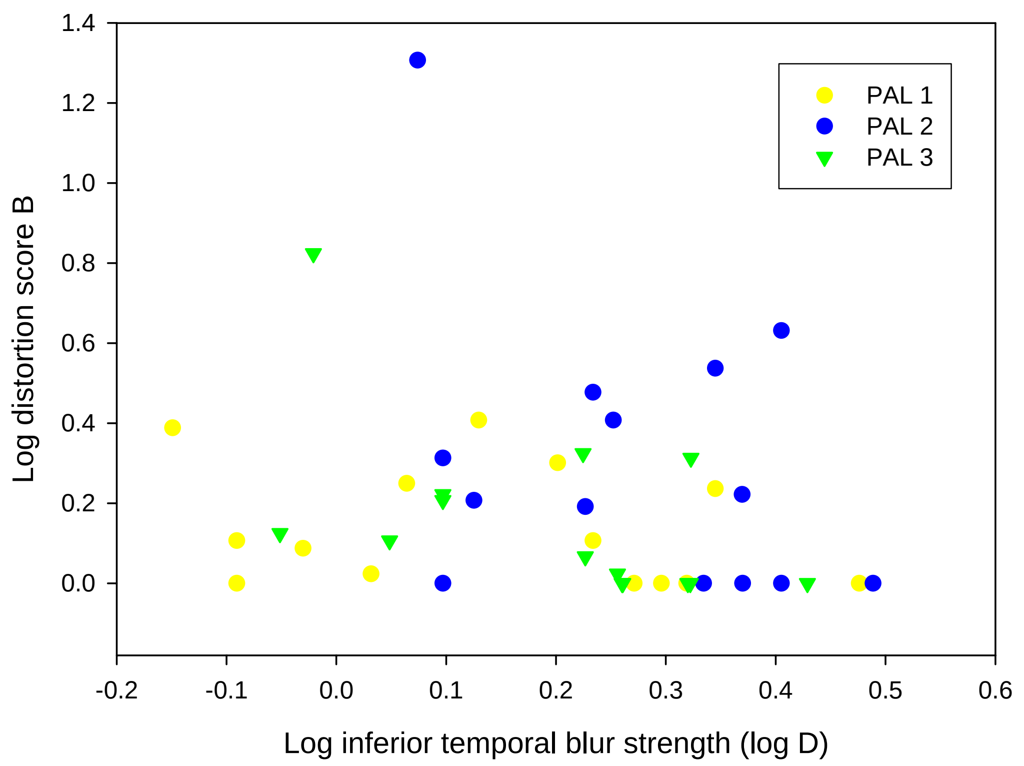

Figure 12.16 Scatterplot of total distortion score against inferior blur strength vector power

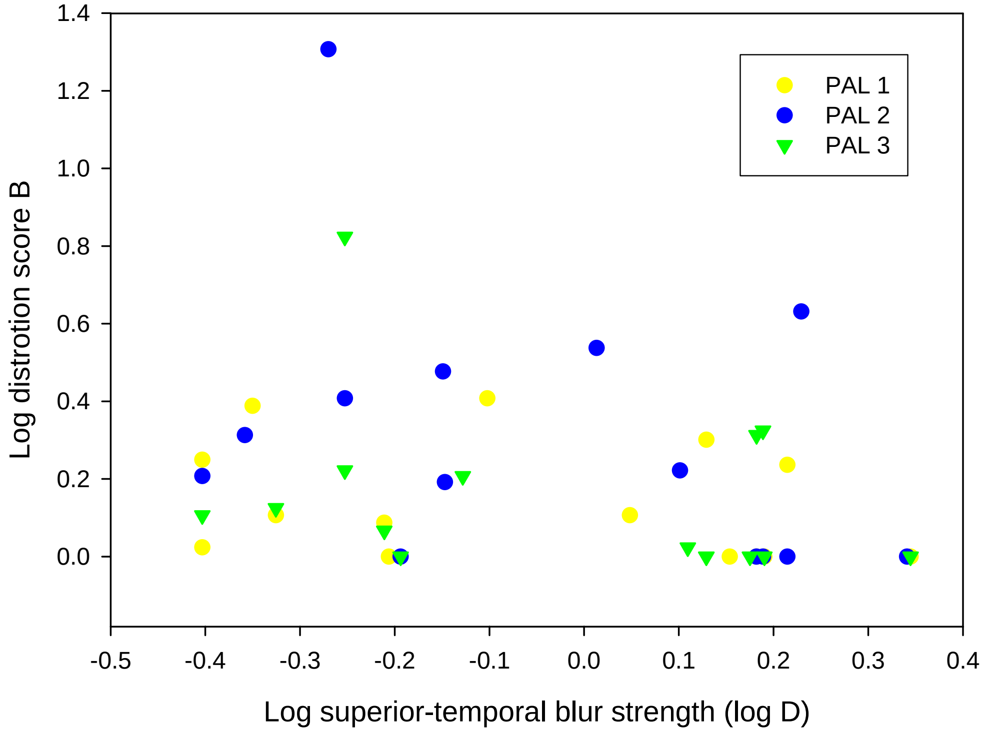

Figure 12.17 Scatterplot of total distortion score against superior blur strength vector power. Note difference in scale for *x-axis* compared to *x-axis* in Figure 12.16.

The scatterplots of distortion score against blur strength power vector show one outlier subject, with a log distortion score of approximately 1.3 for PAL 2. This subject reported that she had significant difficulty with PAL 2 compared to the other two designs when playing tennis, noticing more distortion at the sides of vision and difficulty judging the position of the tennis ball with this lens design. This outlier subject would have influenced the regression equations shown in Table 12.12 below. Removing this outlier subject from the data set and repeating the regression analyses increased p values for the revised regression equations. Points are clustered in approximate straight lines for distortion scores across the range of blur strength vector powers in scatterplots after excluding this outlier subject. Slopes of the regression lines when this outlier subject is excluded from the analysis become closer to zero for distortion score against both inferior and superior blur strength vector power for each lens design.

		Regression Equation	r	r^2	$F_{1,13}$	p
PAL 1	Inferior	log dist score = -0.81 log blur strength + 1.57	0.28	0.078	1.023	0.332
	Superior	log dist score = -0.57 log blur strength + 1.42	0.269	0.073	0.939	0.352
PAL 2	Inferior	log dist score = -1.01 log blur strength + 0.58	0.377	0.142	1.98	0.185
	Superior	log dist score = -0.54 log blur strength + 0.29	0.366	0.134	1.85	0.199
PAL 3	Inferior	log dist score = -5.06 log blur strength + 2.72	0.488	0.24	3.75	0.077
	Superior	log dist score = -1.58 log blur strength + 1.66	0.26	0.067	0.864	0.371

Table 12.12 Regression equations for total distortion score and blur strength vector power. Blur strength vector is not able to predict distortion score for individual lens designs. (log dist score = log distortion score B, log blur strength = log blur strength vector power)

Subjects' perception of spatial distortions, when represented by total distortion score, bears no relationship to the dioptric power of the peripheral zones of the PAL designs measured in this experiment.

Scatterplots for the ratio of distortion scores on inferior and superior blur strength vector are shown in Figures 12.18 and 12.19. Each point represents one data point for each subject for each PAL design. Non-linear relationships are also shown for the ratio of distortion scores and either inferior or superior blur strength vector power, supported by the non significant F ratios from the regression ANOVAs, indicated in Table 12.13. As is the case with symptoms of distortion above, ratio of distortion scores is not able to be predicted by dioptric blur in the inferior or superior temporal zones of the individual PAL designs measured in this experiment.

		Regression Equation	r	r^2	$F_{1,13}$	p
PAL 1	Inferior	log ratio = 0.005 log blur strength + 0.016	0.021	0.0005	0.006	0.942
	Superior	log ratio = 0.007 log blur strength + 0.017	0.043	0.002	0.022	0.884
PAL 2	Inferior	log ratio = -0.27 log blur strength + 0.16	0.36	0.13	1.79	0.21
	Superior	log ratio = -0.14 log blur strength + 0.08	0.342	0.12	1.59	0.23
PAL 3	Inferior	log ratio = -0.19 log blur strength + 0.07	0.398	0.16	2.26	0.16
	Superior	log ratio = -0.04 log blur strength + 0.03	0.16	0.026	0.319	0.582

Table 12.13 Regression equations for ratio of distortion scores on inferior or superior blur strength vector powers. Non-significant F ratios are found; indicating non-linear relationships for ratio of distortion scores and blur strength vector powers.

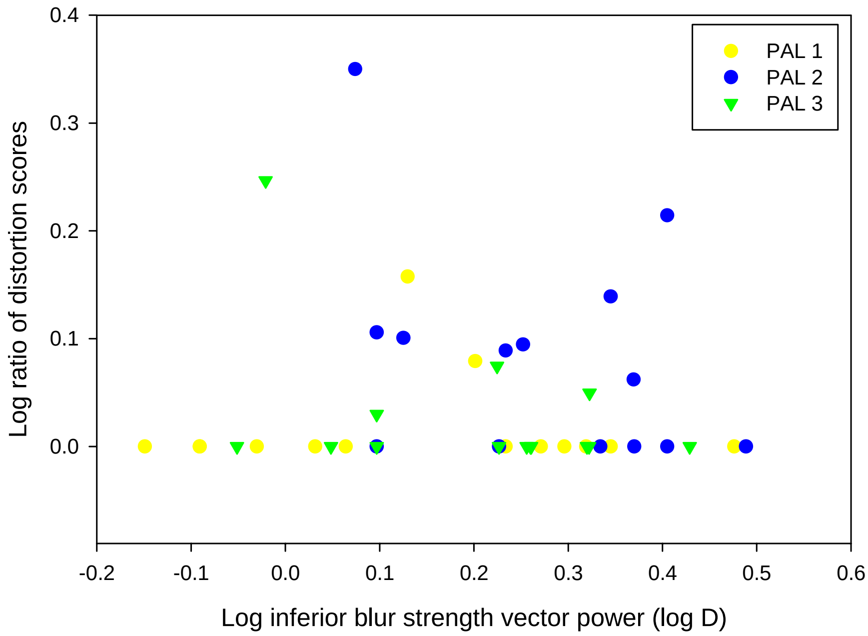

Figure 12.18 Scatterplot of ratio of distortion scores on inferior blur strength vector power. Non-linear relationships are evident

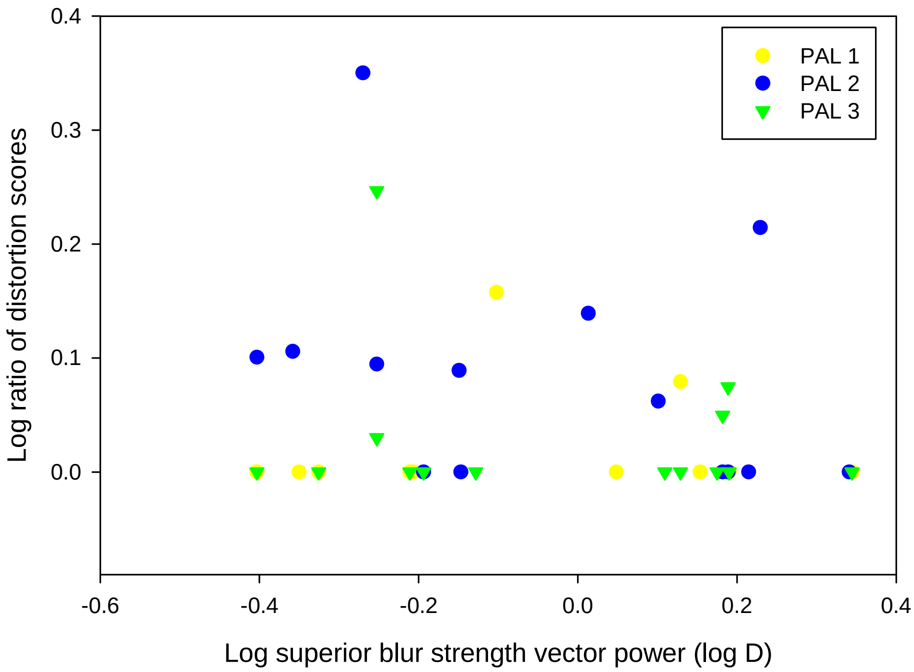

Figure 12.19 Scatterplot of ratio of distortion scores on superior blur strength vector power. Note scale of *x-axis* compared to Figure 12.18. Non-linear relationships are also evident, as in Figure 12.18

12.3.2 Preference scores and design differences

Linear regression was also performed to determine if a relationship existed between subjects' preference scores for lens designs and the blur strength vector power for each PAL design in the inferior and superior zones of the PAL. Preference score (Section 11.2.5 and 12.2.2) was the dependent variable, with blur strength vector power (Section 11.1) for the inferior and superior temporal zones of the PAL design as the independent variable; the log transformed data was used in the regression analysis. Linear regression was performed separately for each PAL design.

Scatterplots of the regression analysis are shown in Figures 12.20 and 12.21 (following pages). Each point represents data for one subject, for each PAL design. Data for all three PAL designs are shown on each scatterplot. Regression equations were calculated for preference score as a function of blur strength vector power for inferior and superior temporal zones of the three PAL designs. Table 12.14 lists the regression equations.

		Regression Equation	r	r^2	$F_{1,13}$	p
PAL 1	Inferior	log pref = -0.42 log blur strength + 0.84	0.402	0.162	2.318	0.154
	Superior	log pref =-0.21 log blur strength + 0.77	0.269	0.072	0.935	0.353
PAL 2	Inferior	log pref = 0.49 log blur strength + 0.29	0.369	0.136	1.886	0.195
	Superior	log pref = 0.20 log blur strength + 0.44	0.274	0.075	0.973	0.343
PAL 3	Inferior	log pref = -0.04 log blur strength + 0.66	0.033	0.001	0.013	0.91
	Superior	log pref = -0.02 log blur strength + 0.655	0.022	0.0004	0.006	0.94

Table 12.14 Regression equations for preference score as a function of blur strength vector power for three PAL designs.

The regression equations show that for individual PAL designs, preference score has no relationship to either inferior or superior blur strength vector power. This is also evident from the distribution of points for each PAL design in Figures 12.20 and 12.21, where points for each PAL design are scattered randomly. While preference score shows no relationship to inferior or superior blur strength vector power, Figure 12.20 shows that the PAL with the higher preference scores, PAL 1, also has lower inferior blur strength vector power than the other 2 PALs, and PAL 2, which has the highest inferior blur strength vector power, shows lower preference scores.

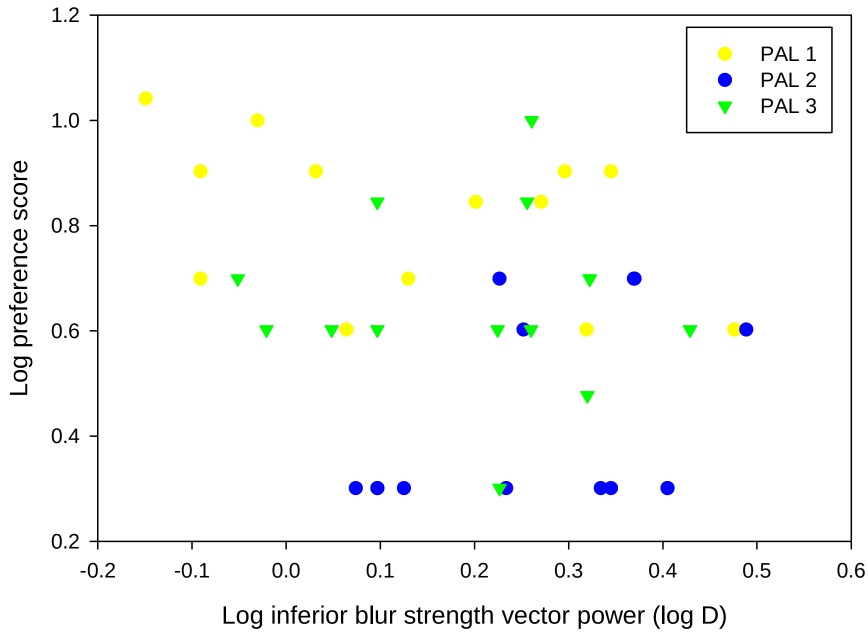

Figure 12.20 Scatterplot of preference scores against inferior blur strength vector power for 3 PAL designs; each point represents data for individual subjects for each lens design

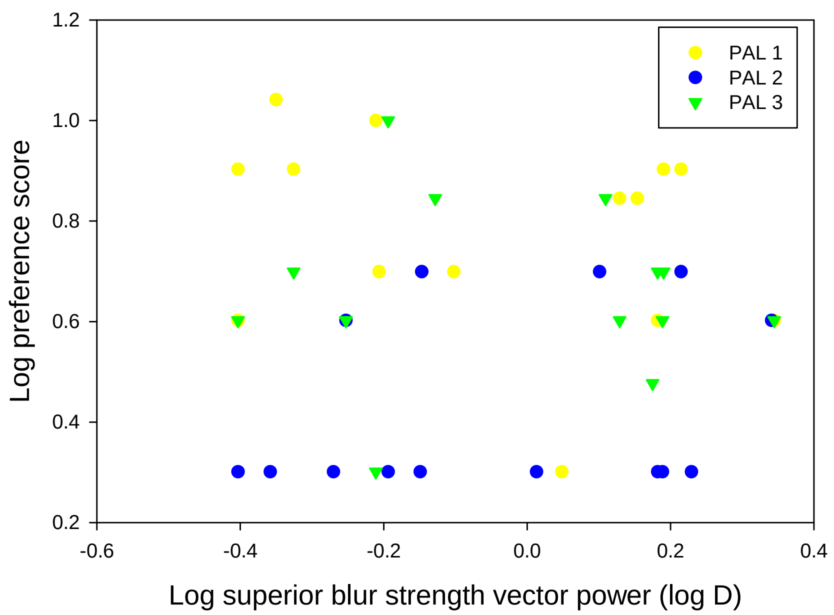

Figure 12.21 Scatterplot of preference score against superior blur strength vector power for 3 PAL designs; each point represents data for individual subjects for each lens design. Note difference in scale for *x-axis* compared to *x-axis* in Figure 12.20.

Figure 12.20 suggests a trend for lower preference score as inferior blur strength vector power increases. To investigate this, data for all subjects for all PALs was grouped together as one data set, and linear regression performed with preference score as the dependent variable and inferior or superior blur strength vector power as the independent variable. Grouping the data was done to increase the power of the analysis, recognizing that all resultant data points are not strictly independent.

Figure 12.22 shows the scatterplot preference score for all subjects plotted against inferior blur strength vector, and Figure 12.23 shows the scatterplot for preference score against superior blur strength vector power.

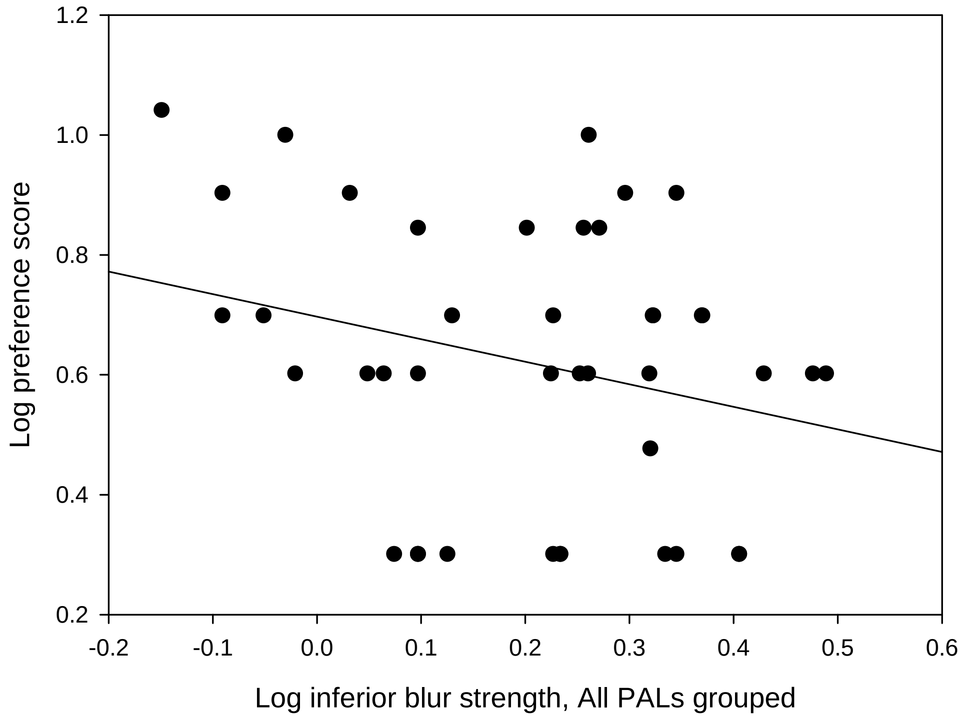

Figure 12.22 Scatterplot of combined data for preference score against inferior blur strength vector power. An inverse linear relationship between preference score and inferior blur strength is indicated.

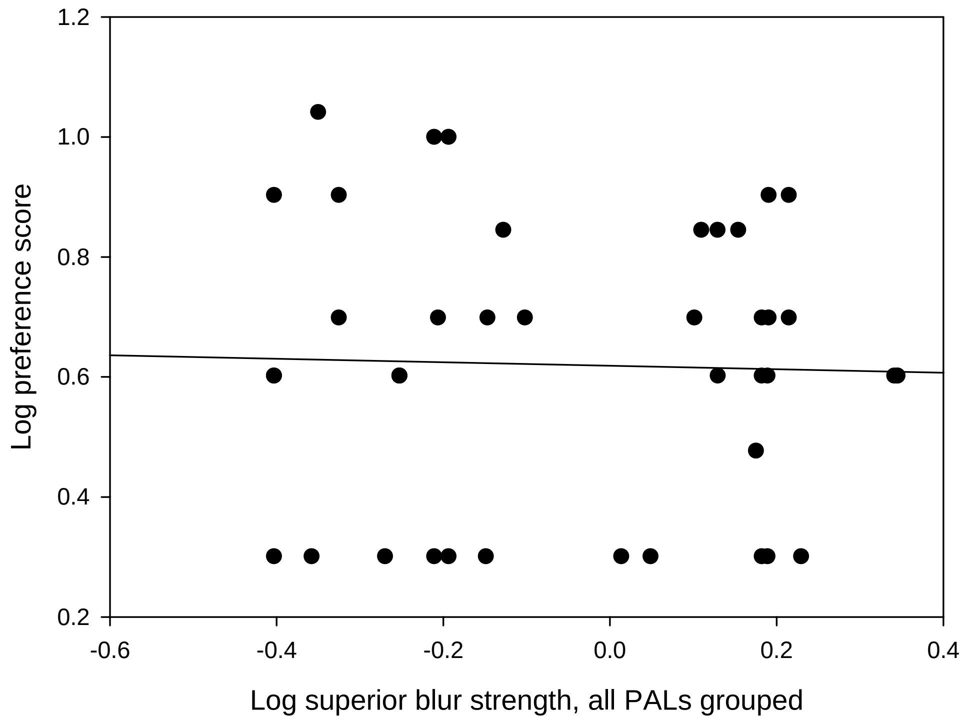

Figure 12.23 Scatterplot of combined data for preference score against superior blur strength vector power. Note difference in scale in *x-axis* compared

	Regression Equation	r	r^2	$F_{1,41}$	p
Inferior	log pref = -0.38 log blur strength + 0.70	0.267	0.071	3.064	0.08
Superior	log pref =-0.03 log blur strength + 0.62	0.031	0.001	0.038	0.847

Table 12.15 Regression equations for preference score on blur strength vector power for combined data

Regression equations from this analysis are shown in Table 12.15. For the combined data set for all PALs, there is no relationship between preference score and superior blur strength vector power, indicated by the lack of significance for the F ratio from the regression ANOVA ($F_{1,41} = 0.031$, $p = 0.847$, Table 12.15). For inferior blur strength vector power, linear regression indicates a trend for preference score to decrease as blur strength vector power increases (Figure 12.12), although the regression ANOVA shows the F ratio to fall short of significance at the $p = 0.05$ level ($F_{1,41} = 3.064$, $p = 0.08$, Table 12.15). Approximately 7% ($r^2 = 0.071$) of the variance in preference score is due to inferior blur strength vector power, suggesting that inferior blur strength may be an influencing factor in subjects' preference for a PAL design. This warrants further investigation with a larger number of subjects.

12.4 Discussion

12.4.1 Design differences

In this experiment, peripheral back vertex power was measured at two locations on the PAL, 30º temporal to the fitting cross and 10º superior or inferior to the horizontal through the fitting cross (Section 11.1). Measurement was taken by placing the peripheral locations of the PAL over the vertometer aperture stop. With this method, increased vertex distance due to eye rotation and the oblique view through the lens periphery that would occur when the PAL is worn in the normal environment is not taken into account. A number of investigations have taken this oblique view into account, whereby peripheral back vertex powers were measured on modified vertometers with rotating lens mounts which allowed simulation of eye rotation (Simonet et al. 1986, Sheedy et al. 1987, Atchison 1987). Atchison et al. (1991) have indicated that an automated vertometer, the Humphrey Lens Analyzer, gives valid measures for off-axis power of lenses with power <3D, whether used in a mode where the lens is rotated around the centre of curvature of its back surface or the centre of rotation of the eye.

Fowler and Sullivan (1989) compared measurements of peripheral off axis back vertex powers of a PAL made with a conventional vertometer (Topcon LM-6, as used in this experiment) used in two ways: with the lens slid manually across the vertometer aperture stop, as in this experiment, and secondly with the lens rotated about the centre of rotation of the eye using a rotating lens mount; and also with a surface reflection vertometer. They concluded that the three methods gave essentially similar measures of peripheral astigmatism, but only for lenses of low distance power, < 3 D. When considered with the work of Atchison et al. (1991) this indicates that the method used in the current experiment provides a valid measure of peripheral back vertex power, considering that all lenses were measured with the same technique and that the PALs used in this experiment were all of low distance power, with mean sphere distance refraction ranging from-0.75 to +2.13 (Table 12.16)

Subject	R sph	R cyl	R axis	L sph	L cyl	L axis	Add	MeansphR
1	*-2.00*	*-1.75*	*110*	*-1*	*-1.25*	*75*	*2.00*	*-2.88*
2	0.25	-0.75	15	0.25	-0.50	10	2.00	-0.13
3	*0.50*			*0.25*			*2.25*	*0.50*
4	-0.50	-0.50	40	-0.50	-0.50	170	2.25	-0.75
5	0.25	-0.50	30	plano	-0.50	155	2.25	0.00
6	*1.75*	*-0.25*	*10*	*1.50*	*-0.25*	*5*	*2.25*	*1.63*
7	1.25			1.25	-0.25	10	2.00	1.25
8	1.25			0.75			2.25	1.25
9	1.50	-0.75	5	1.75	-0.75	158	2.00	1.13
10	0.50	-0.50	100	0.75	-0.75	95	2.00	0.25
11	1.00	-0.50	40	plano	-0.50	40	2.50	0.75
12	plano	-0.25	175	plano	-0.25	20	2.00	-0.13
13	2.25	-0.25	95	2.25			2.00	2.13
14	0.75	-0.25	45	0.75			2.00	0.63
15	plano	-0.50	75	0.75	-0.50	80	2.00	-0.25
16	1.25			0.75			2.25	1.25
17	plano	-0.50	80	-0.25	-0.50	70	2.25	-0.25

Table 12.16 Range of refractive errors for subjects used in PAL design analysis. MeansphR is mean sphere error (sphere + 0.5cylinder) for R lens as used in this experiment. Modified from Table 10.1. Subjects with data in italics and greyed out excluded from this part of experiment (Section 12.1)

Previous studies have shown differences in astigmatic powers in PAL designs. Sheedy et al. (1987) investigated 10 PAL designs commonly in use in the US market at the time of their study. They investigated spherical equivalent power, astigmatic power and axis horizontally and vertically every 3° on the lens surface. They found cylindrical powers ranging from 1.50 D to 3.50D on the lenses level with the distance centre. Atchison and Kris (1993) have also shown astigmatic powers between 3D and 4 D within 25mm lateral and inferior to the distance centre. The astigmatism found in progressive lenses is related to the power of the addition (Charman 1982, Simonet et al. 1986), and also to the rate of power change along the vertex line of the PAL power progression (Minkwitz 1963, Sullivan and Fowler 1991, Sheedy 2004ab), where surface astigmatism changes twice as quickly as the rate of power change.

Simonet et al. (1986) also showed that the ratio of astigmatism to add power was constant within designs but differed between designs in the two PAL designs they studied. More recently, Sheedy (2004ab) has shown that maximum astigmatism, generally located inferiorly in the PAL, is significantly correlated to intermediate zone width. Sullivan and Fowler (1989) have also shown that astigmatism in the peripheral zones of the three designs they investigated had variable axis, being between 30º and 150º in the temporal portion of the lenses, and between either 31º and 51º or 120º to 150º nasally. Axis variations for peripheral astigmatism have also been established by Simonet et al. (1986), Sheedy et al. (1987) and Atchison and Kris (1993). This variability in astigmatic axis makes statistical comparisons of differences between lenses more difficult. The method of analysis using power vectors (Thibos, Wheeler and Horner 1997, Section 12.1) allows a statistical comparison of lens design differences, accounting for variations in astigmatic powers and axes between lenses.

When back vertex power is transformed to vector power components M, J_0 and J_{45} (Thibos, Wheeler and Horner 1997) (Section 11.1 and 12.1), vector power components are able to discriminate between lens designs used in the current study (Figure 12.1, Tables 12.1 and 12.2), particularly for all power vectors in the inferior temporal position. PAL designs showed a significant difference in the superior temporal zone for the J_0 vector only. PAL designs differed significantly for all three vector components in the inferior temporal position. PAL 2 showed significantly higher M and J_{45} vector powers than the other two PALs, with mean difference in M vector being 0.339 ± 0.225 D compared to PAL 1, and 0.251 ± 0.27 D compared to PAL 3; mean difference in the J_{45} vector was 0.303 ± 0.116 D compared to PAL 1 and 0.231 ± 0.19 compared to PAL 3. No significant difference in power vector components for superior temporal measures was found. These differences between lens designs are also evident in the iso-cylinder plots of the lens designs shown in Figures 11.1 to 11.3, where PAL 2 shows increased astigmatism in the inferior temporal half of the lens compared to PAL 1 and PAL 3. The method adopted in this experiment for measuring PAL design differences is able to discriminate between lenses, for the inferior temporal zone of the lenses as measured.

Blur strength also discriminates between lenses, with PAL 2 producing significantly more blur in the inferior temporal zone than PAL 1 or PAL 3. The three PAL designs did not differ significantly for blur strength in the superior temporal zone (Section 12.1.2). Blur strength is a readily obtainable parameter which can discriminate between lens designs, at least in the surface location of the PALs investigated in this experiment. This parameter, for lenses with low distance power, can be measured with vertometers available in clinical practice, with subsequent calculation using spreadsheets. More complex methods of assessing optical performance of PALs, such as wavefront sensing (Villegas and Artal 2006, Blendowske, Villegas and Artal 2006, Villegas and Artal 2004, Villegas and Artal 2003) are less readily available in clinical practice. The potential value of blur strength as a discriminating parameter for PAL lenses needs further investigation in a larger sample of lenses, and more locations on the PAL surface, relating this to other parameters of the optical design of the PAL.

12.4.2 Distortion scores

Perceptions of distortions were assessed by using a six item questionnaire (Section 11.2.2), with the six questions repeated in sub-sections for spatial distortions noticed with distance, intermediate or near vision. Subjects scored the presence of a particular spatial distortion on a five point scale, on its level of annoyance on a seven point scale, and whether it was more noticeable when moving about on a five point scale.

Distortion scores were derived by multiplying subject ratings of distortions on each of the three subscales for each question, and then calculating the subjects' distortion score as a ratio to a perfect score for no distortions noticed (Section 11.2.4). This was calculated separately for distance, near and intermediate, and for all three visual demands combined. Figures 12.7 to 12.9 and Tables 12.4 to 12.6 show mean distortion scores for the three PAL designs. Unit scores without variance can be seen for the question regarding "things in field of vision moving to and fro" (Q6 in the tables) across all three PAL designs at distance, near and intermediate, indicating that no subject reported this spatial distortion at any visual demand or with subject movement. A score of 1 for distortion questions indicates the distortion was not observed. Unit scores without variance were also noticed for distortion question 3 (objects moving up and down) and question 4 (objects moving side to side) for near vision, and for question 4 in intermediate vision. Scores for these questions were also minimal for distance vision. Subjects were not aware of these symptoms of illusory movement ("swim") with the lens designs studied in this experiment. The distortion symptoms that showed the highest distortion scores were for distortion questions 1 and 2, for distance, intermediate or near vision (Tables 12.4 to 12.6). Subjects mostly reported a feeling that objects were distorted (question 1) or that they had difficulty judging distance or position from other objects (question 2), rather than symptoms of illusory movement.

Whilst symptoms of “swim” are anecdotally reported to be a factor in acceptance of PALs as a mode of vision correction, the majority of studies investigating success rates in PALs compared to other modes of correction do not report on subjective symptoms of distortion. For example, Cho, Spear and Caplan (1991) investigating the effect of the power of the near addition on acceptance of PALs indicate “waviness and image distortion are the most frequently encountered symptoms….”, but do not offer evidence to support this. Clinicians also are aware of patients reporting symptoms, but frequency of such symptoms does not appear to be published. The question of what constitutes “swim” is poorly defined. This experiment defined four symptoms of illusory movement, but for the subjects within this study, and for the PAL designs used, the defined subjective symptoms of illusory movement (swim), and the effect of subject movement on perception of swim distortions are not reported by the subjects. This may result from the questions being specific and not general enough, as well as a limited subject number. Additionally, the PALs investigated are modern and the product of 50 years of design improvement, and are well fitted, potentially reducing the possibility of symptoms of spatial distortions. Two subjects only had marked symptoms, one due to a problem with an inappropriate near addition and with one subject who experienced positional difficulties with one lens design compared to the other when playing tennis.

Subjects reported more distortions being present with PAL 2, and these became more noticeable with movement. Mixed (within and between subjects) repeated measures ANOVA showed that distortion scores for *presence x annoyance* (Score A in Tables 12.4 to 12.6) were not significantly different between the three PAL designs (section 12.2.1). When the effect of subject self movement on perception of symptoms was included (Score B; *presence x annoyance x movement* in Tables 12.4 to 12.6), lens design had a significant effect on symptoms. Similarly, PAL design had a significant effect on the ratio of distortion scores (Score B/Score A), because PAL 2 had a significantly higher ratio score than PAL 1 and PAL 3. These indicates that subject movement increased the perception of spatial distortions with PAL 2, with symptoms of spatial distortion becoming more apparent with movement when wearing this PAL design compared to the other 2 designs. These results suggest that rather than the presence, absence, or the level of annoyance of a spatial distortion symptom, it is the effect of movement of the wearer on the symptoms of spatial distortion present that is able to discriminate between lens designs. Further support for this argument is provided where preference score is inversely related to the ratio of distortion scores, indicating the effect of subject self movement, more so than the presence of symptoms themselves (Table 12.11). Inclusion of questions seeking symptoms of to and fro, side to side or up and down movement of objects within subjects' field of vision is not supported by the results of the current experiment. Future studies investigating symptoms of spatial distortions and illusory movement occurring with spectacle lenses should incorporate a variable relating to the effect of self movement of the subject on reported symptoms.

Perception of spatial distortions, represented by the total (or overall) distortion score in this section of the analysis, showed no relationship to blur strength vector power in either the superior temporal or inferior temporal zone of the PAL designs (Section 12.3.1). Linear regression showed negative slopes to the regression lines of distortion score on blur strength vector power (Table 12.12), suggesting that distortion score decreases as blur strength vector power increases for each lens design, but the regression ANOVA showed non-significant F ratios. The ratio of distortion scores was also not significantly related to blur strength vector powers (Table 12.13). The hypothesis that ratings of spatial distortion observed subjectively with PALs are related to peripheral back vertex powers and also to resultant blur therefore is not supported by the results of the experiment. This lack of significance is compounded by lack of statistical power, and further investigation with a larger number of subjects would be worthwhile to determine if perception of distortions or the effect of subject self movement on symptoms is related to blur strength vector power, or to more global measures of optical characteristics of PALs. These findings indicate that a localised measure of optical characteristics of PALs is not related to symptoms of spatial distortions; this may not hold true for more global measures of optical characteristics. Adaptation and swim may be a result of poor adaptation of the VOR to the wide range of situations imposed by PALs, with their changing power profile and resultant magnification, astigmatism, prism in both monocular and binocular vision and aberrations. Individuals who show symptoms of spatial distortions and illusory movement may not be able to make necessary VOR adaptations.

12.4.3 Preference scores

Preference scores for the PAL designs were calculated from paired force choice comparisons of PAL designs (Section 11.2.5), with a higher preference score indicating a particular lens design was the more preferred lens in these comparisons. PAL design had a significant effect on preference score, with PAL 2 showing significantly lower preference scores than PAL 1 or PAL 3, with these designs not differing significantly in preference score (Section 12.2.2).

Total distortion score was not able to predict preference score for each of the PAL designs. Linear regression for preference score as a function of total distortion score A or B, and as a function of the ratio of distortion scores showed non-significant F ratios on the regression ANOVA (Section 12.2.2, Figures 12.10 to 12.12, Table 12.9). Subjects' ratings of spatial distortion did not significantly contribute to their preference for one PAL over another; thus the hypothesis that higher ratings of spatial distortion are related to lower scores for lens design preference cannot be supported.

Linear regression was also performed to determine if blur strength vector power in the superior temporal or inferior temporal zone influenced preference score (Section 12.3.2). Slopes of the regression lines are negative, with preference score lower as blur strength vector power increases for each of the PAL designs. The F ratios calculated in the regression ANOVA are however not significant (Table 12.14). Preference score is not predicted by blur strength vector power in either the inferior temporal or superior temporal zone of the PAL designs. Figure 12.20, a scatterplot of preference score against inferior blur strength vector power for each lens design indicates that the lens with the highest preference scores, PAL 1, has lower inferior blur strength values than the other lenses, and the opposite for PAL 2, which shows lowest preference scores and highest blur strength vector power.

When data for all lenses is combined, Figure 12.22, the relationship between preference score and inferior blur strength approaches significance (Table 12.11), with a trend for preference score to decrease as inferior blur strength vector power increases. Blur strength vector power is calculated from M, J_0 and J_{45} spherical and astigmatic power vectors, and as such reflects the blurring strength of the peripheral astigmatism of the PAL. Reducing peripheral astigmatism has been the developmental trend in PAL designs over time (Sullivan and Fowler 1988, Fowler 1998). Sheedy (2004a) has measured a number of optical parameters on a series of 28 lens designs available at that time in the US, and indicate that the maximum amount of astigmatism in their sample of PAL designs was significantly negatively correlated with the width of the intermediate corridor, and positively with the width of the distance zone 1mm above the fitting cross. Sheedy (2004a) also reported maximum astigmatism found on the PAL is highly correlated with degree of astigmatism at the location of maximum power progression rate, and with degree of astigmatism at the minimum zone widths. They suggest that this supports the use of the maximum amount of astigmatism on the lens as a fundamental measure of the design of the lens. Sheedy (2004b) and Sheedy, Hardy and Hayes (2006) developed these measures of optical parameters into a series of rating criteria based on the optical measures of the PAL, and have rated lenses on such factors as zone widths for distance, near and intermediate vision, and unwanted astigmatism. Their rating criteria award higher ratings (as preferred choice of lens design) to assist clinicians in selecting lenses to match patient visual needs. PAL designs with increased amounts of maximum astigmatism are awarded lower ratings. Increased astigmatism is related to a narrower intermediate corridor. This approach to lens ratings has been criticized by the optical industry, with Tahran (2004) commenting that physical measures of lenses do not predict patient acceptance of lens design in practice, and that criteria such as zone widths, whilst measurable, do not necessarily translate into lens performance.

Results of the current experiment do suggest that an optical measure of the PAL surface, inferior temporal blur strength vector power, may be a likely indicator of lens preference. Higher preference scores were awarded to PAL designs showing lower blur strength values. Other PAL design parameters which were not measured in the current experiment such as width of distance, near and intermediate zones, rate of power progression in the corridor, location of maximum add, locations of maximal astigmatism, and rate of change of peripheral power would also be expected to influence patient preference for a PAL design. These parameters are related to the degree of maximum astigmatism (Sheedy 2004ab). The use of blur strength as a likely indicator for lens preference warrants further investigation with an increased number of subjects, and with measures of blur strength from peripheral zones of other PAL lenses.

Related to the issue of blur strength as a possible indicator for PAL preference is the concept of noticeable, troublesome and objectionable blur (Atchison et al. 2005) and a related concept “bothersome blur” (Ciuffreda et al. 2006). These two studies have used a Badal optometer system to ascertain subjective limits for just noticeable blur, when blur becomes troublesome, and when blur becomes intolerable. Atchison et al. (2005) report blur limits for troublesome and objectionable blur to be 1.6 to 1.8 and 2.1 to 2.5 times greater than the limit of just noticeable blur, with just noticeable blur limits being dependent upon target size. Ciuffreda et al. (2006) report bothersome blur thresholds of between 1.02 and 1.34D for isolated letters or text respectively. Wang and Ciuffreda (2005) also report that just noticeable difference for blur discrimination is about 60% of the depth of focus (or blur detection threshold). This is similar to the ratio of troublesome blur to just noticeable blur determined by Atchison et al. (2005). These studies all however relate to foveal measures, and use spherical blur, although the concept of noticeable and bothersome blur has relevance to PALs and the peripheral astigmatism that occurs in these lenses, as well as to the occurrence of blur as the eye moves toward the edges of the distance, intermediate or near zones of the lenses. Whether these values of just noticeable blur and troublesome blur hold for cylindrical errors is not known; how they relate to cylindrical errors at different axes is also unknown (see below).

Depth of focus increases in the retinal periphery. Ronchi and Molesini (1975) assessed depth of focus in the retinal periphery from eccentricities 7º to 60º in two subjects using monochromatic spots of light subtending 4 min of arc, with defocus induced by spectacle lenses. Depth of focus was dependent upon wavelength, and ranged from 5 to 12 D for blue light and 2 to 7D for red light. Lack of distinct contours within the targets may have increased the depth of focus found, as the criterion used to determine limit of focus was loss of visibility of the target rather than the first occurrence of blur. More recently, Wang and Ciuffreda (2004) report depth of focus increasing linearly from 0.89D at the fovea to 3.51D at an eccentricity of 8^{o}, with depth of focus increasing at a rate of 0.29D/degree. Wang and Ciuffreda (2005) also show blur detection thresholds increase with eccentricity in the near retinal periphery (within 8^{o} of the fovea). They also show that the ratio of blur discrimination threshold to blur detection threshold is constant with eccentricity, at a ratio of 0.56, similar to the finding for the fovea. If the relationship between just noticeable blur and bothersome or troublesome blur also holds for more peripheral retina, increasing astigmatism in the periphery of the PAL could create blur that is apparent to the wearer as it exceeds the depth of focus. Blur created by astigmatism is dependent upon axis, with more oblique axes creating more blur (Bennett and Rabbetts 1984, Peters 1961, Eggers 1945). The measure of blur strength used in the current experiment directly relates to these meridional components of astigmatism, and, as noted above, warrants further investigation as to any relation to visual performance and hence preference for a particular PAL design.

12.5 Statistical analyses

As noted in Section 10.6.4, experimental design used a cross-over trial of three PAL designs, with the PALs worn in different wearing orders. Variables were measured for each lens design within this cross-over trial, thus warranting a within subjects and between groups repeated measures analysis; accordingly, the parametric within subjects between groups (or mixed) repeated measures ANOVA was used. No non-parametric alternative test could be used. ANOVA is robust to violations of its assumptions (Pallant 2002, Tabachnik and Fidell 2001), although the power of these experiments is somewhat reduced because of the variances in the measures studied; greater sample sizes would have been preferred for increased power. Variables were log transformed due to positively skewed distributions to better meet assumptions of normal distributions in ANOVA and linear regression. Alpha level was adjusted to allow for multiple comparisons to reduce the possibility of type II errors.

Chapter 13 Summary and conclusions

13.1 Head movements in common visual tasks

This experiment established parameters for the angular size, average and peak (maximal) velocity of head movements in two commonly undertaken visual tasks: a word-processor based text copying task, and a search task which simulates visual behaviour in a supermarket aisle for example. These two tasks required adjustments in the direction of gaze (combined head and eye movement) in both leftward and rightward directed gaze directions over similar angular extents, but with quite different visual processing demands (Chapter 6 and 7). Required maximal gaze shifts for each task were 34º in the copy task (Table 6.5) and 28º for the search task (Section 6.2.3.1). Frequency distributions showed markedly positively skewed distributions for the absolute values of head movement amplitude (Figures 7.1 and 7.6). The frequency distributions from Figures 7.1 and 7.6 were recalculated as percentage frequencies of the total number of head movements for each task: 3516 head movements in the copy task (15 subjects) and 1164 head movements in the search task (10 subjects). Five subjects completed both tasks. The percentage frequency distributions are shown in Figure 13.1 below. The frequency distributions for absolute angular extent of head movement are similar for both tasks, indicating that, for tasks requiring differing visual processing demands and similar ranges of gaze amplitudes, similar head movement strategies in terms of head movement amplitude were employed across subjects in these two tasks.

The visual task undertaken has an effect on the average and peak velocity of the head movements. Median head movement velocity in the copy task was faster than the median head movement velocity in the search task. Median average velocity in the copy task was 8.18 deg/s, and median peak velocity was 17.8 deg/s. In the search task, median average velocity was 6.16 deg/s and median peak velocity was 13.07 deg/s. The 90th percentiles for both average and peak velocities were also higher in the copy task than in the search task (Sections 7.3.2 and 7.4.2). Head movement velocity in each task was further investigated by considering the main sequence relationships (Bahill et al. 1975, Zangmeister et al. 1981, Stark et al. 1980) between average and peak velocity and head movement amplitude (Section 7.5).

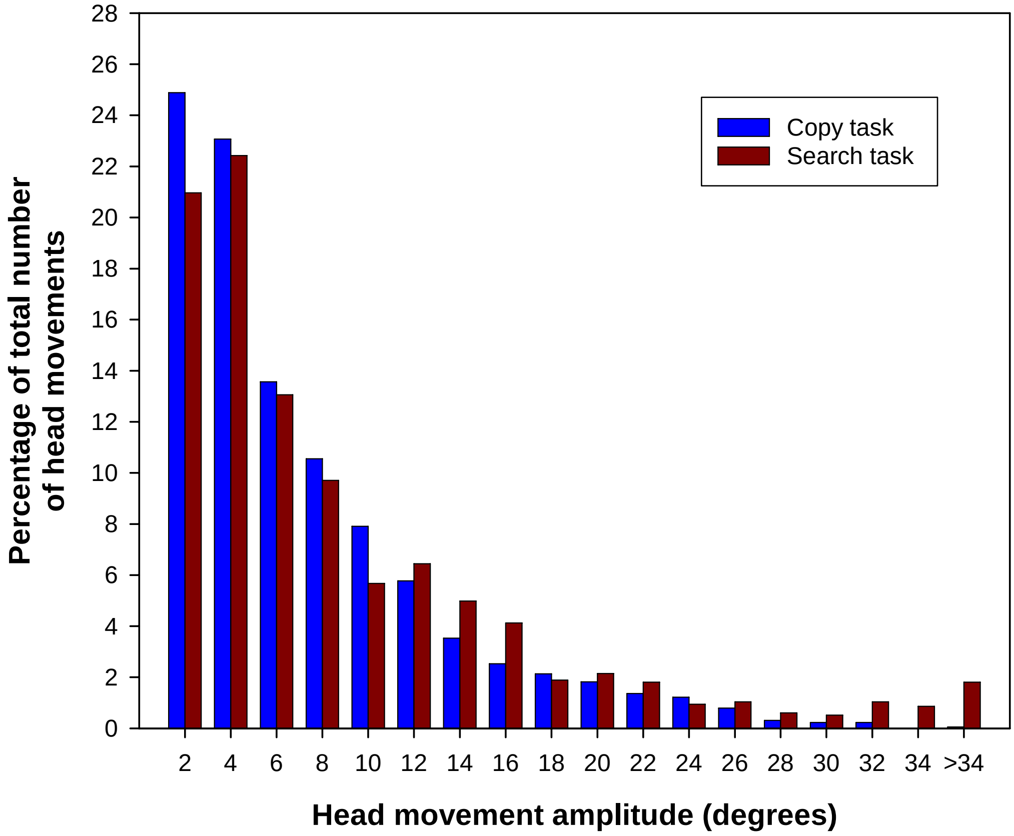

Figure 13.1 Percentage distribution of angular extent of head movement (in degrees) for two different visual tasks.

Main sequence relationships between average and peak head movement velocity with head movement amplitude also showed a task related effect on the slope of the main sequence (Table 7.9, Section 7.5). The main sequence relationships show that greater average and peak head movement velocities occur in the copy task than in the search task, suggesting a task related effect on head movement velocity, consistent with visual processing demands resulting in different head movement strategies as a component of gaze shifts. Task related effects on head movement velocity have also been demonstrated by Epelboim et al. (1985). Visual task therefore affects head movement strategy.

Head movements within tasks also reflect a dependence upon processing needs. When head movements are grouped according to the direction of head movement, rightward and leftward directed head movements in the copy task show significant differences in head movement velocity as amplitude increases, with leftward directed head movements having lower average and peak velocity than rightward directed head movements of similar amplitude (Section 7.6.1.1). This relates to visual processing demands of the task. In the copy task, subjects were required to copy text which was placed to the left of a computer monitor into a word-processing software programme. The difference found in head movement velocities between leftward and rightward directed head movements supports the hypothesis that subjects selected slower head movement strategies for leftward head movements as they needed to return to specific locations within the source text, whereas this was not necessary on the return of gaze to the keyboard or monitor where a more general landing site could be selected. It could be argued that this difference is a centripetal versus centrifugal effect, as in saccadic eye movements, where saccades directed toward the primary position are faster than those moving away from the primary position (Frost and Pöppel 1976, Jürgens et al. 1981, Inchingolo et al. 1987), as rightward head movements in this visual task would be centripetal in the main. A centripetal versus centrifugal effect is not supported by an analysis of head movement velocities for different head movement directions in the search task, where no significant difference was found between rightward and leftward head movement velocities (section 7.6.1.2), suggesting that the effect of head movement direction upon average and peak velocity in the copy task is due to visual processing requirements.

Linear relationships for the main sequence plots of peak velocity on average velocity were also found (Section 7.6.2.1). Slopes of the main sequence for peak velocity on average velocity were not significantly different for direction of head movement nor for visual task. Slopes of the main sequence were also not significantly different for the interaction of head movement direction and visual task. The main sequence for peak on average velocity illustrates the interdependency of amplitude and duration of head movement (the determinants of average velocity) and the peak velocity of the head movement, and would indicate the neural control over the optimal timing of the head movement. This is not affected by task or head movement direction. When considered with the above results showing a task related effect on average and peak velocity related to processing demands, this would suggest the visual system is able to select the head movement component of gaze shifts selectively to allow velocity strategies to suit tasks, but without affecting the optimal timing relationships of the head movement control system.

Figures 7.17 and 7.18, showing average and peak velocity plotted against head movement amplitude in groups of 3º amplitude, show a plateauing of the curve of head movement velocity against amplitude for head movement amplitudes of between 9º and 23º. This is also evident in Tables 7.13 and 7.14. The search task required subjects to detect a visual target arranged in horizontal arrays amidst confusing targets, while subjects searched for the required target; this is effectively a visual acuity task in dynamic conditions of head movement. Figure 7.17 shows a log average velocity of approximately 1.0 log deg/s, equating to an average velocity of 10 deg/s across a head movement range of 15º. If considered as a frequency of head movement, this ranges from head movement frequency of approximately 0.5Hz to 0.8Hz at each 3º head movement range interval. For head movement frequencies of 0.25 to 5 Hz, Steinman and Collewijn (1980) found retinal image speeds did not exceed 4 deg/s. Landolt C and vernier acuities are not affected by retinal image speeds of up to 2-3 deg/s (Westheimer and McKee 1978). Adopting the relatively constant velocity profile for head movement amplitudes as seen in the search task (Figures 7.17 and 7.18) would have meant subjects were able to keep retinal image movement within the ranges that do not affect visual acuity, thus maximizing performance on the task.

The experiments on head movement parameters in common visual tasks have therefore established head movement parameters for these tasks. The experiments also support the hypothesis that control of head movement velocity is influenced by visual processing demands of the task being performed.

One aspect of adaptation to PALs is learning a new head movement strategy to cope with the restricted functional fields of view induced by the optical design of the lenses (Gauthier et al. 1989, Pedrono, Obrecht and Stark 1987, Ali et al. 2000, Cuiffreda et al. 2001, Han et al. 2003ab). The experiments above show that head movement velocity is influenced by task, but that the inter-relationship between head movement velocity, amplitude and duration of head movement is not affected by task. Commencement of PAL wear may affect the velocity profile of head movements as reflected in the variables studied in the first experiment. This was investigated in the second experiment, investigating head movement parameters in a group of first time PAL wearers.

13.2 Head movement parameters in first time PAL wearers

Ten subjects, who were first time wearers of PALs, performed the search task as in the previous experiment on three occasions. Initial measures were made prior to PAL wear with the subjects' habitual mode of correction, then repeated with their PAL correction on collection of the PAL. These two measures occurred on the same day. A repeat measure was made with the PAL one month later to assess the effects of adaptation. The experimental protocol followed that of the first experiment (Chapter 6). Data for head movement amplitude, average velocity and peak velocity of head movement were extracted from the head recorder output. Main sequence relationships for average and peak velocity with head movement amplitude, and for peak velocity with average velocity were calculated as in the previous experiment.

Commencement of PAL wear, and one month adaptation to PAL wear did not alter significantly head movement amplitude, in terms of median (Section 8.3.1), interquartile range (Section 8.3.2) and 5^{th} – 95^{th} percentile range of head movement (Section 8.3.3) compared to the pre-PAL measures. This is in contrast to a number of previous studies, where PALs have been shown to alter head movements (Selenow et al. 2002, Han et al. 2003ab, Bauer et al. 2000, Jones et al. 1982, Preston and Bullimore 1998), where increased head movements have been found with PALs compared to single vision lenses, and head movement differences between PAL designs. The contrasting results between the current experiment and previous studies may relate to the type of visual tasks undertaken. Previous studies (Bauer et al. 2000, Han et al. 2003 a,b) have used text paragraphs with 9 point font at a fixation distance of 60cm with the experimental protocol designed to force the subject to use the progressive corridor of the lenses to perform the required tasks. Selenow et al. (2001) used similar experimental protocols for text placement as Bauer et al. (2000) and Han et al. (2003a,b). Jones et al. (1982) used four text formats, with 5 point to 14 point font at 45 cm. The current experiment used 18 point Helvetica font with letters subtending 22.8 min arc for capital letters and 17.8 min arc for lower case letters at

70cm, equating to a visual acuity of 0.63 logMAR (6/26) and 0.51 logMAR (6/21) respectively. Acuity demands in previous studies above ranged from 6/9 to 6/12 equivalent, a much greater acuity demand than in the current study. Depth of focus for a 6/18 acuity level was found to be 3D by Legge et al. (1987), in subjects with a dilated pupil. Atchison et al. (2005) assessed noticeable, troublesome and objectionable limits of blur using a Badal optometer system and 3 artificial pupil sizes in subjects whose pupils were dilated. They found the defocus limit for just noticeable blur for an 0.6 logMAR letter to be approximately ±0.50D (from their Figure 3a), and for troublesome blur the limit to be 1.6 to 1.8 times larger. Ciuffreda et al. (2006), in a similar experiment, assessed bothersome blur, with results equivalent to the noticeable blur criteria of Atchison et al. (2005). Ciuffreda et al. (2006) also assessed bothersome blur in a subgroup of 3 absolute presbyopes, and found a bothersome blur limit of 1.50 to 1.75D, using a 20/50 letter or text sample (equivalent to 6/18, logMAR 0.48). Subjects in the experiment in this thesis did not necessarily have to use the PAL corridor or intermediate zones to recognize targets in the search task, given target size and the limits of defocus causing blur. If this was the case, PAL wear would not have influenced head movement behaviour. Afanador and Aitsebaomo (1982) investigated eye and head movement behaviour in pre-presbyopic subjects and presbyopes wearing PALs. They found the range of eye movement that occurred before head movement occurred in both subject groups to be similar. Their experiment required subjects to fixate lights spaced 2º apart. Their findings can also be interpreted as indicating that, in an experiment where the visual demand did not necessitate accurate foveal fixation thus not requiring use of the zones of the PAL to recognize the target, head movements were not made to any greater extent in PAL wearers, as in the current experiment.

Head movement average and peak velocity, and the range of velocities (evidenced by the interquartile ranges and the 5th to 95th percentile range) were not significantly different across the three measurement trials (Section 8.4); this indicated that head movement velocity was not affected in first time PAL wearers. Slopes of the main sequence relationships between average and peak velocity with head movement amplitude, and for peak velocity and average velocity were also not significantly different across measurement trials.

Data within this experiment showed significant variability within and between subjects in the measures of head movement amplitude and velocity. The 95% confidence intervals for differences between amplitude and velocity between measurement trials are also wide compared to the mean differences. This variability may have masked differences owing to sample size. Further investigation with a larger number of subjects would be required before the hypothesis that PAL wear increases head movement velocity and its variability can be rejected. Future experiments should also include differing levels of task demand, so that the differences in result between the current experiment and previous studies can be further investigated. Task (and visual acuity) demand influences head movement behaviour as suggested by the current experiment.

As in the first experiment (Section 13.1 above), plots of average and peak velocity against head movement angle in 3º intervals (Figures 8.5 and 8.9) show a similar flattening of the central portion of the curve as in the search task experiment. This lends further support to the theory above that head movement velocity is optimally selected in this range of head movement amplitudes to allow retinal images speeds to be insufficient to degrade visual acuity in the dynamic task requirement. To confirm this, repeat experiments with the inclusion of eye movement recording in addition to head movement recording to allow assessment of the VOR and hence retinal slip velocities would be required.

13.3 Minimum displacement thresholds

In this experiment, minimum displacement thresholds were measured with random dot stimuli at three locations in the visual field, under two measurement conditions, with the head static and with the head moving in approximate sinusoidal motion in a horizontal plane (Chapter 9). Minimum displacement thresholds were firstly measured with a single vision lens with the subject's distance spectacle prescription, and then with three PAL designs, after a two week wearing period, in a cross-over trial design. Measurements were made monocularly with the subjects right eye, the left being occluded. Minimum displacement thresholds were determined in foveal fixation, with the subject directly fixating the random dot target, and at two locations in the right temporal visual field, at 30º temporal and ±10º vertical to the horizontal midline to eye level. Data were analysed by a within subjects/between groups (mixed) repeated measures analysis of variance, with minimum displacement threshold as the dependent variable, and lens type (4 levels) and head movement (2 levels) as the independent factors, and lens wearing order (3 levels) as the between groups factor.

Results showed that minimum displacement thresholds, either with the head static or with the head moving in sinusoidal motion, were not significantly affected by PAL wear for central measures (Section 10.3.1), nor in the inferior temporal field (Section 10.3.2) and the superior temporal field (Section 10.3.3). PAL wearing order also had no effect on minimum displacement thresholds. Minimum displacement thresholds in the inferior and superior temporal visual fields were higher in PALs than with the single vision lens, under all conditions of measurement, but this difference was statistically non-significant.

Head movement significantly increased minimum displacement thresholds across all lens designs and locations in the visual field. Head movement increased minimum displacement thresholds by about 1 min arc in central measures (Table 10.4), 2.9 to 3.9 min arc infero-temporal (Table 10.7) and 3.2 to 4.5 min arc superior temporal. The effect of head movement on minimum displacement thresholds was further investigated by calculating the ratio of the minimum displacement threshold with the head moving to the threshold with the head static (Section 10.4). This ratio of thresholds indicates the change in threshold induced by head movement from the head static baseline. Head movement increased minimum displacement threshold from 44% to 77% across all lens designs (Table 10.111, Figure 10.4). Data for ratio of thresholds was analysed by a within subjects-between groups repeated measures ANOVA with ratio as the dependent variable, with lens design (4 levels) and location in visual field (3 levels) as the independent factors, and PAL wearing order (3 levels) as the between subjects factor.

The ratio of minimum displacement thresholds did not differ significantly between the single vision lens and three PAL designs, and there was no effect of wearing order. Location of the measurement in the visual field had a significant effect on the threshold ratio, post-hoc t-tests showing this to be due to a significant difference in ratio between the central and inferior visual fields, with the ratio being lowest in the inferior visual field. There was no significant interaction effect between location of the threshold measures and lens design, indicating that the ratio of minimum displacement thresholds was lower in the inferior field across all lens designs (Figure 10.4).

The results discussed above show that minimum displacement thresholds were not significantly different between a single vision lens as control, and three PAL designs. The hypotheses that PAL wear increases motion detection threshold in the peripheral field, and that motion detection threshold is a measure of visual function sensitive to differences in PAL design is not supported by the results of this experiment.

To determine if differences in minimum displacement thresholds occur between single vision lens and progressive addition lenses, data for all PAL lenses were grouped (Section 10.5). Minimum displacement thresholds were compared for the inferior and superior temporal areas of the visual field, with the head static and with the head moving. The ratio of minimum displacement thresholds was also compared. Differences were compared with independent t-tests, with a Bonferroni adjustment for multiple comparisons.

Minimum displacement thresholds were higher in PAL lenses compared to single vision lens (Table 10.14 and Figure 10.5). This difference however was not significantly different for either the head static or head moving condition (Table 10.15). Minimum displacement thresholds were measured in this experiment in localised areas of the visual field; results indicate that these localised measures are not influenced by lens design, neither between the PAL designs studied nor between PALs and the single vision lens control. The ratios of minimum displacement thresholds were higher in the superior temporal field than the inferior temporal field for both single vision and PAL lenses (Figure 10.6 and Table 10.16), but differences between the single vision lens group and the PAL group were not significant for either inferior and superior temporal field. Head movement increased minimum displacement thresholds between 44% and 62% compared to head static measures in both lens groups. The ratio of minimum displacement thresholds is higher in the superior temporal field than the inferior temporal field in both the single vision lens group and the PAL group; variability of the ratio is also higher in the superior temporal field. This difference could relate to the anisotropy between superior and inferior retina in detecting the direction of vertical motion (Naito et al. 2000), where the extrastriate cortex has a directional preference for downward movement in the superior field whereas no such difference exists in the inferior field. This preference may have increased variability of subjects responses, influencing thresholds; other issues such as attentional and processing demands created by the experimental conditions potentially affecting variability may also play a part in this difference (Section 10.6.3). The difference in the ratio of minimum displacement thresholds between superior and inferior visual fields may also relate to an intrinsic difference in the processing of motion between the two halves of the fields; further investigation is required to test this hypothesis.

In the only other report of motion thresholds in the presence of head movement (Patel and Bedell 2002), motion thresholds were measured with and without voluntary head movement at a frequency of 1.5Hz. They found mean motion threshold for a 3.3 sq degree random dot target increased from 0.7 deg/s in head static measures to 1.5 deg/s in head moving measures, a two-fold increase. Subjects in the current experiment were required make a 10º head movement within a 700 ms interval (Figure 9.2), resulting in a head movement frequency of 0.7Hz. In the current experiment, head movement increased minimum displacement thresholds by approximately 50%. This suggests the effect of head movement on motion thresholds is frequency related. Further investigation with a range of head movement frequencies is warranted to investigate the effect of head movement frequency on minimum displacement thresholds. Any such experiments however should use methods of inducing head movement other than subjects' making voluntary (active) head rotations, to minimize effects of subject fatigue and variability in response (Section 10.6.3).

13.4 Measures of PAL design differences

Astigmatism found in the peripheral regions of PALs can be significant in its magnitude (Sheedy et al. 1987, Atchison and Kris 1993), and is related to the power of the reading addition (Charman 1982, Simonet et al. 1986) and to the rate of power change along the vertex line of the PAL power progression (Minkwitz 1963, Sullivan and Fowler 1991, Sheedy 2004ab). Peripheral astigmatism in PALs also is variable in its axis (Sullivan and Fowler 1989, Simonet et al. 1986, Sheedy et al. 1987, Atchison and Kris 1993).

The experiment described in this thesis has analysed peripheral power differences in three PAL designs by measuring back vertex power in three locations on the PAL surface: the distance power circle used for verification of lens power, and at 30º temporal and ±10º to the horizontal axis through the fitting cross of the lens; these latter two locations being 15.6mm and ±2.75mm across the surface of the lens from the fitting cross. Back vertex powers were converted to the power vectors M, J_0 *and* J_{45} according to the method of Thibos, Wheeler and Horner (1997) (Section 11.1). These power vectors reduce back vertex power to three variables which can be subject to statistical analysis (Thibos, Wheeler and Horner 1997, Raasch 1995, Thibos and Horner 2001), which is not easily performed with the standard clinical expressions of sphero-cylindrical power and axis. Power vectors are able to discriminate between PAL designs, in the regions of the PAL investigated in this experiment, with statistically significant differences being found between lens designs for the power vector components (Section 12.1).

Blur strength power discriminates between PAL designs. No significant difference was found for superior temporal blur strength power between the PAL designs (Figure 12.2) with one-way repeated measures ANOVA with lens design as the independent variable. Blur strength power was significantly different in the inferior temporal zone, with PAL 2 producing significantly more blur in the inferior temporal zone than either PAL 1 or PAL 3, which were not significantly different from each other (Section 12.1.2, Table 12.3).

Blur strength vector power is a parameter which can discriminate between lens designs, at least in the locations on the PAL surface studied in this experiment. The potential value of this parameter in discriminating between lens designs needs investigating with a larger sample of lenses, and in more locations on the PAL surface, and relating blur strength to other parameters of the PAL design. Construction of blur plots may be an alternative method to the traditionally used astigmatic power contour plots in describing lenses. Additionally, blur strength vector power can be readily calculated in clinical settings for moderate lens powers, with the assistance of a vertometer and a spreadsheet.

13.5 Distortion scores

Subjects rated their perceptions of spatial distortions and symptoms of illusory movement (swim) on Likert scales, which scored distortions and swim symptoms in terms of presence, level of annoyance of the symptom, and the effect of subject self movement on the symptoms. Two distortion scores were derived from these questionnaire scales, one for the presence x annoyance of the symptom (Score A), and the second including the effect of subject self movement (Score B) (Section 11.2). Scores were calculated separately for distance vision, intermediate vision and near vision; and an overall distortion score.

Subjects reported more distortions present with PAL 2, and these became more noticeable with movement. Within subjects and between groups repeated measures ANOVA showed that distortion scores were significantly different between the three PAL designs studied, but only for score B, which incorporates the effect of subject self movement on symptoms (Section 12.2.1).

The ratio of distortion scores was calculated as the ratio of the distortion scores including the effect of movement to the distortion score without the effect of movement. The higher this ratio, the more the subject noticed the distortions; with a unit value indicating subject self movement did not make distortions more noticeable. Lens design had a significant effect on this ratio, with this due to a significant increase in the ratio of distortion scores with PAL 2 compared to PAL 1 or 3. The effect of subject self movement on the subjects perception of spatial distortions discriminates between lenses. This finding, and that for Score B (above) suggests that rather than a symptom of a spatial distortion or of illusory movement being present or not, or how annoying this may be, it is the effect of the subject’s self movement that is the discriminating variable. This has impact on studies investigating adaptive symptoms with PALs, in that questionnaires investigating adaptive symptoms should include a variable relating to the effect of subject self movement on reported symptoms.

Symptoms questionnaires used in this experiment also showed unit scores without variance for some of the symptoms of illusory movement (swim) that were investigated. Unit scores indicate that no subject reported these symptoms as being present. For example, no subject reported things in the field of vision moving to and fro (question 6, Section 11.2.2) at distance, intermediate or near vision; unit scores without variance were also seen for question 3 (up and down movement in the field of vision) and question 4 (side to side movement) in near vision (Tables 12.4 to 1.6 and Figures 12.7 to 12.9). Scores for these questions were also minimal for distance vision. These questions sought particular aspects of illusory movement (swim) that were not reported by subjects with the PAL designs used in this experiment. This means either the lens designs did not induce these particular symptoms of illusory movement, or the description of the symptoms is not specific enough to visual symptoms experienced by subjects.

The perception of spatial distortions also showed no relationship to blur strength vector power for both inferior and superior temporal zones of the PALs (Section 12.3.1, Figures 12.16 and 12.17), with regression ANOVAs resulting in non significant F ratios. The hypothesis that symptoms of spatial distortion and illusory movement relate to optical factors of the PAL design is not supported.

13.6 Preference scores

Subjects wore the three PAL designs on a crossover wearing trial, with a two week wearing period for each lens. Subjects made forced choice comparisons between lens designs, indicating a preference and the strength of the preference for one design over another for each of the combinations of lens designs (1-2, 1-3, 2-3) (Section 11.2.5). Preference scores were generated from these forced choice comparisons, with a higher preference score indicating the more preferred lens. Repeated measures analysis of variance showed a significant effect of lens design on preference score (Section 12.2.2), with PAL 2 having significantly lower preference scores than the other two designs, which were not significantly different. Preference scores were not able to be predicted from distortion scores, including the effect of subject self movement, for an individual lens design (Figures 12.10 to 12.12, Table 12.9). However, when data for all PALs were grouped, preference scores show a significant inverse linear relationship to the ratio of distortion scores, with preference score decreasing as ratio of distortion scores increases (Figure 12.15, Table 12.11). This supports the argument above (Section 13.5) that the effect of subject self movement on perceived symptoms of distortion is the important factor in determining lens preference.

Within individual lens designs, preference score was also not able to be predicted from either inferior blur strength vector (Figure 12.20) nor superior blur strength vector power (Figure 12.21), where regression ANOVA resulted in non-significant F ratios for each lens design. Figure 12.20 though suggests a trend for lower preference score as inferior blur strength vector increases. When data for all PALs were grouped, preference score shows an inverse linear relationship to inferior blur strength vector power, with the regression ANOVA falling short of significance at $p = 0.08$.

Results of this experiment indicate that an optical measure of the design of the PAL, blur strength vector power is able to discriminate between lens designs, and is a potential indicator for lens preference, with higher preference scores being awarded to PAL designs with lower blur strength values in the inferior temporal visual field. This warrants further investigation with a larger number of subjects to increase the power of the analysis, and with measures of blur strength from other peripheral zones of PAL lenses.

13.7 Summary of findings

The main findings of the experiments described in this thesis are outlined below

1. Parameters for amplitude, average and peak velocity of head movement, and the linear relationships between amplitude and velocity have been established for two commonly undertaken visual tasks
2. Visual task and processing demands have an effect on the average and peak velocity of head movement, and on the slopes of the main sequence

regressions of average and peak velocity with amplitude of head movement; indicating selective control of head movement velocity in differing processing demands. Task and processing demands do not influence the relationship between average and peak velocity of head movement.

3. The commencement of PAL wear in first time PAL wearers had no significant effect on amplitude or velocity parameters of head movement, in contrast to previous studies. This finding may relate to the visual task undertaken in this experiment.
4. Minimum displacement thresholds were not significantly different for either head static or head movement measurement conditions between single vision and PAL designs; thus minimum displacement threshold is not a measure of visual function that is sensitive to PAL design, in the lenses studied in this experiment
5. Head movement increases minimum displacement threshold by approximately 45-75% in both central and peripheral temporal visual field; with a greater effect of head movement in the superior temporal field
6. A method to statistically compare PAL designs is developed, with blur strength vector power being a potential discriminating variable between lens designs
7. Subjective ratings of spatial distortions and illusory movement were not significantly different between lens designs, nor were they related to blur induced by peripheral zones of the lenses.
8. The effect of subject self movement on reported symptoms of distortion appears to be a discriminator between PAL designs, rather than the symptoms themselves.
9. Blur strength vector power in the inferior temporal visual field may be an indicator of subjects' preference for a PAL design

13.8 Further work

Experimental measures showed wide variability, both within subjects and between subjects, thus affecting comparisons due to insufficient power in the analyses. Repetition of experiments with increased numbers of subjects would be worthwhile to:

1. further investigate task demand and processing demand effects head movement velocity in a larger number of subjects undertaking the same tasks
2. confirm or reject the hypothesis that PAL wear increases head movement velocity
3. investigate blur strength as a discriminating parameter for PAL designs over a larger number of lens designs, and for an increased number of peripheral zones of PALs
4. investigate blur strength as a predictor variable for preference for one PAL design over another

Additionally, further experiments could:

1. include eye movement recording in addition to head movement recording to investigate retinal slip velocities in visual search type tasks to test the hypothesis that head movement velocity for a given head movement amplitude is selected to optimize visual performance in a dynamic task
2. include differing levels of task demand in investigating head movement parameters in PAL wear, as results suggest differences in the effect of PAL wear on head movement parameters dependent upon demand of task used.

Appendix A Calibration trials, head movement recorder

Calibration of the head movement recorder for both the copy task and the search task was established by mounting the sensor cube of the recorder on a rotating protractor, and recording position of the sensor cube in relation to the transmitter cube for a sequence of leftward and rightward rotations of 10º and 20º, followed by a return to the zero position after each rotation. The rotating protractor was placed in the approximate head position which would be used by subjects during the experiment. The zero reference point of the head movement recorder was set at the commencement of the calibration trial. The head movement recorder output leftward rotation and upward elevation as negative values (Section 6.1), and data for azimuth were plotted against elevation. Mean and standard deviation of azimuth data were calculated for each rightward or leftward rotation, and for the zero rotation position.

A.1 Calibration in the copy task

Figure A.1 illustrates the head movement recorder output for the 10º and 20º rotations, with the rotating protractor positioned as for the subject position in the copy task.

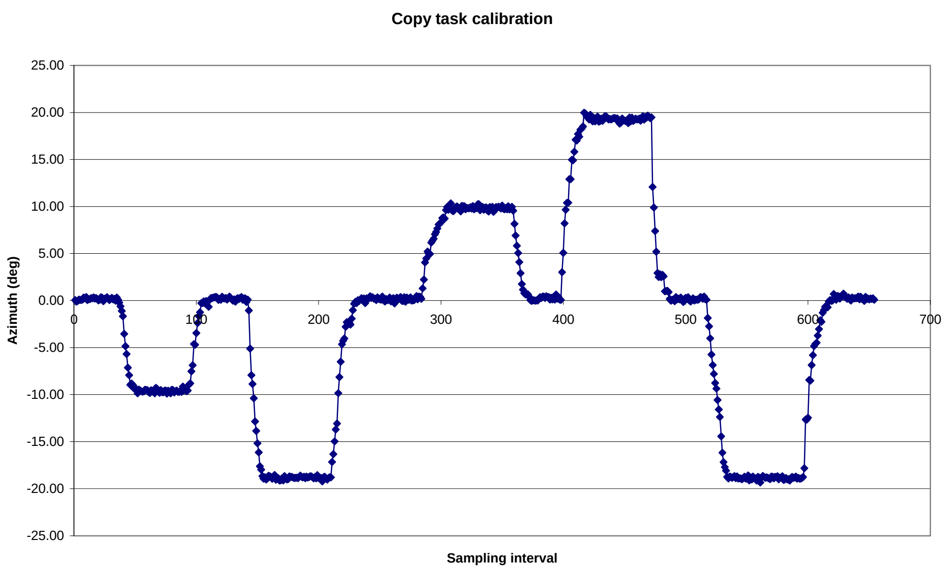

Figure A.1 Head movement recorder output for copy task calibration. Downward deflection for azimuth (negative values) is leftward rotation. Position is underestimated for 20º rotation.

The head movement recorder output is zero when the rotating protractor was in its zero position, and is very close to 10º for a 10º sensor rotation, but shows a slight under estimate in output for the 20º sensor rotation. Means and standard deviations for the head movement recorder output for each of the 10º and 20º rotations are shown in Table A.1 below.

Theoretical position	Mean of azimuth values	Difference in means	Sampling point range
initial zero	0.16 ± 0.13		0 -35
10º left	-9.60 ± 0.16	-9.76	48 - 92
2nd zero position	0.12 ± 0.23		103 -141
20º left	-18.83 ±0.14	-18.95	154 - 207
3rd zero position	0.16 ± 0.17		231 - 283
10º right	9.85 ± 0.20	9.69	307 - 349
4th zero position	0.21 ± 0.18		372 - 397
20º right	19.33 ± 0.23	19.12	416 - 471
5th zero position	0.12 ± 0.14		487 - 507

Table A.1 Means and standard deviations of head movement recorder output for 10º and 20º rotations. Negative values indicate leftward movement. Difference in means indicates extent of measured rotation

Head movement recorder positional accuracy in azimuth (i.e. for horizontal positioning) is within 0.25º of the zero alignment position, and within 0.4º for 10º rotations and within 1º for 20º rotations. The head movement recorder is therefore accurate for horizontal head position to within 1º or less of actual position. The head movement recorder output however is inaccurate for vertical head positions; Figure A.2 shows a 2-3º vertical alignment error for head position at 10º or 20º leftward rotation, and 2-5º vertical error for rightward rotation. Horizontal head position only was therefore studied in the experiment (Chapter 6-8).

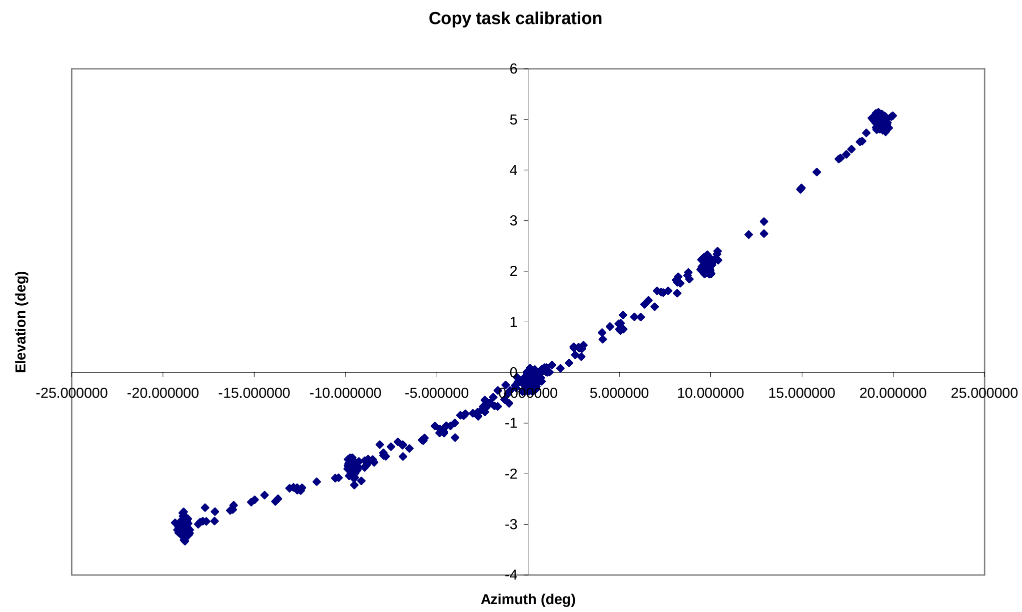

Figure A.2 Head movement recorder output for elevation plotted against azimuth, for calibration in the copy task. Vertical position error is evident for horizontal movement to 10º and 20º extent.

A.2 Calibration in the search task

Calibration in the search task was investigated in the same manner as above. Figure A.3 below shows head movement recorder output for 10º and 20º leftward and rightward rotation of the sensor cube mounted on the rotating protractor, which was positioned as for subject position in the search task. Head movement recorder output approximates zero for the expected zero position of the sensor cube, but underestimates position for both 10º and 20º rotations, with this underestimate larger at the 20º rotation position.

Means and standard deviations of the recorder output were calculated for the 10º and 20º leftward and rightward rotations, and for each of the intervening zero positions. These are shown in Table A.2 (below)

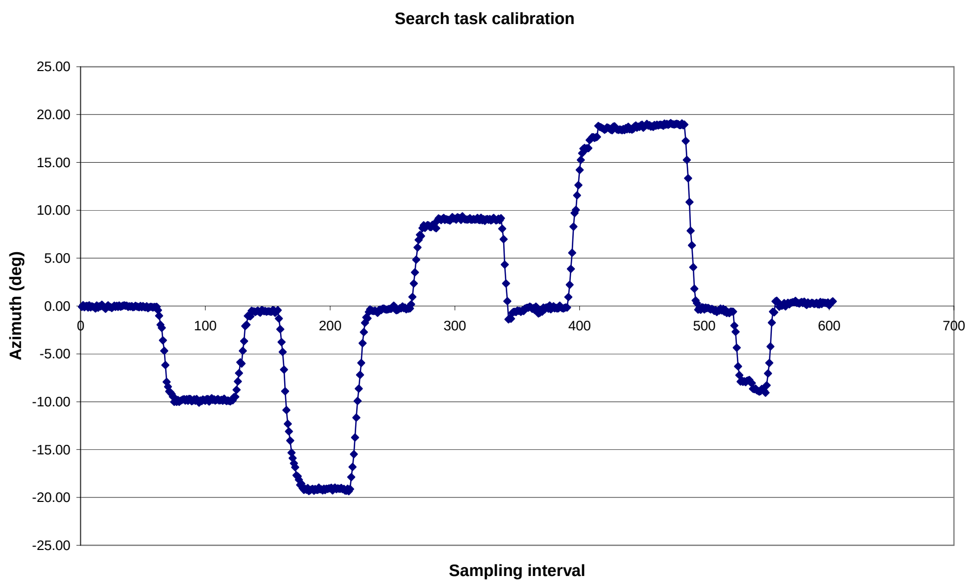

Figure A.3 Head movement recorder output for search task calibration. Downward deflection for azimuth (negative values) is leftward rotation. Position is underestimated for 20º rotations.

Theoretical position	Mean of azimuth values	Difference in means	Sampling point range
initial zero	-0.06 ± 0.03		0 - 60
10º left	-9.84 ± 0.11	-9.78	74 - 121
2nd zero position	-0.54 ± 0.06		136 - 154
20º left	-19.20 ± 0.15	-18.66	175 - 215
3rd zero position	-0.32 ± 0.17		231 - 264
10º right	9.02 ± 0.23	9.34	281 - 330
4th zero position	-0.24 ± 0.18		355 - 389
20º right	18.75 ± 0.21	18.89	415 - 483
5th zero position	-0.45 ± 0.16		500 - 522

Table A.2 Means and standard deviations of head movement recorder output for 10º and 20º rotations. Negative values indicate leftward movement. Difference in means indicates extent of measured rotation

The head movement recorder output for 10º and 20º angular rotations is within 0.75º of expected for 10º rightward and leftward rotations, and within 1.4º of expected for 20º rotations. As above, the head movement recorder output shows vertical positional error for these horizontal only movements (Figure A.4); horizontal head movements only were therefore studied in the experiments using the search task (Chapters 7 and 8).

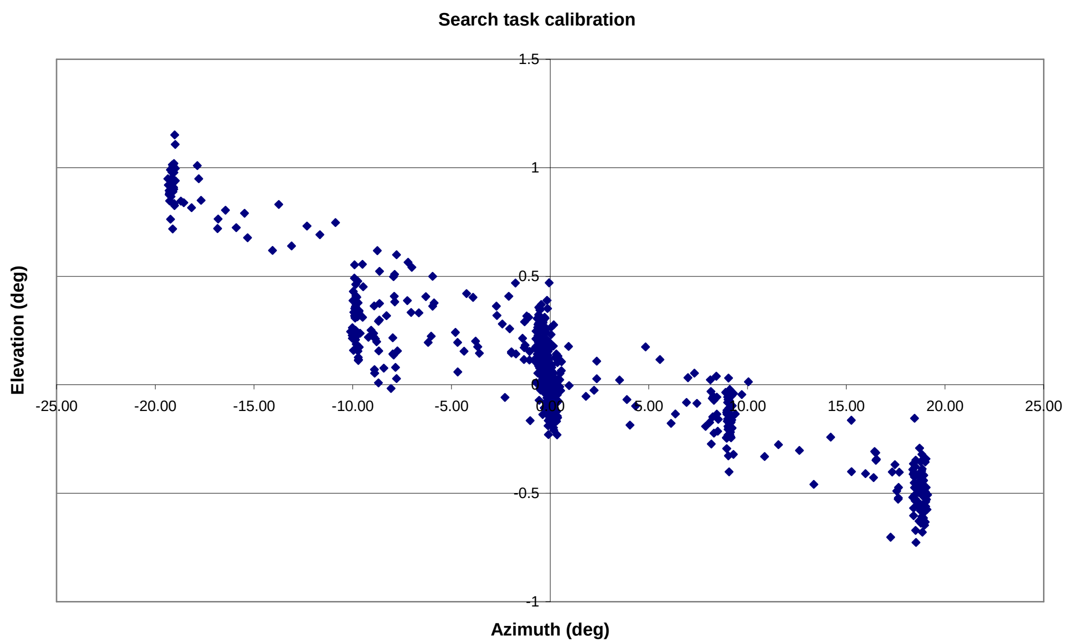

Figure A.4 Head movement recorder output for elevation plotted against azimuth for calibration in the search task. Vertical position error is evident for horizontal movement to 10º and 20º extent. In contrast to Figure A.2, more noise is evident in head movement recording, due to greater distance between transmitter and sensor in this task.

Appendix B Thresholding programme

```
{==================================================================
               DRIFT:  Head Movement, moving random dot field

==================================================================}
USES crt, dos, graph, BgiDriv, BgiFont, Utils,
        StrUnit, FormPrms, FormUnit, Defs;

CONST
      HiFast = $04;                      { divide by 1193 to get
milliseconds }
      LoFast = $A9;                      { 1193 = $04A9
}

       {----- variables for timer -----}
VAR yr,mon,day,dofw,hr,min,sec,s100 : word;
      int1Csave : pointer;                  { address of intr $1C,
BIOS timer }
      clock_installed : boolean;

      {----- Misc variables -----}
      left, ok, sw_active, Present_Stim, resp_req, dout_flag :
boolean;
      timeout, Trig_time, win_start, win_end, met_start, met_end
:longInt;
      limit_sw_time :longint;
      r, Trial, head_dir, sw, rsp, mode, speed_valid :integer;
      num_rev, num_correct, reversals, speed_dir, phase :integer;
      speed_mode, cycle_time, cond, err, dist_mon, scan_width
:integer;
      DegSec :real;
      old_speed, speed :integer;
      k :char;
      Correct, filename, st :string;
      ref_time :LongInt;
      fLog :text;

procedure SetNextTimes(tm :LongInt); forward;
```

```
{--------------------------------------------------------------------}
procedure CallIntr(p : pointer);
{--------------------------------------------------------------------}
begin
       inline($9C/                        { PUSHF           }
                  $FF/$5E/$04);                       { CALL FAR
[BP+4] }
end; { CallIntr }

{--------------------------------------------------------------------}
procedure clock;                                       {  INTERRUPT
ROUTINE  }
{--------------------------------------------------------------------}
                          { This routine is not called from prog, it
is interrupt driven }
interrupt;            { push and pop everything      NO interrupts
in here }
var regs:registers;
begin
       callIntr(Int1Csave);  { call real intr   }
       inline($FA);          { cli disable intr }
       inc(TmSec);           { TmSec is global  }
       inline($FB);          { sti enable intr  }
end; { clock }

{--------------------------------------------------------------------}
procedure change_freq(Hifast,Lofast:byte);
{--------------------------------------------------------------------}
begin
       port[$43]:= $36;                       { Reset the timer to
milliseconds }
       port[$40]:= Lofast;
    port[$40]:= Hifast;
end; { change_freq }

{--------------------------------------------------------------------}
procedure install_clock;
{--------------------------------------------------------------------}
var regs : registers;
begin
```

```
     getTime(hr,min,sec,s100);                         { store time
and date }
        getDate(yr,mon,day,dofw);
        getIntVec($1C,Int1Csave);                         { get
vector Intr 1C }
     setIntVec($1C,@clock);                { point intr $1C at clock
routine }
     clock_installed:= true;
     change_freq(Hifast,Lofast);       { set DOS tick to 1 mSec, not
55 mSec }
end; { install_clock }

{--------------------------------------------------------------------}
procedure adjust_time;
{--------------------------------------------------------------------}
begin
     s100:= s100+(TmSec DIV 10);
     sec := sec+(s100 DIV 100);                         { Total no. of
seconds }
     s100:= s100 MOD 100;
     min := min+(sec DIV 60);                           { Total no. of
mins    }
        sec := sec MOD 60;
        hr  := hr+(min DIV 60);                            { Total no.
of hours   }
     min := min MOD 60;
     day := day+(hr DIV 24);                            { Total no. of
days    }
     hr  := hr MOD 24;
end;                                   { Could be wrong if past end
of month }

{--------------------------------------------------------------------}
procedure uninstall_clock;
{--------------------------------------------------------------------}
var regs:registers;
begin
       if not clock_installed then exit;
       change_freq(0,0);                      { Restore the
original DOS tick }
```

```
       setIntVec($1C,Int1Csave);       { Restore the original '1Ch
int' vector }
       adjust_time;                                { Adjust the
internal timer  }
       setTime(hr,min,sec,s100);                   { for correct hrs,
mins etc. }
       setDate(yr,mon,day);
end;

{--------------------------------------------------------------------}
procedure SetNextTimes(tm :LongInt);
var met_offset :integer;
begin
      met_offset := WIN_TIME - MET_TIME;                     { set
metronome tick }
      Met_Start := Win_Start + met_offset;             { position
in window }
      Met_end := Met_Start + MET_TIME;
      Win_end := tm + WIN_TIME;
      Trig_time := Win_start + CYCLE_TIME div 2;             { set
the trigger point }
      Win_start := tm + CYCLE_TIME;
end;
{--------------------------------------------------------------------}
function Analyse_Resp(left :boolean; resp :integer) :boolean;
begin
      case resp of
            0: Analyse_Resp := false;           { timeout }
            1: Analyse_Resp := not left;        { right button }
            2: Analyse_Resp := left;            { left button }
            3: Analyse_Resp := false;           { both buttons were
pressed }
      end;

end;
{--------------------------------------------------------------------}
procedure Feedback(st :string);
begin
      SetFillStyle(SolidFill, Black);
      FillPoly(4, RECT);
      OutTextXY(20, 7, st);
```

```
end;
{----------------------------------------------------------------}
                        convert number of pixels moved to
Degrees/Second
-----------------------------------------------------------------}
function Degrees_Sec(NumPix, Subj_dist, mon_width :integer) :real;
var mm, speed : real;
begin
      speed := NumPix * (1000 / STIM_PERIOD);
{ pixels per second  }
      mm := speed * mon_width / 640;                      { mm. per
second     }
      Degrees_Sec := ArcTan(mm/subj_dist) * 180/PI;       { degrees
per second }
end;

{=================================================================
                        M A I N   P R O G R A M
=================================================================}
BEGIN
      clrscr; nosound;
      ok := GetParams;                                { display
parameter entry form }

      if (not ok) then exit;                           { ESCAPE
pressed - exit the program }

      val(Ent[1], cond, err);                              {
condition, speed/stimulus height }
      val(Ent[2], dist_mon, err);            { distance to monitor
(mm)         }
      val(Ent[3], scan_width, err);          { scan width on screen
(mm)        }
      val(Ent[4], num_correct, err);         { number correct to
decrease speed }
      val(Ent[5], num_rev, err);             { number of reversals }
      val(Ent[6], target_pc, err);                    { target size,
percent of H & W    }

      case cond of
            1..3: begin
```

```
                        speed_mode := 1;
      { stationary }
                        cycle_time := SLOW_MOVE;
                  end;
            4..6: begin
                        speed_mode := 2;            { slow
head movement }
                        cycle_time := SLOW_MOVE;
                  end;
            7..9: begin
                        speed_mode := 3;                    {
fast head movement }
                        cycle_time := FAST_MOVE;
                  end;
      end;

      Filename := Ent[0] + '.txt';
      Assign(fLog, Filename); Rewrite(fLog);          {**** Debug
only ****}
      filename := Ent[0] + '.csv';                      { open data
output file }
      Assign(fout, filename); Rewrite(fout);
      WriteLn(fout, 'Trl,Cond,DegSec,Correct,Rev,Pxls,HdSpd'); {
headings, data file }

      port[$378] := $F0;                                  { power for
pullup R's, green LED off }

      install_clock;
      initialise;
                  { set up graphics drivers }
      RandSeed := 13911;
              { same pattern every trial }
      SetLimits;                                                  {
set movement rectangle }
      MakeDotScreen;                                  { setup random
dot screen }
      wait(1000);
      Feedback('Calibrate');
      dot_time := round(GetCalibTime/100)+1;              { time
to move rect 1 pixel }
```

```
      Feedback('');
      Randomize;                                    { randomise
the movements }

      k := #0; head_dir := 0; mode := 0; Trial := 0;
      Speed_dir := SLOWER;
      max_speed := round(STIM_PERIOD/dot_time);  { no. of dots that
can be moved }
      speed := max_speed;
      if (target_pc < 30) then                      { set the
starting speed }
            speed := max_speed div 2;
      if (target_pc < 20) then                      { set the
starting speed }
            speed := max_speed div 16;

      Last_correct_speed := max_speed;
      last_touch_time := 0;
      last_head_speed := 0;
      dout_flag := false;
               { flag - data to be saved }

      reversals := 0;
      phase := 1;                        { indicates first run,
single steps }
      sw_active := false;                      { flag - limit
switch active    }
      Present_Stim := false;                   { flag - ok to
present stimulus }
      resp_req := false;                            { flag - subj
response required }

      wait(3000);
      Flush_Kbrd_Bufr;
      win_start := TmSec;

      {--------------------- Main program loop -------------------}


             { Keep looping until ESC key pressed }
```

```
      repeat                               { or the no. of reversals
is reached }
            case mode of
                  0: if (TmSec >= Win_Start) then begin
                              mode := 1;
                              SetNextTimes(Win_Start);
                              Ref_Time := TmSec;
                        end;

                  1: if (TmSec >=  Met_Start) then begin
                              mode := 2;
{ref_time := TmSec;}
                              sound(500);     { metronome on }
                        end;

                  2: if (TmSec >= Met_End) then begin
                              mode := 3;
                              nosound;        { metronome off }
                        end;

                  3: if (TmSec >= Win_End) then begin
                              mode := 0;
                              if (speed_mode = 1) then begin
            { stationary mode only }
                                    inc(head_dir);
                                    head_dir := head_dir and 3;
                              end;
                        end;

            end;  { case }

            {------- Is this movement suitable to present a
stimulus? ------}

            if (speed_valid > 1) and (head_dir = 2)
                  then Present_Stim := true
                  else present_stim := false;

            {----- check the trigger time & present stimulus if
appropriate -----}
```

```
            if (TmSec >= (Trig_time-40)) then begin
                  Trig_time := (TmSec + CYCLE_TIME);
                  sw_active := false;
            { clear limit switch flag }

                  if (Present_Stim) then begin               { do we
present a stimulus? }
                        present_stim := false;
                        sound(1000); wait(40); nosound;
      { cue - response required }
                        resp_req := true;                    { flag -
subj response required }
                        timeout := TmSec + RESP_PERIOD;  { set the
subj response timeout }

                        left := (random(2) < 1);                    {
set stimulus direction }
                        if (left)
                              then MoveDotsLeft(speed, STIM_PERIOD)
                              else MoveDotsRight(speed,
STIM_PERIOD);        { speed, time  }

                        {--- force speed to be re-validated by limit
switches ---}
                        { ie. if limit sw's not touched speed would
have stayed valid }
                        speed_valid := 0;
                        port[$378] := $F0;
                                { green LED = off }
                  end;
            end;

            {-------------- Check for  subject response or timeout -
-------------}

            if (resp_req) then begin
                  rsp := GetSubjResp;

                  {------ process subject response and save the data
------}
```

```
                if (rsp > 0) or (TmSec > timeout) then begin    {
has subj responded? }
                        resp_req := false;
                        data[trial].correct := Analyse_Resp(left,
rsp);

                        if (data[trial].correct)
                              then correct := 'Y'
                              else correct := '-';
                        Feedback(correct);            { feedback,
displayed at top left of screen }

                        data[trial].trl := trial;             { save
data assoc with this response }
                        data[trial].speed := speed;
                        data[trial].cond := cond;
                        data[trial].speed := speed;
                        data[trial].DegSec := Degrees_Sec(speed,
dist_mon, scan_width);
{                       data[trial].correct := correct;}
                        data[trial].reversals := reversals;
                        dout_flag := true;
{                       Writeln(fout, Trial, ',', cond, ',',
DegSec:7:2, ',', correct,',', speed:5,',', reversals);
}
                        old_speed := speed;

                        {--------------- check the phase, 1 or 2 ---
------------}

                        case phase of                        {---
phase 1 = initial run ---}
                              1: if (data[trial].correct) then begin
        { reduce speed }
                                          Last_correct_speed :=
speed;
                                          speed := speed - ((speed
div 3) + 1);           { large change }
                                          if (speed < 1) then speed
:= 1;
                                    end
```

```
                                    else begin
{ increase speed }
                                          phase := 2;
                                          speed := speed +
(last_correct_speed-speed) div 2;   { smaller change }
                                          if (speed > max_speed )
then speed := max_speed;
                                          reversals := 1;
                                    end;

                        { phase 2 = all subsequent runs }
                              2: if (data[trial].correct) then begin
                                          if
(Last_n_Correct(num_correct, trial)) then begin
                                                speed :=
New_Speed(trial);

      Speed_Reversal(speed_dir, speed, old_speed); { set dir change?
}
                                          end;
                                    end
                                    else begin
                                          speed := New_Speed(trial);
                                          if
(Speed_Reversal(speed_dir, speed, old_speed))
                                                then inc(reversals);
                                    end;
                        end; { case }

                        inc(Trial);
                  end;  { if rsp > 0 }
            end;   { if resp_req }

            if(speed_mode = 1) then begin
                   if (dout_flag) then begin
                         if (data[trial-1].correct)
                               then correct := 'Y'
                               else correct := '-';

                         Write(fout, data[trial-1].trl, ',',
data[trial-1].cond, ',', data[trial-1].DegSec:7:2, ',');
```

```
                         Write(fout, correct, ',', data[trial-
1].reversals, ',', data[trial-1].speed, ',', last_head_speed);
                         Writeln(fout);
                         dout_flag := false;
                   end;
            end;

            {--------- check L & R limit switches, validate head
speed ---------}

            if (speed_mode > 1) then begin                   { Fast
& Slow head movement modes }
                  sw := GetLimitSwitch;

                  if (sw > 0) and (sw_active=false) then begin
                        sw_active := true;                  { flag
leading edge of limit sw }
                        head_dir := sw;                     { flag
dir the head is turning  }

                        last_head_speed := TmSec-last_touch_time;
                        last_touch_time := TmSec;

                        limit_sw_time := TmSec + round(CYCLE_TIME *
1.5);

                        if (dout_flag) then begin
                              if (data[trial-1].correct)
                                    then correct := 'Y'
                                    else correct := '-';

                              Write(fout, data[trial-1].trl, ',',
data[trial-1].cond, ',', data[trial-1].DegSec:7:2, ',');
                              Write(fout, correct, ',', data[trial-
1].reversals, ',', data[trial-1].speed, ',', last_head_speed);
                              Writeln(fout);
                              dout_flag := false;
                        end;
```

```
                        Writeln(fLog, ref_time, ',', TmSec,',',
TmSec-Ref_time, ',', sw, ',', last_head_speed); { log file,
touch/window }

                        if (mode > 0)                              {
is leading edge inside the window? }
                              then begin
                                    inc(speed_valid);
        { YES, head speed is valid }
                                    port[$378] := $F1;
                    { green LED = on }
                              end
                              else begin
                                    speed_valid := 0;
                   { NO, invalid head speed }
                                    port[$378] := $F0;
                        { green LED = off }
                              end;
                  end; { if sw > 0 }

                  {--- has a limit switch been missed? ---}
                  if (TmSec > limit_sw_time) then begin
                        speed_valid := 0;
                        port[$378] := $F0;
                  end;
            end
            else begin
             {---- head stationary mode ----}
                  speed_valid := 3;
            end;if (KeyPressed) then k := ReadKey;
      until (k = #27) or (reversals > num_rev) or (trial >
MAX_TRIALS);  {--- Terminate test? ---}
nosound;
      Close(fout);
      Close(fLog);                       {**** DEBUG ONLY
****}uninstall_clock;
      Closegraph;
      WriteLn('Finished');
      Writeln('No. of trials: ', trial, '    Reversals: ',
reversals-1);
END.
```

Appendix C: Questionnaires

The symptoms questionnaire and rating scales for lens preference forced choice comparisons follow this page.

Part 1
General Information

Subject ID:
Lens Pair:
Order:

1. How many hours a day did you wear the glasses? ☐

When wearing the spectacles, please rate:

		Very Poor	Poor	Acceptable	Good
2	your peripheral vision at far distances	☐	☐	☐	☐
3	your peripheral vision at mid distances	☐	☐	☐	☐
4	your peripheral vision at near distances	☐	☐	☐	☐
5	your vision when moving about	☐	☐	☐	☐

Distance vision

Distance vision involves viewing distances greater than 2 metres, that is beyond about two arm's lengths. Examples: driving, watching TV, looking out the window, looking across the road, watching a play or movie.

When wearing the spectacles, did you notice:

6. A feeling that objects in the sides of your vision were distorted?

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

7. Difficulty judging distance or position from other objects?

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐	☐	☐	☐	☐

8. **Things in your field of vision seeming to move UP AND DOWN:**

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

9. **Things in your field of vision seeming to move SIDE TO SIDE**

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

10. **Things in your field of vision seeming to SWAY OR TILT**

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

11. Things in your field of vision seeming to move TO AND FRO:

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

Intermediate Vision

Intermediate vision involves viewing distances of between 1/2 metre and 1 metre, around one arm's length. Examples: Looking at a computer screen, working at a desk, or bench using tools, ironing, face-to-face conversation, cooking, general kitchen jobs.

When wearing the spectacles, did you notice:

12. A feeling that objects in the sides of your vision were distorted?

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

13. Difficulty judging distance or position from other objects?

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐	☐	☐	☐	☐

5 4 3 2 1

14. Things in your field of vision seeming to move UP AND DOWN:

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

15. Things in your field of vision seeming to move SIDE TO SIDE

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

16. Things in your field of vision seeming to SWAY OR TILT

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

17. Things in your field of vision seeming to move TO AND FRO:

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

Near vision

Near vision refers to objects from about 50 cm or closer. Examples: reading this questionnaire, writing, sewing, fine handicrafts, using a map or telephone book.

When wearing the spectacles, did you notice:

18. A feeling that objects in the sides of your vision were distorted?

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

19. Difficulty judging distance or position from other objects?

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

20. Things in your field of vision seeming to move UP AND DOWN:

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

21. Things in your field of vision seeming to move SIDE TO SIDE

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

22. Things in your field of vision seeming to SWAY OR TILT

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

23. Things in your field of vision seeming to move TO AND FRO:

Always	Frequently	Sometimes	Infrequently	Never
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

If you noticed this, was it:

very annoying		annoying		a little annoying		never annoying
☐ 7	☐ 6	☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

How much more noticeable was this if you were moving about?

very much	much	a little	just a little	no different
☐ 5	☐ 4	☐ 3	☐ 2	☐ 1

Lens Preference

Subject ID: [ ]
Order [ ]

Active vision

When looking and moving around or turning their head some people report that their spectacles distort the natural motion of objects and/or their view appears to be 'warped', 'swaying' or 'rocking' making them feel disoriented or uneasy.

Please indicate for each comparison your preferred lens pair for for **ACTIVE vision** tasks?

1 vs 2

1	2
[ ] 1	[ ] 2

What was the strength of your preference. My preferred pair was...

no different	just better	better	much better	very much better
[ ] 1	[ ] 2	[ ] 3	[ ] 4	[ ] 5

1 vs 3

1	3
[ ] 1	[ ] 2

What was the strength of your preference. My preferred pair was...

no different	just better	better	much better	very much better
[ ] 1	[ ] 2	[ ] 3	[ ] 4	[ ] 5

2 vs 3

2	3
[ ] 1	[ ] 2

What was the strength of your preference. My preferred pair was...

no different	just better	better	much better	very much better
[ ] 1	[ ] 2	[ ] 3	[ ] 4	[ ] 5

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